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DEPARTMENT OF MINES AND TECHNICAL SURVEYS

BULLETIN 68

THE GEOLOGY OF THE ATHABASCA FORMATION

W. F. Fahrig

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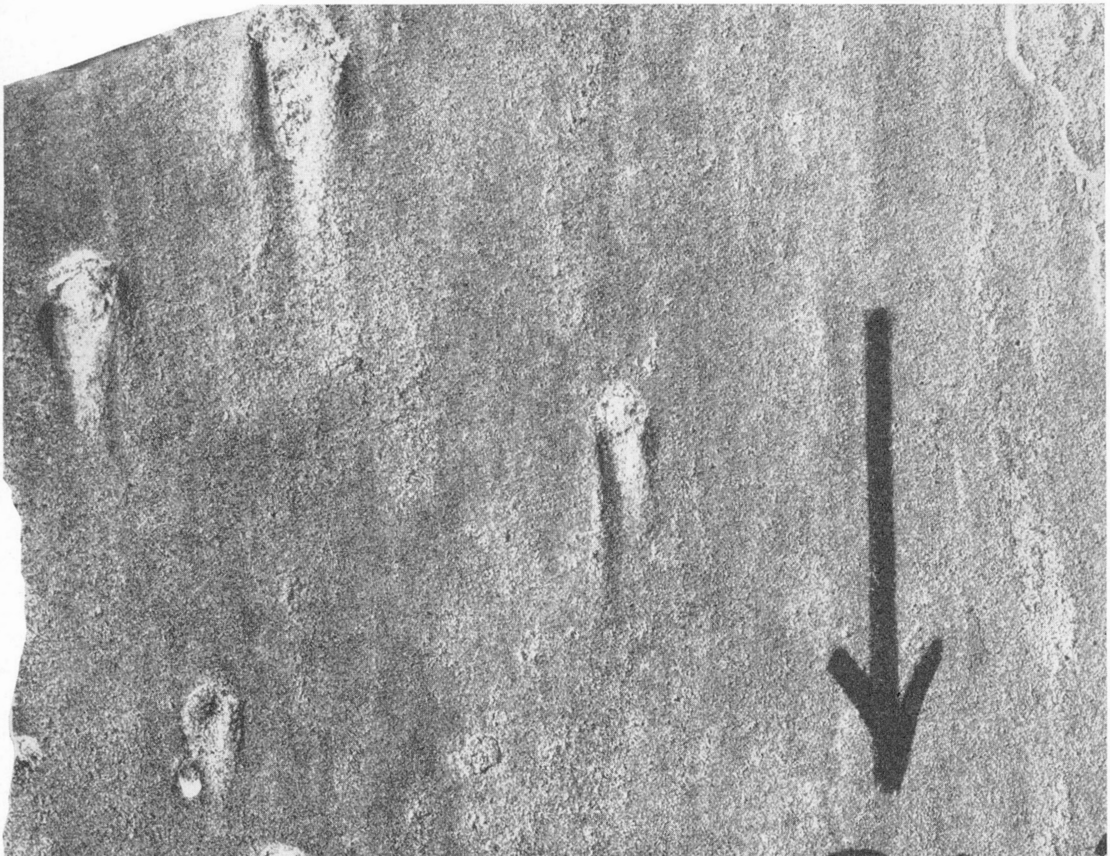

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Plate 1 Imbricate shale chips and current lineation (current direction shown by arrow).

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PREFACE

Several areas within the western part of the Canadian Shield are underlain by sequences of unfossiliferous rocks that are relatively undeformed and unmetamorphosed. The age and regional correlation of these rocks are doubtful. One of these sequences, composed of the Athabasca and Carswell formations, lies near known Palæozoic strata and it was hoped that a study of this sequence would reveal new data on its age and on its method of accumulation, both features of interest for petroleum prospecting.

The results obtained by the author, embodied in this report, include significant new data on the history of the sedimentation, and on the age and correlation of the Athabasca and Carswell formations. The description of the remarkable circular structure in the Carswell Lake area is also included.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, March 21, 1960

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THE GEOLOGY OF THE ATHABASCA FORMATION

Abstract

A systematic study was made of the Athabasca formation to determine the history of its sedimentation, its regional correlation, and its age.

This formation, covering an area of 40,000 square miles in northern Saskatchewan, is predominantly sandstone with minor shale and conglomerate beds. Shale chip fragments are abundant on bedding planes throughout the formation. The measurement of 1,200 crossbeds and other current features showed that the sands were carried into the basin from the east and southeast and that the lines of transportation converged as they passed towards the northwest. As the Martin formation north of Lake Athabasca was deposited in an area of high relief and the direction of transport of the Athabasca is towards this area, it seems unlikely that the two formations were deposited contemporaneously.

The crossbedding of the Athabasca is predominantly in the form of narrow 'troughs' and the coarse material is poorly sorted and lensy, suggesting scour and fill deposition in the beds of fluctuating streams. The shale chips probably indicate extremely shallow water and temporary withdrawals. These and other data suggest that the Athabasca was predominantly a fluviatile deposit in a coastal plain environment.

The sandstones are mature, with a small heavy mineral content and considerable chert. These data suggest that the sandstone is a multicycle product derived from a largely sedimentary terrain.

The Carswell formation, a dolomite sequence overlying the Athabasca, is present as a ring of intensely folded strata about 18 miles in diameter. Basement gneiss outcrops within the ring suggesting a domal structure. The dolomite indicates that the predominantly fluviatile environment of the Athabasca was replaced by a marine environment.

The Athabasca formation is locally folded and intruded by diabase dykes. Pitchblende veins that cut the formation have been dated as about $4x10^8$ years. The Athabasca formation is probably of Precambrian age.

Résumé

On a effectué une étude systématique de la formation Athabasca afin de retracer le processus de sa sédimentation et pour déterminer sa corrélation régionale et son âge.

Cette formation s'étend sur une superficie de 40,000 milles carrés dans le Nord de la Saskatchewan et renferme surtout du grès, ainsi que quelques petities couches de schiste et de conglomérat. Dans toute l'étendue de cette formation, des fragments de schiste abondent sur les plans de stratification. L'étude de 1,200 cas de stratification entrecroisée et d'autres traits propres aux courants a démontré que les sables qui avaient été charriés dans le bassin, provenaient de l'est et du sud-est et que les directions de transport convergeaient vers le nord-ouest. Étant donné que la formation Martin, sise au nord du lac Athabasca, s'est déposée dans une région à relief accentué et que la direction de transport de la formation Athabasca est orientée vers cette région, il semble peu probable que ces deux formations soient des dépôts contemporains.

La stratification entrecroisée de l'Athabasca se présente surtout sous forme d'étroits «fossés»; les matériaux grossiers y sont mal classés et lenticulaires, et laissent croire à une déposition par affouillement et remplissage dans des lits de cours d'eau à tracé variable. Les fragments de schiste sont un indice probable d'eau extrêmement peu profonde et de régressions temporaires. Ces constatations et d'autres données portent à croire que la formation Athabasca se compose principalement de sédiments fluviatiles déposés dans un milieu apparenté à une plaine côtière.

Les grès sont du stade de maturité et contiennent beaucoup de chert et bien peu de minéraux lourds. D'après ces renseignements, ce grès serait un produit à cycles multiples provenant d'un terrain en grande partie sédimentaire.

La formation Carswell est une succession de roche dolomitique surjacente à la formation Athabasca. Elle se présente sous la forme d'un anneau à strates très plissées d'un diamètre d'environ 18 milles. Les gneisses anciens affleurent au sein de l'anneau, ce qui suppose une structure en forme de dôme. La dolomie indique que le milieu principalement fluviatile où s'est déposée la formation Athabasca a, par la suite, donné place à un milieu marin.

La formation Athabasca est plissée en certains endroits et entrecoupée de dykes de biabase. On a établi à environ $4x10^8$ années l'âge des filons de pechblende qui coupent cette formation. La formation Athabasca remonte probablement au Précambrien.

INTRODUCTION

The Athabasca sandstone, particularly south of Lake Athabasca, has attracted relatively little geological attention since it was first discovered during the last century. This is because the rock itself is not promising from an economic standpoint and the region is generally heavily drift covered. Such major aspects as the age of the sandstone and the conditions of its formation have remained in doubt. During the summers of 1957 and 1958 the writer continued the field study begun by D. A. W. Blake in 1952.

The writer proposes a partly new terminology for some of the unmetamorphosed rocks of the Athabasca region. This is intended to replace some of the older nomenclature and constitutes a more rigorous application of stratigraphic rules as applied to the naming of Precambrian rock stratigraphic units. Among other advantages it will simplify reference to the various units (*see* Fig. 1).

Athabasca formation is the term applied to the generally flat-lying, predominantly sandstone sequence occurring south of Lake Athabasca, on islands south of Crackingstone Peninsula, and at isolated points along the northwest shore of the lake. *Carswell formation* is applied to the carbonate sequence that overlies the Athabasca formation, and forms a ring of outcrops which is intersected by Carswell Lake. *Martin formation* includes the 'red-bed' sequence that outcrops just north of Lake Athabasca, notably around Martin Lake and the east end of Tazin Lake (*see* Fig. 1), and which is lithologically distinct from the Athabasca formation.

The reasons for this proposed terminology become evident in the later discussions of the various units; detailed descriptions of the Athabasca and Carswell formations are given in this report and a detailed description of the Martin formation is available in Christie (1953) and in Tremblay (1955).

ACKNOWLEDGMENTS

R. Fulton and W. Parker ably assisted the writer during the 1957 and 1958 field seasons, respectively. A number of other persons besides his colleagues of the Geological Survey of Canada gave interested help and advice on the project, among whom were G. E. Ellingham, Saskatchewan Geology Survey; P. E. Potter, Illinois State Survey; D. A. W. Blake and W. C. Gussow. B. R. Pelletier of the Geological Survey of Canada provided much appreciated advice and criticism. His study of Pocono Paleocurrents (Pelletier, 1958), although more extensive than the present work, was used as a model for many of the subjects covered.

PREVIOUS WORK

The rocks of the Athabasca intracratonic basin have previously been examined mainly on reconnaissance geological trips or where they underlie parts of more economically interesting bordering map-areas. The beginning of this project by Blake in 1952 constituted the first attempt to study the rocks of this basin as a unit.

In 1888, R. G. McConnell (1893) examined the south shore of Lake Athabasca from the Athabasca River to William Point and noted "granular siliceous sandstone", which he called 'Athabasca sandstone', at Pointe de Roche (Stone Point), and at a point 7 miles to the east. As specimens collected in 1882 by A. S. Cochrane from the east end of the lake were indistinguishable from those at Pointe de Roche, McConnell believed that the 'Athabasca sandstone' probably extends along the entire south shore. From its general character and its position, he suggested that the sandstone belongs to one of the divisions of the Cambrian.

J. B. Tyrrell (1896) reported on trips made by himself and his assistant, D. B. Dowling, in the country between Lake Athabasca and Churchill River. That report includes many observations on the 'Athabasca sandstone' as it outcrops on Fond du Lac and Cree Rivers and on the shores of Lake Athabasca. Tyrrell's map that accompanies his report defines fairly well the extent of the sandstone to the south of the lake, and he stated (p. 18) "Cree Lake lies largely within the area underlain by these rocks, and Lake Athabasca seems to lie entirely within it, for the red sandstones compose many of the islands and more prominent points of its northern shore". With regard to the age of the Athabasca (p. 18) he stated: ". . . while exploring the country northward towards Chesterfield Inlet, similar sandstones were found overlying the Archæan, associated with quartz-porphyries, diabases, etc., like those of the Keewenawan rock of Lake Superior. The likeness is so pronounced that there would seem to be little doubt that the two sets of rocks belong to the same geological horizon."

Tyrrell was of the opinion that the horizontal, red, quartzite-boulder conglomerate on islands south of Crackingstone Peninsula was probably the same age as the Athabasca. Of the rocks on Cree Lake, he reported (p. 41) "Some soft calcareous spots have possibly been fossils, but they now show no trace of structure". Also in a section near the mouth of Beaver River he observed (p. 71) ". . . at the base a bed of light-coloured fine-grained sandstone is found to contain many small disc-like nodules of irregular shape, of a light green cherty material". Tyrrell was the first to report a diabase dyke within the Athabasca formation on the southwest side of Cree Lake and the highly altered sandstone exposed northwest of the dyke. 'Falsebedding' in sandstone on Cree River and ripple-marking west of Black Lake were noted by him.

Alcock (1920) used the term 'Athabasca series' to include three areas of rock: the sandstones south of Lake Athabasca, the smaller areas of red beds north of the lake, and the large area of sandstone around Dubawnt Lake, Northwest Territories. He noted that the 'series' was extensively crossbedded and that south of

Lake Athabasca "the prevailing type consists of diagonal layers bounded above and below by horizontal beds". He stated further:

> At the eastern end of the lake the slope of the foreset beds is uniformly to the southwest indicating a source of supply from the northeast.
>
> In the areas north of Lake Athabasca the same type of crossbedding is dominant. In the small outcrops between Sand and Big Points, however, a more irregular type is presented, showing curved and foreset beds irregularly truncated by other curved beds above. This type, however, is on a smaller scale, and is much less abundant than the variety first described.

This writer reported sun-cracks only in the fine-grained rock north of Beaverlodge and attributed the paucity of these structures to the coarse clastic nature of the 'series'. One example of rain-prints south of Stone River was noted, as well as ripple-marking in several localities. He referred to 'clay-balls' as follows:

> South of Stone River a number of round impressions filled with clay were found in the sandstone. These vary in size from one to two inches in diameter, and are very thin, their method of occurrence was found to be the same in every case, for they were only observed in the plane between the foreset laminae and the top-set laminae of the underlying stratum.

Alcock pointed out that the thickness of the flat-lying series south of the lake is more than 400 feet whereas more than 8,000 feet of folded conglomerates, arkoses, and sandstones are exposed north of Beaverlodge. With regard to intrusions, he stated that the series is traversed by dykes and sills of diabases of contemporaneous age.

The association of the Athabasca 'series' with intrusive and extrusive diabase, Alcock felt, favours a Precambrian (Keewenawan) rather than a Cambrian age. On conditions of deposition he concluded: ". . . broad subsiding basins between mountains of considerable relief; a semi-arid climate, in which erosion and disintegration proceeded rapidly, loading up the streams to their ultimate capacity; torrential floods in which the coarse materials were spread over the river flood-plains, followed by dry seasons in which the sediments were exposed to the air, and their iron content oxidized. The farther the materials were transported, the more would the feldspar content be sorted out, until finally the detritus would consist of practically quartz grains only. Progressive subsidence and rapid erosion would eventually give rise to a thick series with all the features characteristic of the formation." Alcock (1936, p. 21) summarized previous work on the Athabasca sandstone and provided a more extensive description of the folded red-bed sequence around Beaverlodge. In correlating these folded sediments with the flat-lying sandstones and conglomerates on islands south of Crackingstone and south of the lake he stated (p. 22): "North of the lake are a number of other areas underlain by conglomerates and arkoses. Some of these have high dips in contrast with the flat or low dips in the type area, but on the basis of lithology they have been correlated with the Athabasca sandstone."

Sproule (1938) described the Athabasca formation as it occurs in the Cree Lake area, Saskatchewan, and his description included: "Many of the massive as well as the crossbedded, strata contain numerous, irregular-shaped light coloured lime pellets up to an inch in diameter". With regard to the contact of the Athabasca formation with underlying rocks, he commented: "The exact contact was not anywhere observed, but all along the boundary zone the crystalline rocks exposed are rotted and disintegrated by long weathering, in sharp contrast to the same rocks freshly truncated and polished by glaciation."

The term 'Athabasca formation' was used by Sproule (1940), Sproule and Downie (1940), and Sproule, Ells and Downie (1940) in their legends, and the formation was placed in the late Precambrian although they indicated in their descriptive notes that it may be of Palæozoic age. Presumably the Athabasca was assigned to the Precambrian because it is unfossiliferous. On the other hand, because the sandstone is flat lying and unaltered some doubt was felt about this designation.

Christie, A. M. (1953) discussed the Athabasca 'series' as it is represented in the Goldfields-Martin Lake map-area which lies chiefly northeast of Crackingstone Peninsula. He grouped in the Athabasca 'series' the flat-lying sandstones that outcrop on islands in Lake Athabasca east of Crackingstone Peninsula and also the belt of folded sedimentary rocks northeast of Beaverlodge Lake and on the east end of Tazin Lake, and made the following comment (p. 54):

> The character of the conglomeratic, arkosic, and crossbedded sediments in the folded areas indicates that they were deposited near shore in shallow water. Mud flats occur locally. This type of deposition is common in basins of interior drainage or in deltaic or shallow water littoral deposits. Because of the talus type conglomerates, with angular pebbles at the base of the series, and the location of known faults, it is believed that the Athabasca sediments were deposited in separate basins formed by earth movements resulting, mainly, in faults.
>
> The flat-lying Athabasca sedimentary strata of the islands in Lake Athabasca differ from the beds of the folded areas in that, except for a few minor pebble bands, they contain no conglomerates, and are more siliceous and less arkosic, being dominantly feldspathic sandstones or sandstones. They may be grey, to pink, to red, commonly exhibit crossbedding, and more rarely exhibit mud-cracks in the finer grained bands.

In correlating the folded rocks north of Lake Athabasca and on islands in the lake with the sandstone south of the lake, he stated (p. 55): "(1) the change in composition and structure is gradational from the arkosic rocks of the folded basins to the north of the lake, to the less feldspathic and flat-lying sandstones of the islands in the southern part of the map-area, to the siliceous sandstone with well-rounded quartz grains described by Alcock from the type-area of this series south of Lake Athabasca; (2) their unconformable relations with the older rocks and their similar degree of consolidation; and (3) the strata of both areas contain basic igneous rocks and are intersected by northeast and east northeast striking regional faults." Christie placed the Athabasca 'series' in the Proterozoic.

Hale (1954a, b, and 1955) mapped an area north and west of Black Bay on Lake Athabasca and in his preliminary accounts concluded that a major unconformity exists within the Athabasca rocks of that map-area.

Fraser (1954), after mapping the southwest part of Crackingstone Peninsula and islands to the south, reported that at least some of the movement along the Black Bay fault, a major structural element of the area, has taken place since the deposition of the Athabasca 'series'.

Blake (1956) summarized previous work on the Athabasca 'series' and reported many new observations that he made during the 1952 field season. He described a previously unknown belt of carbonate rock exposed in ridges westward from Carswell Lake as follows: "Its colour may be cream, buff, pink, or reddish, and beds vary from very fine to very coarse. The limestone is everywhere fine-grained or aphanitic but secondary calcite crystals up to ⅛ inch across may be found. In addition to having been severely folded into major anticlines and synclines, where strata dip up to 80 degrees, the rock has locally been deformed on a small scale. Zones of intense brecciation, intricate contortion, and rupture occur in many places. Although most of this deformation may be attributed to the compressional forces that produced the major folds it is probable that some of the deformation may also be due to forces at work during the lithification of limestone. Small concentric fragments seen in some places were thought possibly to be of organic origin, but Dr. W. A. Bell (personal communication) determined them to be concretions." Deposition and deformation of the carbonate prior to the deposition of the Athabasca sandstone were suggested because of the undeformed nature of the surrounding sandstone. Also, as the limestone is unmetamorphosed and the Tazin does not include this rock type, a post-Tazin age was suggested.

Some interesting observations with regard to deformation in the main sandstone area were made by Blake. He reported intense folding and recrystallization of sandstone on the southeast shore of Fir Island and Black Lake and brecciation and hydrothermal alteration of sandstone where it has moved down along a fault on the northwest shore of Black Lake. In addition minor warping of the sandstone strata between Turner Point and Archibald River, south of Riou Lake and on Fond du Lac River east of Black Lake was reported.

Blake also discovered a 5-foot diabase dyke intersecting the sandstone about 4 miles east of Turner Point, Lake Athabasca.

In discussing the relation of the sediments north and south of Lake Athabasca, he stated as follows:

> However, the rocks north and south of the lake differ lithologically in many respects and have apparently formed under different conditions. Rocks south of the lake are composed almost entirely of well-rounded quartz grains. With few exceptions, conglomerate beds and feldspar grains are virtually absent and the red colour so prevalent north of the lake is lacking. These facts indicate that the sediments have been transported a great distance and deposited in a broad, nearly level surface, and suggests that the correlation is unwarranted. On the other hand, both Christie and the writer believe that there is a transition from the arkosic type north of Lake Athabasca southward to the feldspar-free sandstone south of the lake.

He pointed to the deformation of the sandstone and intrusion by diabase as supporting a correlation and stated: ". . . that the clastic sediments north and south of Lake Athabasca were formed in the same general geological age but not necessarily simultaneously." With regard to the age of the Athabasca formation, Blake pointed out that pitchblende in the red beds of the Beaverlodge Lake area is of Precambrian age, that the formation has been deformed by folding and faulting and that it is intruded by diabase. These facts suggest a Precambrian age for this unit.

Gussow (1957, 1959) suggested that the Athabasca formation is Palæozoic in age and stated:

> Regionally, the flat-lying Athabasca and the flat-lying Palæozoic formations of the Interior Plains are structurally conformable, and both lie with angular discordance on the crystalline rocks of the Churchill georogen. Obviously the Athabasca formation is very much younger than even the youngest rocks of the basement complex—the Martin Lake series—and is much more closely related in age to the Palæozoic section of the Plains.

By Martin Lake 'series' the writer meant the relatively unmetamorphosed, folded red beds north of Lake Athabasca (Martin formation). He referred to an unpublished thesis by J. C. Mawdsley at the University of Alberta in which the conclusion is reached that the presence of "optically oriented" authigenic tourmaline indicates a marine origin for the Athabasca sandstone. This is not, however, an established criterion for distinguishing between marine and freshwater sedimentary formations. Gussow tentatively correlated the Athabasca sandstone with Devonian strata at Contact Rapids on Clearwater River.

Gravenor (1959) compares three samples of sandstone from the Fidler Point area with four samples of Athabasca sandstone, three of the latter from near Stone Point, and stated: "It is possible that Fidler Point sandstone is a facies of the Athabasca sandstone but the writer prefers to consider that the Fidler Point sandstone is slightly older than the Athabasca sandstone and *possibly is a remnant of the source rocks of the Athabasca sandstone.*" Neither of these suggestions is valid in the light of the history of Athabasca sedimentation which is developed in this study.

GENERAL GEOLOGY OF THE ATHABASCA FORMATION

Gross Lithology

The Athabasca formation consists of interbedded shale, sandstone and conglomerate. Siltstone and shale beds were observed at fewer than ten localities and at these points generally total a foot or less in exposed sections which are as much as 100 feet thick. One maroon shale layer exposed along the rapids below Davey Lake is about 5 feet thick. Shale beds are believed to constitute less than one per cent of the total section of Athabasca formation exposed at the present erosion level of the basin. The remainder of the formation is chiefly sandstone; approximately 2 per cent is grit and conglomerate if these are defined as rocks containing more than 10 per cent of the appropriate coarser fraction.

About half of the particles in the sandstone fall in the coarse to very coarse ($\frac{1}{2}$ to 2 mm) sand size range and a minor amount falls in the fine to very fine ($\frac{1}{4}$ to 1/16 mm) range (*see* Fig. 3). Granules (2 to 4 mm) and pebbles (4 to 64 mm) probably form less than 5 per cent of the entire formation, including in this estimate grit and conglomerate beds. Cobbles and boulders are lacking in the Athabasca formation, except in the lower few feet, where coarse cobbles and boulders were observed at several points.

An attempt was made to outline regional variations in sediment size within the exposed part of the formation. Because of practical difficulties in terms of time and work involved in accurate, systematic sediment size determination, this was made by recording the coarsest material present at each outcrop locality. Areas were outlined within which the coarsest material is medium grained ($\frac{1}{4}$ to $\frac{1}{2}$ mm) to very coarse grained (1.0 to 2.0 mm), very coarse grained to granule-sized (2.0 to 4.0 mm), and granule-sized to pebbly (4 to 64 mm). The results of this attempt to show size variation throughout the exposed parts of the formation are shown on Figure 1. The most significant feature is a more or less central zone, just southeast of Lake Athabasca, in which granules and pebbles are rare. This area is surrounded by areas in which either gritty and pebbly material were commonly observed or only gritty material was observed.

Shale chip fragments, either polygonal or ovoid, are common throughout the entire basin. These have been referred to by previous workers in the area as 'soft calcareous spots', 'clay balls', 'irregular-shaped light-coloured lime pellets', etc. The shale fragments observed by the writer were mainly cream in colour but a few dark red ones were observed. Shale chips occur chiefly on horizontal bedding planes and their presence in the rock is indicated chiefly by casts on exposed bedding planes (*see* Pl. II). The soft clay constituents are almost entirely removed by recent weathering. They are also sparsely and locally present on inclined surfaces of some crossbed units. Their size varies from 1 mm to about 5 cm, and locally their casts form an almost continuous pavement. Very rarely they show evidence of being actively transported by currents (*see* Pl. I). Shale chips were seldom observed in outcrops of coarser, pebbly sandstone. It is clear that they represent

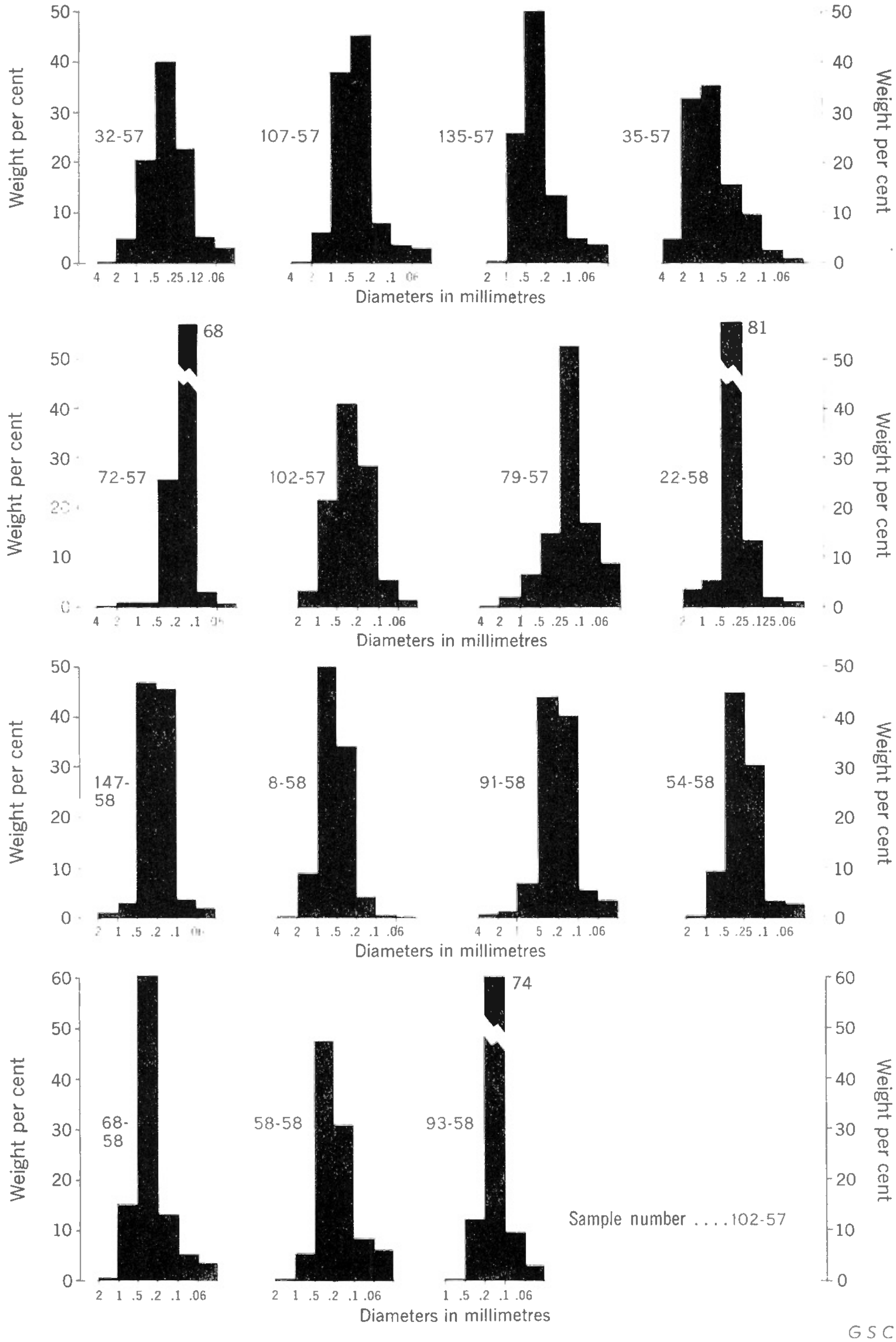

Figure 3. ***Histograms showing detrital grain diameters in the Athabasca formation.***

rhythmic deposition and subsequent disturbance of thin shaly layers. They indicate a very local source for the shale and suggest that currents of considerable intensity were present to erode, transport, and incorporate them to form intraformational breccias. Although the shale pebble layers are numerous and in some localities occur at intervals of about a foot through the section, they contribute only a minor amount of fine material to the bulk composition of the formation.

It is probable that the observed large-scale variation in size of clastic material in outcrops indicates a vertical stratigraphic variation (Fig. 1). Though the uppermost and lowermost zones contain lenses of coarser and finer material the lower tens and probably hundreds of feet of the Athabasca sediments contain considerable amounts of grit and conglomerate-sized material (Fig. 1). These materials are relatively rare in the upper part of the formation. Aside from this very general vertical size variation, the interbedding of coarse with fine material appears to be irregular and lensy in distribution throughout most of the formation. A local example of vertical stratigraphic variation may be observed in the vicinity of McLeod Lake. The base of a scarp about 8 miles northeast of McLeod is composed of medium- to coarse-grained sandstone which is overlain near the top of the scarp by a grey or pink sandstone containing about 25 per cent of pebbly beds. This coarse layer, which is thick-bedded, strongly crossbedded, and lacks ripple-marks and shale chips, extends a few miles west of McLeod. It is apparently overlain farther west by a layer of flat-bedded, medium- to coarse-grained pink sandstone containing small shale chips and minor ripple-marks. This is overlain by thin-bedded, medium- to coarse-grained sandstone with well-developed trough crossbedding. This series of beds is buff-pink, maroon, and brick-red in colour, The same stratigraphic sequence appears to be present between McFarlane Lake and Davey Lake. The upper varicoloured beds were observed above Davey Lake and in the rapids below the lake. Shale intervals are probably more common in this upper thin-bedded varicoloured sandstone than in other parts of the sequence.

The unconformity between the Athabasca sandstone and the underlying rocks has been described at a number of points along the northern rim of the basin (Blake, 1956). At the western outlet of Middle Lake, 2 to 5 feet of creamy, friable, intensely altered, Archæan gneiss is overlain by 2 feet of cream-coloured, medium-grained sandstone which in turn is overlain by thick units of maroon and cream, crossbedded, gritty and pebbly sandstone. This coarse-grained, predominantly maroon sequence is about 50 feet thick and is overlain by light grey, medium-grained to gritty sandstone. The lower Athabasca beds, and the underlying unconformity are exposed at a number of points on the shore of Lake Athabasca east of Poplar Point. At one place 5¼ miles east of the Point the basal Athabasca consists of maroon, hematite-rich sandstone with layers of angular, Tazin quartzite boulders (*see* Pl. III). The beds there dip in a northeasterly direction at angles up to 20 degrees and the trend of the axes of small crossbed troughs is about parallel with the strike of the beds. The Archæan-Athabasca contact zone at a point 4 3/5 miles east of Poplar Point consists of Tazin quartzite overlain by a few feet of buff coloured pebbly grit and then by varicoloured purplish grit. There is no apparent

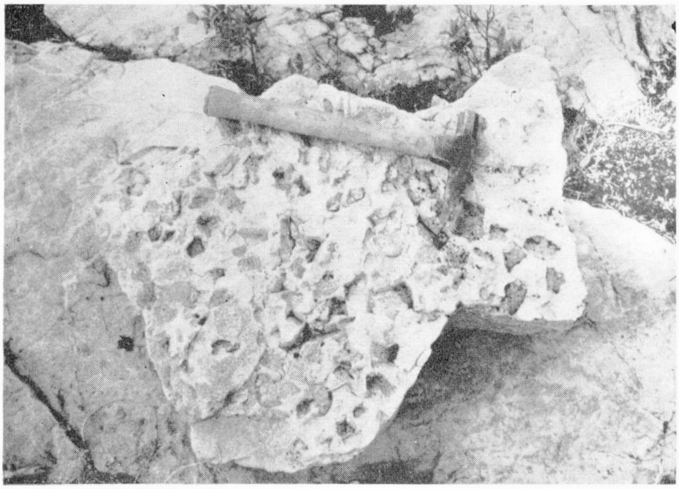

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Plate II

Shale chip casts on Athabasca bedding plane.

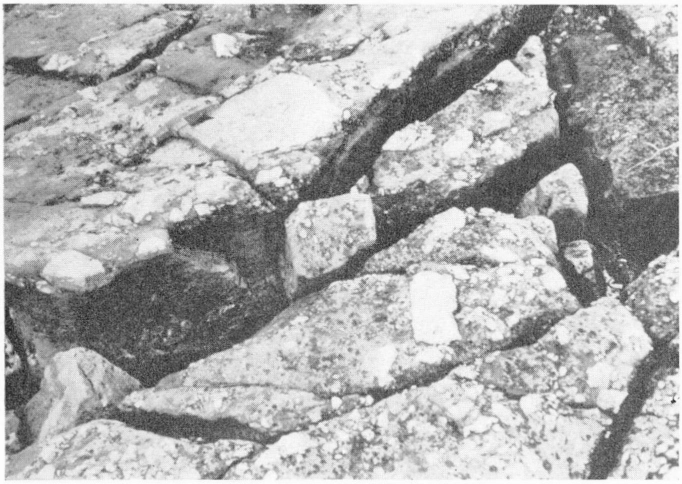

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Plate III

Angular boulders of Tazin quartzite in the Athabasca sandstone.

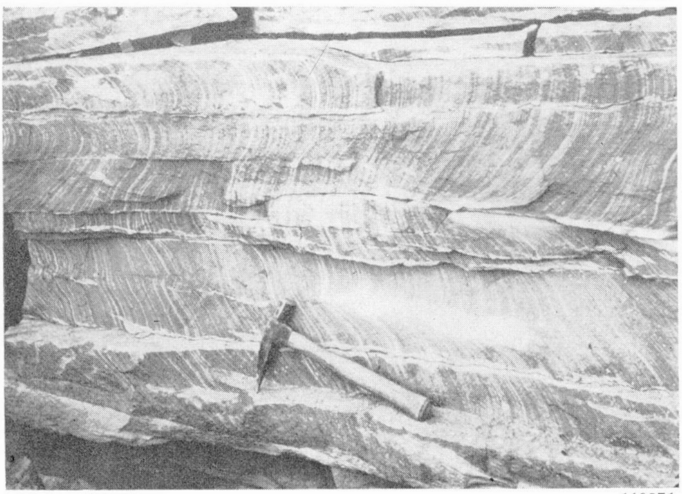

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Plate IV

Horizontally bedded Athabasca sandstone with cross-cutting red colour banding and later bleaching along bedding planes.

regolith developed on the Tazin quartzite. On Course Island, buff to purple Athabasca sandstone fills sharp depressions between knobs and ridges in Tazin quartzite. At this point there is no pebbly material but the sandstone contains a few angular Tazin quartzite boulders. These boulders probably were derived from the immediately adjacent Tazin quartzite knobs. No regolith was observed there. The contact between Athabasca and older rocks is exposed on other islands south of Crackingstone and on Slate Island. Regolithic material underlies the Athabasca sandstone at Fidler Point.

Arenaceous and coarser grained rocks of the Athabasca formation are generally rather easily disaggregated although the degree of cementation and ease of disaggregation vary considerably. Blake (1956) pointed out that many outcrop surfaces look hard and may exhibit glacial polish and grooving yet prove remarkably friable under the hammer. L. P. Tremblay (personal communication) attributes polish and fine grooves on outcrops of sandstone in the Firebag River area to the scouring action of post-glacial wind-blown sand. The general friability of the sandstone and the ease with which joint blocks were removed by scouring and plucking is indicated by the thick cover of Athabasca-derived sand, particularly in the west part of the sandstone area, and by the presence of huge sandstone erratics particularly noticeable where they form part of drumlinoid ridges in the east-central part of the area. Quartz cement is visible in most specimens as brilliant crystal facets resulting from the deposition of quartz in crystallographic continuity with the quartz grains.

The most common colours of the Athabasca formation are light buff, grey, white, cream, and various combinations and mixtures of these. Light to dark purplish colours and shades of red from light pink to brick-red and maroon are common. The red coloration does not seem to have a pronounced, systematic regional distribution. Some of the reddest strata were observed near the base of the sequence east of Poplar Point, along McFarlane River above and below Davey Lake, and among steeply tilted sandstone beds west of Carswell Lake. The shaly material, either in the form of shale layers or in shale chip layers, that is interbedded with these red sandstone horizons is also typically red or maroon. Most of the red colour results from a fine film of hematite around quartz grains but hematite forms a cement in a few instances. It forms several per cent of some sandstone layers exposed in the rapids below Davey Lake.

Some of the red coloration conforms to the bedding planes giving rise to pronounced horizontal colour banding, but much of the colour is present as wavy layers of alternating dark and light colour which intersect the horizontal or crossbed planes. In these cases the colour bands are continuous across the bedding planes but are generally deflected somewhat as they pass across them (*see* Pl. IV). This colour banding reflects the diffusion of iron through the sandstone body, however the original form of the iron in the sandstone is not known.

A good deal of the red colour has been removed as a result of later selective reduction of the hematite, particularly along horizontal or crossbed planes and along fracture planes (*see* Pl. IV). Round or more irregular reduction areas were also noted on many rock surfaces. Some of the circular reduction spots may be tubular, rather than spherical, when observed in three dimensions. Reduction of iron in sediments is frequently attributed to action of organic material. Nothing is known of any original organic material in these rocks, but reduction by organic solutions might be much younger than the deposition of the sandstone.

Sandstone

The typical sandstone of the Athabasca formation has a very high quartz content, both in terms of detrital framework and cement. It therefore falls into the orthoquartzite group of sandstone as defined by Krynine (1948).

The sorting of the Athabasca sands is illustrated in the accompanying histograms (*see* Fig. 3) which are representative of the exposed parts of the formation. The finer material shown by the sieve analyses is partly a result of grinding action during disaggregation but in part is due to finely disseminated clay material and the inclusion in the sandstone of shale chips. Besides the increases in fines due to minor chipping during disaggregation, some of the coarse sand and granule-sized polycrystalline grains have a tendency to split thus decreasing the percentages in the coarser grades and increasing them in the intermediate sizes. Some of the percentage groups are probably shifted slightly towards the coarser end of the scale because of the adherence of secondary quartz cement to clastic quartz grains. Most of the samples have material ranging over six or seven Udden size classes so the sorting would be described as fair. In most samples the mode falls in the 0.25 to 0.50 mm class.

Heavy minerals were separated with the use of bromoform from disaggregated samples from eighteen widely separated localities. The heavy mineral content of almost half of these samples was between 0.01 and 0.02 per cent and the content of another 30 per cent of the samples was 0.02 to 0.03 per cent. Tourmaline and zircon are the only non-opaque minerals present in significant amounts. The tourmaline grains characteristically exhibit clear authigenic overgrowths.

One hundred and four randomly distributed samples of sandstone were examined in thin section. The particles in forty-two of these samples were well sorted (largest diameters eight or fewer times the smallest) whereas in forty-five the sorting was fair or poor (largest diameters more than eight times the smallest diameters). The clastic constituents of those slides that show minor recrystallization were compared with the roundness classes illustrated in Pettijohn (1957, p. 59). In fifty-seven slides the particles were predominantly 'well rounded' whereas in seventeen the roundness was less well developed. In a few of the latter cases the particles are predominantly 'subangular' or 'subrounded' whereas in most of these seventeen slides 'rounded' grains predominate. The high degree of roundness as compared with the moderate degree of sorting is somewhat anomalous. It suggests a provenance giving rise to well-rounded material (possibly a multicycle sediment) combined with a depositional environment providing conditions that produced only moderate sizing (possibly a fluvial environment).

Recrystallization, as indicated by disappearance of primary grain boundaries and by evidence of grain compaction, is moderate or pronounced in thirty-one of the one hundred and four sections. The grains in one section from tilted sandstone beds lying within the ring of Carswell dolomite exhibit notable evidence of crushing.

Highly altered cloudy grains thought to be potash feldspar were observed in only thirteen of the sections indicating that potash feldspar is present in negligible amounts.

Polycrystalline quartz grains believed to have been originally meta-quartzite or recrystallized chert were observed in thirteen sections and chert grains in six sections. Both constituents are indicative of a sedimentary source for some of the clastic material.

Very fine grained sericite and chlorite were observed in about one third of the slides. The minerals occur as thin films around quartz grains, as irregular interstitial patches, and form small shale chips. The irregular patches may be due to compaction of shale chips whereas the thin films may be due to infiltration of clay or minor entrapment of suspension load during deposition of the sands. Although these constituents are quantitatively minor in amount they are probably indicative of rapid sedimentation.

In a few slides coarser muscovite grains were observed. These lie parallel with the sedimentary laminations and this coupled with a lack of recrystallization of the surrounding constituents indicates a clastic rather than a metamorphic origin. In six slides coarse secondary chlorite is visible and in some of these it occurs as feathery terminations on clastic muscovite. The secondary chlorite and the recrystallization previously alluded to indicate a mild metamorphism of the sandstone in part of the basin.

Tourmaline was noted in seventeen slides, zircon in thirteen, rutile in one, and notable amounts of hematite in nine. Tourmaline and zircon are consistently well rounded in section and attest to the rigour of the abrasion they have undergone. This is suggestive of a source rock consisting of reworked sedimentary strata. Where hematite occurs in large amounts it forms a cement. The maximum amount observed was 15 to 20 per cent in slides from east of Squirrel Lake. The complete absence of noticeable heavy mineral grains, with the exception of minute amounts of iron ores, from many thin sections confirms the paucity of these materials as previously indicated by heavy mineral separations.

Both igneous (unstrained) and metamorphic (strongly undulose) quartz are very common in all the slides examined. Metamorphic quartz is more abundant in total.

A thin layer of fine-grained subgreywacke was observed near the base of the Athabasca formation east of Turner Point. This rock consists of subangular quartz with muscovite, albitic plagioclase, and microcline in a very fine grained, cherty-chloritic matrix. It also contains small secondary carbonate patches.

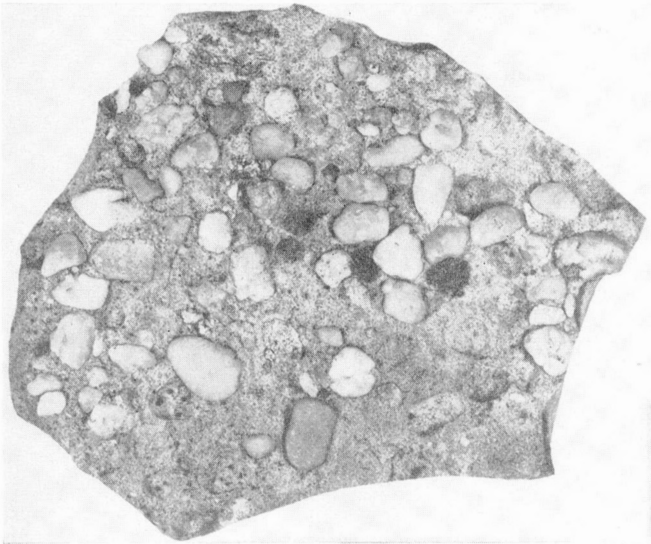

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Plate V

Single pebble layer in the Athabasca sandstone, mainly vein quartz and chert. (Reduction $2\frac{1}{2}$x)

Grit and Conglomerate

Granules and pebbles appear to occur in two ways within the Athabasca formation. In one, the coarse material forms a thin layer, commonly one grain thick, of well-sorted pebbles (*see* Pl. V) and in the other the coarser grains occur in poorly sorted lenses or in inclined or flat beds of graded material. Most pebbles in the Athabasca conglomerate are less than 2 cm long and the largest, excluding the cobbles and boulders in the basal zone of the formation, are between 6 and 7 cm long. The pebbles are mainly rounded vein quartz and chert, including jasper varieties, but pink feldspar, granite, granite-gneiss, quartzite, greenstone and white feldspar were also identified. The roundness of the pebbles varies from subangular to round within the same sedimentation unit. In general the coarser parts of the Athabasca formation are lensy, intensely crossbedded and associated with coarse-grained, crossbedded sands. Conglomerates with a composition, distribution and internal structure such as those in the Athabasca formation are generally called oligomictic conglomerate.

The dominance of vein quartz and chert, materials that are most resistant to chemical and physical decomposition, indicates a long history of abrasion and suggests that the pebbles are not first cycle products. Furthermore the chert pebbles must originally have been derived from sedimentary strata. The small quantity of less stable components suggests that the provenance of the Athabasca formation was a complex one which was predominantly sedimentary but which included lesser areas of rock whose lithology was more typical of the present Shield.

Structure

Blake (1956) reported deformation of Athabasca strata at a number of points, the most notable of which are in the Black Lake area. He noted folded Athabasca strata on the southeast shore of Fir Island and pointed out:

> . . . diamond drilling on the Nisto Property on the northwest shore of Black Lake revealed that the Athabasca sandstone has been down-faulted against Tazin-type rocks. An examination of the drill core showed that the sandstone has been brecciated, pulverized to a gouge, and considerably altered by hydrothermal solutions at the fault contact.

The writer has corroborated Blake's findings in the Black Lake area. Post-Athabasca movement on the Nisto fault is also suggested by sediment transport direction. The gneisses west of the fault could not have been in their present position relative to the Athabasca sediments when the sands were being laid down, because the sediment was transported towards an area which is now topographically higher than the sediments. The folding on Fir Island probably was due to normal movement on the Nisto fault or movement on a fault closer to the folded zone.

A number of workers, Christie (1952), Hale (1954b, 1955, note his Athabasca series, upper part), have recorded small dips at various outcrops of Athabasca formation along the north shore. Many of these dip directions form a large angle with the local paleoslope. They cannot therefore be depositional in origin and must reflect the later tilting of Athabasca strata. Post-depositional basement adjustments, which can be inferred from present topography and known paleoslope, would be expected to result in some tilting of Athabasca strata.

Tilted Athabasca strata were also encountered at many points within the main parts of the basin. The dips are mainly 3 to 5 degrees but at a few points they are greater, the maximum being 25 degrees. Still higher dips were observed in the Carswell Lake area but this is a special case which is described later under the geology of the Carswell formation. The above data suggest that the strata of the Athabasca formation have undergone a gentle tilting towards the central parts of the main sandstone area, and locally steeper dips have resulted from fault movements in the basement rocks.

Diabase Intrusions

Tyrrell (1896) first reported diabase that cut the Athabasca formation on the west shore of Cree Lake. The dyke he described is one of a number that outcrop in this general area and appear to form a local swarm (*see* Fig. 4). No dykes have been reported in the sandstone of the map-areas directly to the west (Maps 577A, 578A).

The dyke described by Tyrrell forms a prominent ridge, the top of which rises at least 150 feet above surrounding Athabasca formation and hence at least this distance above the pre-Athabasca erosion surface. The contact between the diabase and sandstone was not observed but it is likely that the dyke is intrusive into the sandstone.

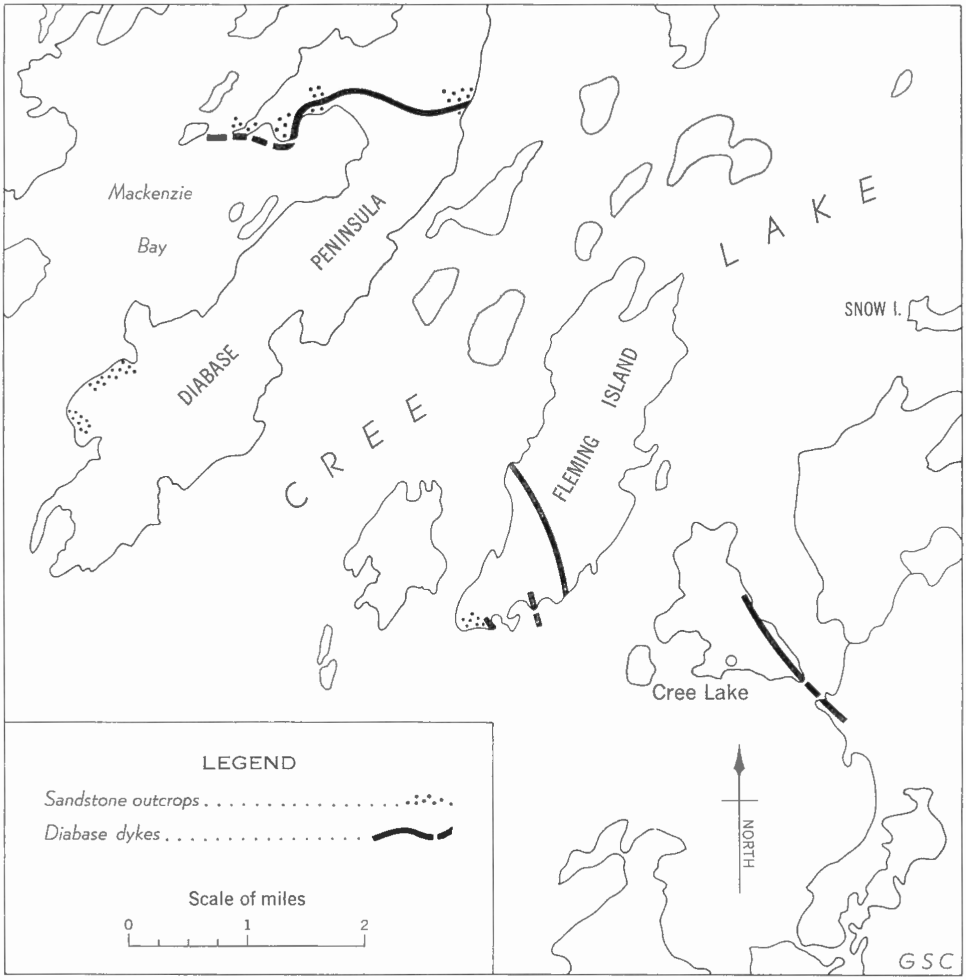

Figure 4. **Diabase dykes on Cree Lake.**

Blake (1956) referred to a narrow basic dyke that cuts the Athabasca formation on the south shore of Lake Athabasca.

Two elongate magnetic anomalies in the region of Carswell Lake are probably caused by diabase dykes (*see* Fig. 5). The calculated maximum depth[1] to the most southerly of these anomalies is only 332 feet, which suggests that it intrudes the sandstone.

A collection of oriented samples was made by the writer to study the remanent magnetism of both the Athabasca formation and the Cree Lake diabase. P. Dubois, Geological Survey of Canada, attempted to make these measurements but found it was possible to measure only the remanent magnetism of the diabase. According to Dubois, these measurements indicate a polar orientation that is consistent with a Keewenawan age for the intrusions.

[1]A. S. MacLaren, Geological Survey of Canada, personal communication.

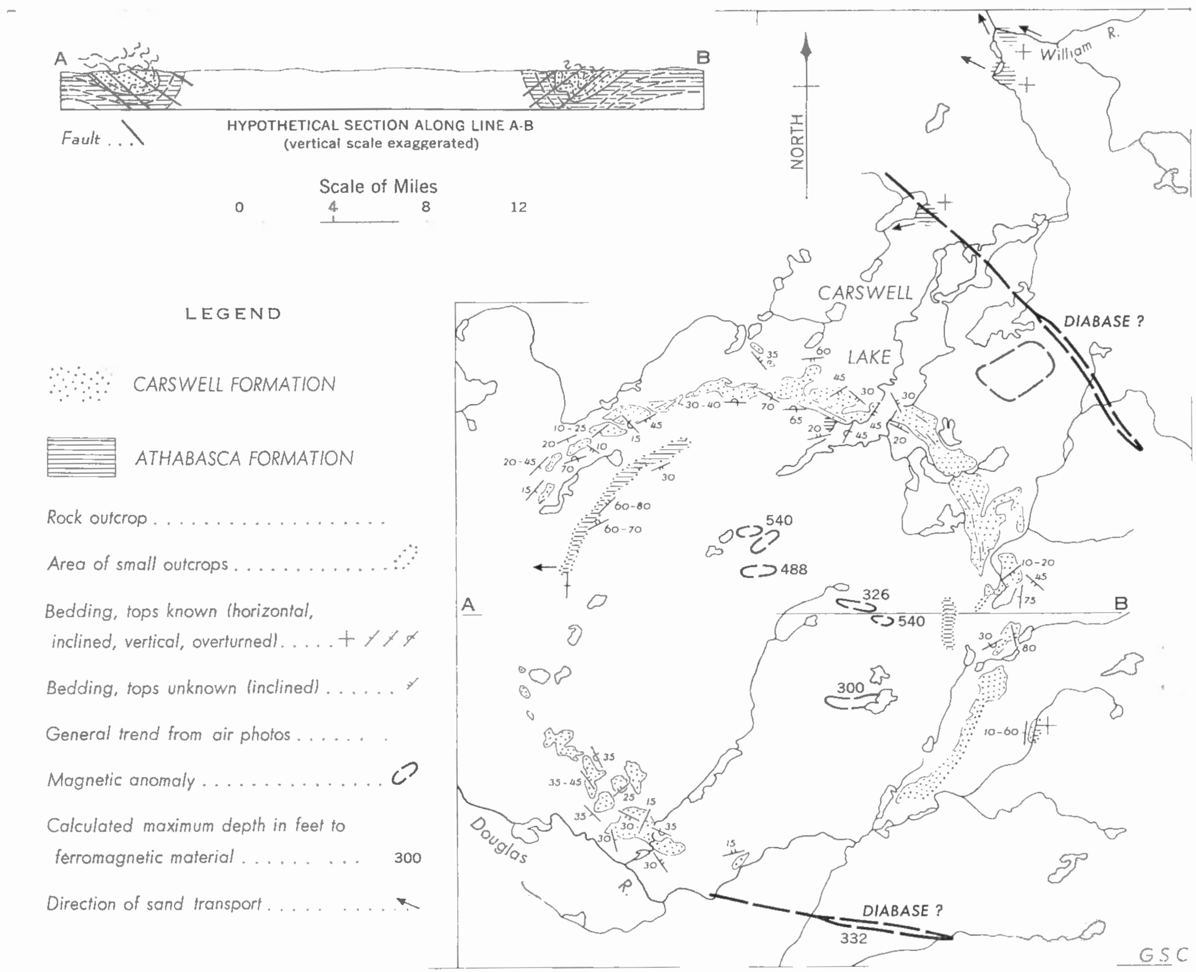

Figure 5. Geology of the Carswell dome.

GENERAL GEOLOGY OF THE CARSWELL FORMATION

Blake's (1956) description of the 'Trout Lake limestone'[1] is the first published reference to the Carswell formation. It is shown on his accompanying map as an arcuate belt running roughly east-west. He pointed out that the formation is intensely folded, several times repeated across the exposed width, exhibits small-scale deformation, and contains zones of intense brecciation and intricate contortion. Small concentric structures were observed in the dolomite. Blake examined the area briefly, but he felt that the presence of folded dolomite in an area of flat-lying Athabasca sandstone suggested a pre-Athabasca age for the carbonate rocks. He also noted several subangular fragments of diabase float within a small distance of one another in the dolomite area, and suspected that the Carswell formation is cut by diabase (personal communication).

During the 1957 field season the writer made additional reconnaissance observations of the Carswell formation. The major areas of dolomite outcrops are shown on Figure 5. These suggest that the formation is present as a complete ring with a remarkably circular outline. The ring has an inside diameter of about 18 miles and an apparent width of about 3 miles. The formation forms a number of prominent ridges and its circular outline is fairly easily discerned on photo mosaics of the region.

The dolomite of the Carswell formation is probably of two major types. One is finely laminated and light buff or pink weathering, the other is generally darker and is characterized by cryptozoan structures. Both of these rock types are locally intensely contorted and fragmented giving rise to coarse calcarenite and breccia layers (*see* Pl. VI). Layers of brecciated rock overlain and underlain by unbrecciated strata suggest the penecontemporaneous nature of the brecciation. Thin oolite and lensy chert layers are fairly common. Much of the pink dolomite and some of the buff-grey has a network of bright red carbonate veinlets.

The cryptozoan structures of the dolomites vary from rather faint convexities to pronounced bun-shaped concentric structures. The latter are probably algal structures. Although their origin may be problematical, they provide criterion for determining the tops of beds and so are valuable in working out the major structure.

Some structural determinations of the dolomite are shown on Figure 5. These do not show the structure of the formation in detail but do allow some generalizations regarding the overall deformation of the Carswell. It is notable that many beds, particularly those outcropping towards the inner edge of the ring, are overturned towards the outside of the ring, whereas most of the dips and tops around the outer edge of the ring are towards the interior of the ring. The pattern and scale of deformation is illustrated in Plate VII.

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[1] Trout Lake is the local name for Carswell Lake. A partial analysis of finely laminated, buff weathering rock yielded the following weight per cents: CaO—33.3, MgO—18.7, insolubles—1.4. Analyst—G. Bender, Geol. Surv., Canada. More properly the rock should be called a dolomite.

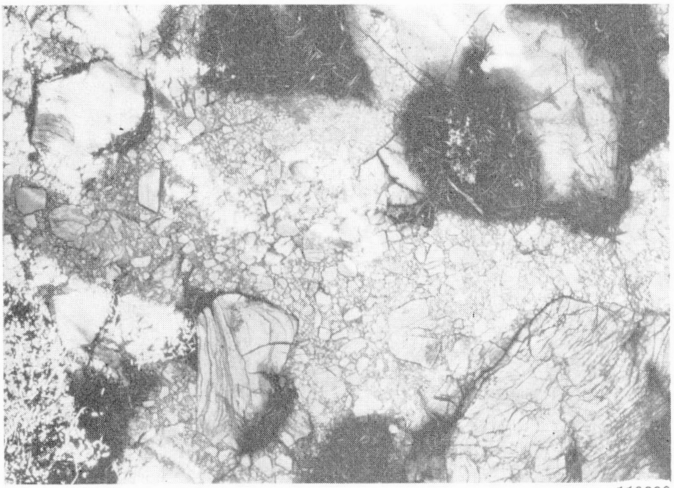

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Plate VI

Brecciated Carswell dolomite.

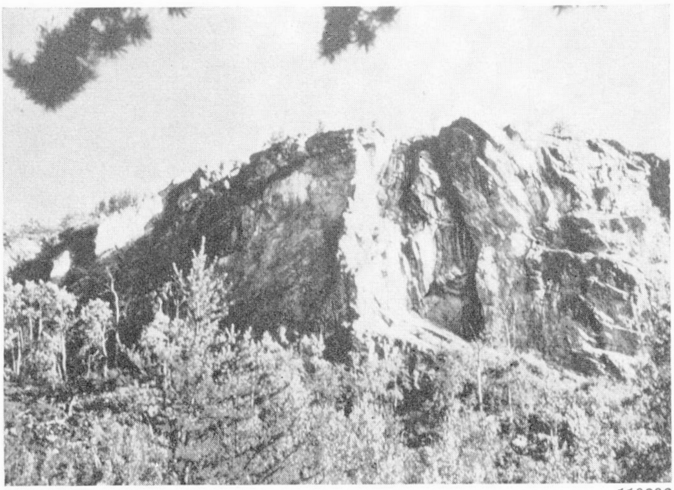

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Plate VII

A fold in the Carswell formation.

These data are interpreted as indicating the action of stress outward from the interior of the ring. The intensity of deformation suggests diapiric movement rather than a simple doming of the area, or possibly a combination of doming and gravity flow. The presence of tilted Athabasca sandstone beds within the ring and flat-lying beds (*see* Fig. 5) around the perimeter indicate the abruptness of the deformation.

While carrying out recent prospecting in the Carswell Lake area W. S. Kennedy[1] discovered outcrops of basement gneiss within the dolomite ring at about the same topographic level as the surrounding folded strata. This corroborates the writer's interpretation of a domal structure and seems to eliminate meteorite explosion as a possible cause of the structure. The Athabasca-Carswell contact was not observed but the above structural interpretation (*see* cross-section, Fig. 5) suggests that the Carswell overlies the Athabasca formation. The alternative possibility is that the Carswell occurs as a lens within the Athabasca, however the lack of infolded material from overlying horizons suggests a break between the deposition of the Carswell and the deposition of any younger strata.

If deformation in this area had commenced during deposition of the Athabasca formation it would have been reflected in the local transport direction of clastic material but outcrops are too few in the immediate vicinity of the limestone to apply this test. The outcrops within the dolomite ring are small and shattered and at only one point was crossbedding observed. The age of the deformation of the Carswell and Athabasca formations in this area is not known, but, as no infolded Palæozoic strata are present, it is probably pre-Palæozoic.

Some very large, friable erratics of quartzite breccia consisting of angular buff orthoquartzite in a lighter coloured orthoquartzite matrix were observed about 2 miles northwest from the south tip of Carswell Lake. This rock type undoubtedly forms bedrock in this area but its significance could not be ascertained.

A magnetic survey was flown over the Carswell dome in 1955 and the resulting map was made available to the writer by J. F. V. Millar. The more prominent magnetic anomalies and the calculated maximum depths to the ferromagnetic material causing some of the magnetic anomalies are shown in Figure 5. These show maximum depths ranging from 332 to 1,300 feet. There are two pronounced linear anomalies which are probably due to the presence of diabase dykes. A. S. MacLaren, Geological Survey of Canada, who made the depth determinations suggests that the magnetic anomalies within the dolomite ring are not due to an igneous plug.

In summary, the writer feels that the structural data and the erratics of brecciated Athabasca formation within the dolomite ring can best be explained by postulating mechanical dislocation caused by pressure upward and outward from below. The tectonic environment is typical of that observed in the formation of diatremes, crypto-volcanic structures and intrusions of alkaline plugs (De Sitter, 1956, p. 263). It is suggested that an igneous mass was intruded at depth pushing upward a plug of overlying basement gneiss and flat-lying sediments. The Athabasca and Carswell would be tilted outward around a circular zone of faults. This type of dislocation coupled with outward slumping of Carswell strata could have caused the structures observed in the ring of Carswell and Athabasca outcrops. The erratics of brecciated Athabasca strata may have resulted from dislocation

[1] Personal communication, December 1959.

of the Athabasca during upward movement of the magma and later collapse due to partial magmatic withdrawal. The absence of a distinctive magnetic anomaly indicating the presence of an igneous plug is attributed to the blanketing effect of brecciated basement gneiss which still overlies the igneous intrusive mass. The Carswell Lake feature is tentatively called a crypto-volcanic structure. The alkaline igneous material in the neighbouring Dubawnt group (Brown and Wright, 1957, p. 89) suggests more advanced igneous activity of the type postulated in the Athabasca area and in the same tectonic environment.

DIRECTION OF SEDIMENT TRANSPORTATION IN THE ATHABASCA BASIN AND MARTIN LAKE SYNCLINE

Crossbedding

Crossbedding is the most prominent sedimentary structure within the Athabasca formation and forms an excellent indicator of the direction of transportation of clastic material during Athabasca sedimentation. Most workers in the region have referred to this structure. Alcock (1936, p. 22) stated:

> South of Lake Athabasca the common type observed consists of diagonal layers bounded above and below by horizontal beds. A similar type is to be seen on Beaverlodge Lake. Locally a more irregular type is presented showing curved foreset beds irregularly truncated by other curved beds.

He was referring to the two types of crossbed units generally recognized. One forms a channel-like deposit and is referred to variously as concave, trough, or festoon crossbedding. The other has more or less planar foreset beds and a planar lower surface and generally is referred to as torrential or planar crossbedding. All gradations from crossbed 'channels' a few inches across and less than an inch thick to planar units more than 4 feet thick exist within the Athabasca formation. Plates VIII, IX and X show examples of the most common types of these structures. Plate X is particularly interesting as it shows a number of narrow crossbed troughs truncating obliquely the foreset beds of what appears to be a large planar crossbed.

It is generally assumed that both trough and planar crossbedding give a precise indication of local transportation direction at the time of their formation. Some mechanisms for the origin of the planar types of crossbeds have been recognized, but the origin of trough crossbedding is not well understood. Some writers (Potter and Glass, 1958) believed that a complete gradation exists between planar and trough crossbeds hence the conditions of their formation should be gradational. In a recent study Sundborg (1956) illustrated the formation of planar crossbeds in the bed of the Klaralven River through the agency of transverse river bars. Trough (festoon) crossbeds apparently do not form or are not recognizable in these river deposits. A major question in considering the origin of trough crossbeds is whether an erosional channel the length of the crossbed feature existed during the initial stage of their development, or whether local erosion and filling action, by migrating downstream, leaves in its wake the crossbed-filled trough. The writer believes that discontinuous, asymmetrical, concave ripples, such as those shown by Sundborg (op. cit., p. 206, Fig. 19, left), may form trough crossbedding by erosion of a shallow depression on the concave downstream side and continuous filling during downstream migration of the ripple. The formation of festoon crossbeds by continuous cut and fill during the migration of barchan-shaped ripples is suggested by such features as pinch and swell in the channels and rather abrupt changes in the direction of the channels. Many writers, however, believe that true troughs are eroded and filled to form these structures. See for example, Knight (1930), or Potter and Siever (1956). Sundborg (1956) indicated that a break exists in the mechanism of formation of asymmetrical ripples

Plate VIII

Planar crossbed on William River.

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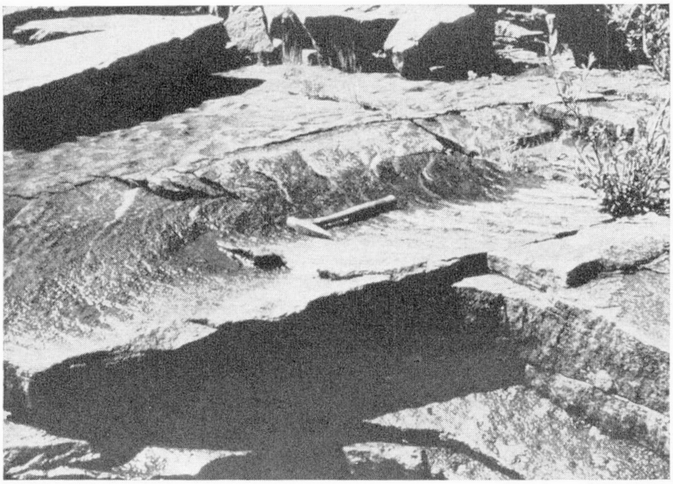

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Plate IX

A crossbed trough with most of the trough-filling removed.

Plate X

Large planar crossbed north of Newnham Lake with small crossbed troughs scoured into the foreset beds.

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and transverse bars so that if asymmetrical ripples and transverse bars are responsible for the two distinctive types of crossbeds, a break should exist in the conditions under which the two types of crossbeds form.

Within the Athabasca basin most of the crossbedding is of the trough type. In the northeast section of the basin, many bedding planes are striped by large numbers of crossbed troughs whose median width is between 3 and 10 feet and whose axial thickness is 2 to 6 inches. Planar crossbeds, the foreset beds of which commonly show undulation along strike (*see* Pl. IX), are present though less common throughout most of the Athabasca sandstone. The outcrops examined in the central part of the basin (*see* Fig. 1), which is probably an upper part of the sandstone sequence, have fewer and less pronounced crossbeds. The average size of the clastic grains is somewhat less in this area.

The stubby arrows on Figure 2 show average directions of crossbeds at outcrop localities where measureable crossbeds were observed. They represent a total of twelve hundred measurements. Because outcrops are uncommon in many parts of the area and parts of the sandstone area are difficult of access, crossbed measurements could not be made in as systematic a manner as was desired. However, the consistency of the data available suggests that they are adequate to indicate the transportation trends within the basin. The small variation in the local flow directions (*see* circular histograms, Fig. 2) as compared to that found in many similar studies may be attributed to at least two factors. First the local transportation direction within the Athabasca formation may be more constant than in other formations studied and this would indicate a steeper paleoslope. Secondly, at least 80 per cent of the measurements made in the Athabasca were on essentially flat, well-exposed, bedding planes and represent the axes of troughs or the dip direction of planar crossbeds averaged over a considerable distance along strike. In many similar studies, measurements have been made on poorer exposures and on folded strata, both of which will tend to increase the deviation from the median direction.

It was found necessary to rotate crossbed readings to correct for tilt of strata at only two localities. These were the readings in the Martin formation made around Martin Lake and in the Athabasca formation on Fir Island.

An interesting feature of the circular histograms (Fig. 2) is the extent to which the measurements in each histogram deviate from the median value. Visual inspection indicates a smaller deviation in crossbed measurements along the northern and eastern parts of the basin than to the south and west. If, as is suggested later in this paper, the sandstones are primarily fluvial deposits, this observation is consistent with a smaller paleoslope and a more pronounced meander pattern in the downstream direction.

Some crossbed units in the vicinity of Mayson Lake and east of McLeod Lake exhibit overturning of the upper parts of the foreset beds (*see* Pl. XI). These units are generally overlain by highly contorted beds and overturning is attributed to drag on the crossbeds resulting from preconsolidation mass flowage of the overlying layers. This too suggests a steep paleoslope.

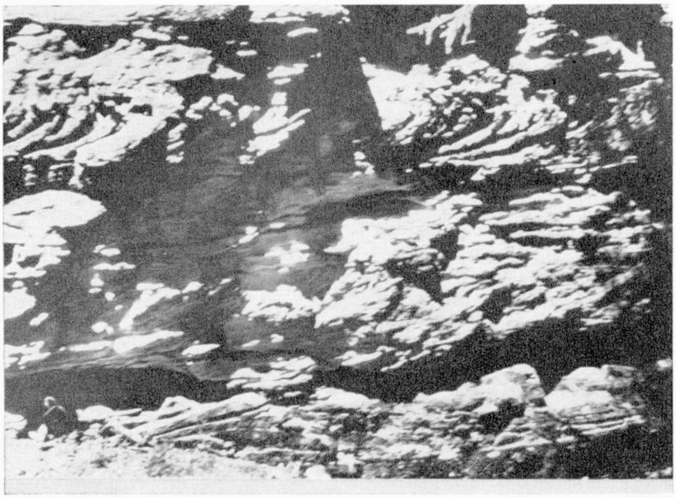

Plate XI

Overturned crossbedding on Mayson Lake.

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Ripple-Marks

Ripple-marking is a common bedding plane feature of the sandstones. Most of the ripple-marks observed appear essentially symmetrical and vary in wave length from about a foot to a fraction of an inch. At a few localities the ripples seem to have been developed on surfaces scoured into the underlying sandstone but only one edge of the hypothetical depressions was observed at each point. The edges of these channels are at right angles to the contained ripples and parallel with the regional paleoslope.

Density of ripple-marking is greater in the coarser grained, probably lower, part of the Athabasca sandstone sequence.

The average direction of ripple-crests along the individual ripple-marked surfaces is shown on Figure 2. The ripple-crests tend to lie at right angles to the local transportation directions as indicated by crossbedding. This suggests that although ripple-marks, which appear symmetrical, are not vectorial features they may contribute valuable data in cases where there is some knowledge of regional paleoslope and there exists locally a paucity of other transportation indicators. They may also indicate standing bodies of water and trends of nearby shore zones.

Minor Features Indicative of Transportation Directions

Pebble Orientation

Much of the pebbly and gritty material of the Athabasca occurs in very thin layers, many only one particle thick. This makes the determination of pebble orientation particularly easy. At two localities, north of Brudell and west of McLeod, pebbly surfaces were chosen at random, marked off into squares and the directions of the long axes of all the pebbles within the squares were measured. In each case one hundred measurements were made as a practical working figure.

The two orientation patterns are remarkably similar (*see* Fig. 2) and the pebbly surfaces (*see* Pl. V) are probably near the same stratigraphic level. When these patterns are compared with local crossbed directions, it is apparent that the orientation of pebble axes is about parallel with local direction of transportation. This suggests that the last movement of the pebbles was a rotation, bringing the long axes of the pebbles roughly parallel with the flow direction.

Current Lineation

Primary current lineations of the type frequently observed in sandstones, consisting of flat depressions alternating with flat-topped ridges, were observed at only a few points in the Athabasca formation. Another type of lineation was observed east of Turner Point on Lake Athabasca. This was caused by a deflection of current by imbricate shale pebbles resulting in a sort of dune effect (*see* Pl. I). A feature such as this is unlikely to be incorporated and preserved unless the sand transportation phase is followed by less vigorous current conditions which, as in the case observed, may result in the deposition of an overlying, finer grained layer. A lineation such as this is valuable in providing a precise indication of the local direction of sedimentary transportation.

Summary of Transport Data

In studies of this type it is assumed that if measurements of transportation direction are made on a large number of strata within a formation, then the results may be applied to the formation as a whole, including many layers containing no features indicative of transportation direction. This is true where transport features are well distributed vertically and horizontally in the sequence. Transport data on the Athabasca formation are so consistent throughout the basin that generalizations made from them appear to be valid for the sediments of the unit as a whole.

The various data on transportation direction within the Athabasca basin are summarized on Figure 2. These indicate that sediment transport was predominantly from an east and southeast direction with a minor amount from the northeast as indicated by Alcock (1920). Two axes of convergence are present. A minor east-west axis through Wapata Lake and the major axis of convergence passing northwest through Lake Athabasca.

The directions of transportation of sediments in some crossbedded parts of the Martin formation are shown on Figure 2. These measurements were made around the southwest part of the syncline and the average of the measurements forms a large angle with nearby Athabasca paleocurrent trends.

According to C. K. Bell (personal communication) the boulders in Athabasca conglomerate on islands off the southwest tip of Crackingstone Peninsula are composed entirely of Tazin quartzite. Geological Survey maps, preliminary Map 54-8 and Map 1015A, indicate Tazin quartzite on islands to the east of these outcrops which corroborates the view that paleocurrents passed in a northwesterly direction across this area.

The determination of paleoslopes from the directions of transportation of material within the Athabasca and the Martin formations contributes information on a number of problems, such as paleogeographic reconstruction, provenance of the sediments, post-Athabasca regional warping, possibility of syngenetic ore deposits in the Athabasca basin and correlation of the Athabasca formation with possibly related strata.

Sediment Transport and the Possibility of Syngenetic Radioactive Deposits in the Athabasca Formation

Many important radioactive deposits of the world, for example those of the Blind River and Witwatersrand, are believed to have originated through sedimentary processes. It is of interest to consider the possibility of such deposits in the basin of Proterozoic sedimentary rock occupied by the Athabasca formation; particularly because these rocks lie immediately adjacent to syngenetic and epigenetic uranium deposits of great importance.

The known area of intense uranium mineralization in the Lake Athabasca region extends along the north shore of Lake Athabasca from west of the Alberta-Saskatchewan border, includes the concentration of deposits in the Beaverlodge region and extends at least as far east as the Black Lake-Charlebois Lake areas. In addition to this belt of mineralization some occurrences have been discovered in the main body of Athabasca sediments. The following description of these is from Blake (1956):

> It was discovered that radioactivity is located at intervals along most of the sandstone scarps that extend northwestward from Middle Lake. The radioactivity is found in beds of sandstone and conglomerate anywhere from the unconformity to the top of the scarp. It is, however, generally concentrated in the basal layers and underlying regolith. In many places the radioactivity extends into the underlying Tazin-type rocks but not below the zone of weathering. Most of the radioactivity is due to autunite, a secondary mineral thought to be derived from uraninite and/or pitchblende from which some uranium has been leached, carried by ground waters, and concentrated in the clay material of the regolith. Thus the unconformity between the Athabasca series and underlying rocks seems to control the deposit.

These deposits have probably formed either, as Blake suggests, by leaching of uranium from the older gneissic terrain with transportation and precipitation by ground or surface waters, or they may represent the erosion, concentration, deposition, and alteration of uranium-rich clastic particles. The paucity of heavy minerals in the sandstones makes Blake's hypothesis seem more likely.

The paleoslope, as indicated by sedimentary transportation directions, is shown on Figure 2. Only in the section between Poplar Point and Black Lake did sediments, surface waters, and presumably ground water, move from the northern belt of uranium-rich rocks towards the main basin of sediment accumulation. Assuming that the major areas of uranium-rich Archæan rocks are known, then the obvious areas of syngenetic uranium deposits in the main body of Athabasca sandstone should be limited to that part east of Poplar Point and north of latitude 59°00′. The previously described autunite deposits are found within this area.

Mawdsley (1958) has discussed a number of radioactive pegmatite occurrences that lie to the east and southeast of the Athabasca formation, from which direction the bulk of Athabasca sands were derived. The sparsity of these occurrences and their low grade suggest that the radioactive pegmatite part of the terrain is unlikely to have provided much radioactive material for sedimentary concentration. However, this does not mean that this vast area of predominantly metamorphic rock could not as a whole supply a huge volume of radioactive heavy constituents capable of concentration into deposits of ore grade.

If the pattern of sediment transport is extrapolated northwest of Lake Athabasca any Precambrian rocks similar in age to the Athabasca group would lie in the downslope direction from the radioactive occurrences on the north shore. Also, as paleoslopes show great persistence in time, Palæozoic rocks northwest of Lake Athabasca might be favourable for uranium concentration by sedimentary processes.

AGE AND CORRELATION OF SEDIMENTARY ROCKS OF THE ATHABASCA REGION

The problem of the stratigraphic relationship between the relatively unaltered sedimentary rocks that lie north of Lake Athabasca and the flat-lying sandstones south of the lake was recognized by Alcock in 1935. He grouped all of the unmetamorphosed sedimentary rocks that outcrop for some distance north of Lake Athabasca with the sedimentary rocks to the south of the lake and described them collectively under the heading 'Athabasca series'. Alcock (1936, p. 21) stated:

> The series outcrops on a number of islands in Lake Athabasca immediately east of Black Bay and at several places on the north shore of the lake. North of the lake are a number of other areas underlain by conglomerates and arkoses. Some of these have high dips in contrast with the flat or low dips in the type area, but on the basis of lithology they have been correlated with the Athabasca sandstone. The largest of these surrounds Beaverlodge Lake.

In addition to the rocks of the 'Athabasca series', Alcock defined two older predominantly sedimentary series of rocks on the north shore of Lake Athabasca. He called these the Tazin group (older) and the Beaverlodge group (younger). The distribution of the three groups of sedimentary rocks is shown on Geological Survey of Canada Map 363A. In 1947 and 1948, A. M. Christie carried out more detailed mapping of Goldfields-Martin Lake area and concluded that no unconformity had been proven by Alcock to exist between the rocks of the Beaverlodge series and the Tazin group. He placed these strata together in what he called the Tazin group. This reduced the classification of sedimentary strata in this region from three to two units. These were the Tazin group (Archæan) and the Athabasca series (Proterozoic). During the period 1951-53, W. E. Hale mapped Black Bay, Gulo Lake, and Forcie Lake map-areas and concluded that the sedimentary rocks of his study area fell into three groups. He assigned much of the sedimentary rock mapped as Tazin (Archæan) by Alcock (Map 363A) to a new unit which he called Athabasca series (Lower Part). Hale's inclusion within the Athabasca of rocks previously assigned to the older Tazin group necessitated a consideration of these rocks in the present study as well as of the unmetamorphosed strata previously correlated with the Athabasca.

A Major Unconformity in Athabasca-type Rocks of the North Shore

Hale first suggested a major unconformity within 'Athabasca-type' rocks after studying the Gulo Lake area in 1953. In this map-area and in the area to the west (Forcie Lake), he concluded that most of the older Tazin rocks of Alcock should be grouped with the younger Athabasca-type rocks. According to Hale they are separated from an 'Upper Part' of the 'Athabasca series' by an angular unconformity and presumably unconformably overlie Tazin rocks. The distribution of these rocks is shown on Geological Survey of Canada preliminary Maps 53-15, 54-6 and 55-4, and may be compared with Alcock's less detailed study of the same area, Map 363A. Alcock and Hale agree in general that some patches of relatively undeformed sedimentary rocks in the vicinity of Ellis Bay are 'Athabasca type'. Hale (1954) described his Athabasca rocks, Lower Part, in the Gulo Lake area as follows:

> The strata of the Athabasca series are similar to those of the series in nearby areas to the east except that basalt as at Martin Lake, 10 miles to the southeast, has not been recognized and a dark grey to dark green greywacke is present. Most of this greywacke exhibits bedding and is markedly schistose parallel with bedding. In many outcrops the clayey materials are recrystallized so that the beds resemble closely those of Tazin group greywacke. About Gulo and Wellington Lakes greywacke passes downward into arkose and at a few localities into conglomerate. Greywacke shows the effects of deformation more strikingly than the underlying arkose or conglomerate.

Hale described evidence for an angular unconformity between the above described strata and an overlying 'Athabasca series, Upper Part'. He considered his 'Athabasca series, Lower Part' to be the equivalent of the Athabasca-type strata (Martin formation) in the area around Martin Lake and Taz Bay.

Part of the 1958 field season was spent examining the rocks around Thluicho Lake in order to consider the hypothesis of an unconformity within 'Athabasca-type' rocks of the north shore. The following is the writer's brief description of Hale's 'Athabasca series, Lower Part' there:

1. ***Sedimentary facies***—The most abundant sedimentary rock forms a thick sequence of grey and grey-green phyllite and meta-greywacke beds with minor reddish arkosic and silty layers. This probably lies stratigraphically above polymictic conglomerates which are composed predominantly of round to subangular pink granite boulders in a chlorite-rich matrix. The conglomerate contains numerous cobbles of vein quartz and some chloritic lenses which may have been ferromagnesian-rich cobbles.

The phyllites and greywackes locally show graded bedding. There is little evidence around Thluicho Lake of ripple-marks, crossbedding, mud-cracks, and red hematite cement, which are all abundant in the sediments around Martin Lake (Martin formation). The sedimentary features exhibited by the rocks around Thluicho are more typical of geosynclinal than continental sedimentation. The Martin formation seems to be typical of continental sedimentation.

2. ***Structure***—As indicated by Hale, his 'Athabasca series, Lower Part' is intensely deformed and at numerous points the bedding is overturned. Along the contacts with the surrounding gneissic rocks the bedding is parallel with the banding of the gneisses and contacts are gradational and locally very steep; at some points the contact and neighbouring banding and bedding dip away from the area of sedimentary rocks towards the surrounding gneisses. The sedimentary and gneissic strata around Thluicho Lake appear to have been deformed together at considerable depth to produce these conformable relationships. In contrast, Christie's map (1952) of Goldfields-Martin Lake area shows an abrupt truncation of older gneisses by younger 'Athabasca-type' sediments (Martin group).

3. *Metamorphism*—Hale (1954b) referred to the marked schistosity of most of the greywacke beds of his 'Athabasca series, Lower Part' and to the recrystallization of clayey materials in these beds. Further in his report he stated: "Conglomerate, believed to be of the Lower Part, occurring just northwest of the mouth of Charlot River contains pebbles deformed into lenticular bodies in such a manner as to justify the designation pebble 'gneiss' ". The writer observed such deformed conglomerates at two points on Thluicho Lake and noted at these points an apparent gradation through a recrystallized zone into neighbouring granitoid gneiss. At both points the lensoid pebbles are parallel with the gneissic banding. In addition to the phyllitic appearance of many of the sedimentary strata around Thluicho Lake, there is widespread quartzo-feldspathic vein development, and clastic grain boundaries have disappeared from the rocks. It is probable that Hale's 'Athabasca series, Lower Part' in the Thluicho Lake area has undergone regional metamorphism and has locally undergone incipient granitization. The 'Athabasca-type' sediments of the Martin Lake area (Martin formation) have not been regionally metamorphosed.

Because of the differences in sedimentary facies, deformation and metamorphism between Hale's 'Athabasca series, Lower Part' and the so-called Athabasca-type (Martin formation) to the east, the writer believes that the two should not be correlated. Christie (1953) in referring to the Tazin group stated: "To the west of the map-area, as far as Camsell Portage, the grade of metamorphism of the mafic rocks is commonly lower, most of these rocks being of the chlorite grade of metamorphism, and rocks containing garnet are rare. There is, thus a general decrease in metamorphism from east to west". It is probable that Hale's 'Athabasca series, Lower Part', is a low-grade metamorphosed remnant of Tazin rocks.

Although the Tazin group may contain unconformities of importance, these would be difficult to trace except locally, and under these circumstances the setting up of additional stratigraphic units within the Tazin would be of doubtful value at present.

Correlation of the Martin and Athabasca Formations

It has been generally believed by workers in the Athabasca region that the Athabasca formation and Martin formation are correlatives in the sense of having been formed in the same general geological period, if not contemporaneously. This view was expressed in recent years by Alcock (1936), Christie (1953), and Blake (1956). The minimum age of the Martin formation has been established, on the basis of the age of pitchblende veins, as almost 2 billion years (Robinson, 1955; Eckelmann and Kulp, 1956). The general correlation of the two formations would mean that the Athabasca formation has an age on this order of magnitude. Clearly recognizable strata of the Athabasca formation occur on islands south of Crackingstone Peninsula and Martin strata occur around Langley Bay, so in this area the two rock types outcrop about 6 miles apart.

Knowledge of the tectonic conditions existing during the deposition of the Martin formation and of the Athabasca formation, is valuable in considering the possibility of their correlation. It is known from the extreme immaturity of the Martin sediments, their great thickness, red colour and associated amygdaloidal basalt flows that they are representatives of the 'red-bed' facies of sedimentation. This fact plus the association of the sediments with major faults serves to define the tectonic framework of the sedimentation. The Martin strata represent terrestrial deposits, formed under unknown climatic conditions, probably as alluvial fans radiating out from normal faults. They were deposited in an area of great relief. They have not undergone true 'Alpine type' deformation and they have not been infolded into the underlying gneissic rocks. The two major belts of 'red-beds' shown on Figure 1, which are located around Martin and Tazin Lakes, are probably genetically related to the Black Bay and Tazin River faults respectively. The position of the two belts of sediments relative to the faults indicates, in both cases, that most of the material was probably derived from the north side of the fault. This is corroborated by the transportation direction of sediments in the Martin Lake area (Fig. 2).

One characteristic that is common to deposits such as the 'red-bed' Martin formation is the rapid thinning of the formations away from the rift valley or graben zone of maximum sediment accumulation. It is conceivable on a basis of rapid facies change that the thick 'red-bed' sequence grades rapidly into the stable platform facies of the Athabasca formation. On the other hand, it seems unlikely that an area of great relief in the Martin Lake area could have existed while adjacent to it Athabasca sands were being laid down by a consistent pattern of northwesterly moving currents, particularly as the Black Bay fault strikes southwest into the Athabasca basin and the area of considerable relief probably extended southwest along this fault.

This analysis of depositional conditions indicates that the Martin formation and the Athabasca formation were not contemporaneous. Furthermore, the absence of Martin rocks beneath the Athabasca formation in such close proximity to the thick accumulation at Martin Lake, suggests that a period of erosion intervened between the deposition of the two sequences.

Age of the Athabasca Formation

Because of the unfossiliferous nature of the Athabasca rocks it has proven difficult to determine with certainty the age of the formation. Some attempts have been made to correlate it with other sedimentary strata but these attempts have resulted either in correlations with strata of unknown age or in correlations based on questionable lithologic and stratigraphic grounds. The best approach in these circumstances is to attempt to box in the age of the sandstones by determining by geochemical techniques the ages of secondary minerals in the formation and the ages of the youngest pre-Athabasca minerals in the older basement rocks. S. C. Robinson, Geological Survey of Canada, suggested to the writer that the mineral autunite, a uranophosphate occurring in the sandstone at Middle

Lake, east of Stony Rapids might be useful in providing a minimum age for Athabasca sedimentation. Similarly, G. E. Ellingham, Saskatchewan Geological Survey, pointed out that pitchblende veins intersect Athabasca strata on the south side of Stewart Island, south of Crackingstone Peninsula. There again it was possible to obtain a minimum age for the sandstone as the veins post-date deposition of the Athabasca sands. The material from Middle Lake yielded an age of only 100 million years[1], an age that is of little use in dating the Athabasca formation. The pitchblende from Stewart Island gave the following data:

Sample	Pb^{206}/Pb^{207}	Pb^{207}/U^{235}	Pb^{206}/U^{238}
346A	646 m.y.	486 m.y.	448 m.y.
346B	516 m.y.	438 m.y.	418 m.y.

Correction based on 500 m.y. common lead
346A = 1.5 amp. fraction
346B = 0.2 amp. fraction

Wanless (personal communication) feels that of these ratios the Pb^{206}/U^{238} ratio provides the most reliable age. The Stewart Island pitchblende veins are then about 400 m.y. old and represent the youngest of the three periods of pitchblende mineralization defined by Robinson in the Beaverlodge area (1955). The Athabasca formation, which is intersected by these pitchblende veins, is therefore more than and may be much more than 400 m.y. old. The age of regional metamorphism and granitization in the Beaverlodge area is suggested by the age of monazite and pegmatite minerals from that area (*see* op. cit., p. 91). The age of this metamorphism is around 1,800 m.y. which provides a maximum age for the Athabasca sedimentation. The age of the Athabasca therefore lies between the limits 400 m.y. and 1,800 m.y. As the Athabasca post-dates the regional metamorphism of all the rocks on its boundaries it must be younger than any minerals related to the regional metamorphism. The future determination of the age of biotites in the gneisses near the Athabasca may serve to reduce the 1,800 m.y. maximum age figure.

The distribution of Proterozoic volcanic and sedimentary rocks of the Northwest Territories and northern Saskatchewan is shown on Figure 6 (*after* Brown and Wright, 1957). Of these rocks the Dubawnt group northeast of Lake Athabasca is remarkably similar to the Athabasca formation as it represents the same orthoquartzite-carbonate facies and reflects similar tectonic conditions. Its age is not definitely known, but numerous potassium-argon dates have been made on micas from underlying rocks. These dates are in the 1,700 m.y. range so this represents the greatest age possible for the Dubawnt. In addition, biotite from Dubawnt porphyry has been dated as 1,500 m.y. and G. M. Wright (personal communication), who submitted this material, considers this figure to be a first

[1] This determination and the Stewart Island determinations were made in laboratories of the Geological Survey of Canada under the supervision of Dr. R. K. Wanless.

approximation of the age of Dubawnt sedimentation. It will be particularly interesting to determine the sedimentary transportation direction of the Dubawnt sands in order to compare this direction with that of the Athabasca formation. The only absolute data at present available indicate that the Athabasca is between 400 m.y. and 1,800 m.y. old. Moreover the lack of fossils in these rocks and their intersection by diabase dykes suggest a Precambrian age. Their similarity to the Dubawnt, which is 1,500 m.y. old, is so striking that this must be kept in mind when the Athabasca is correlated with any other group on the basis of stratigraphic or structural similarity.

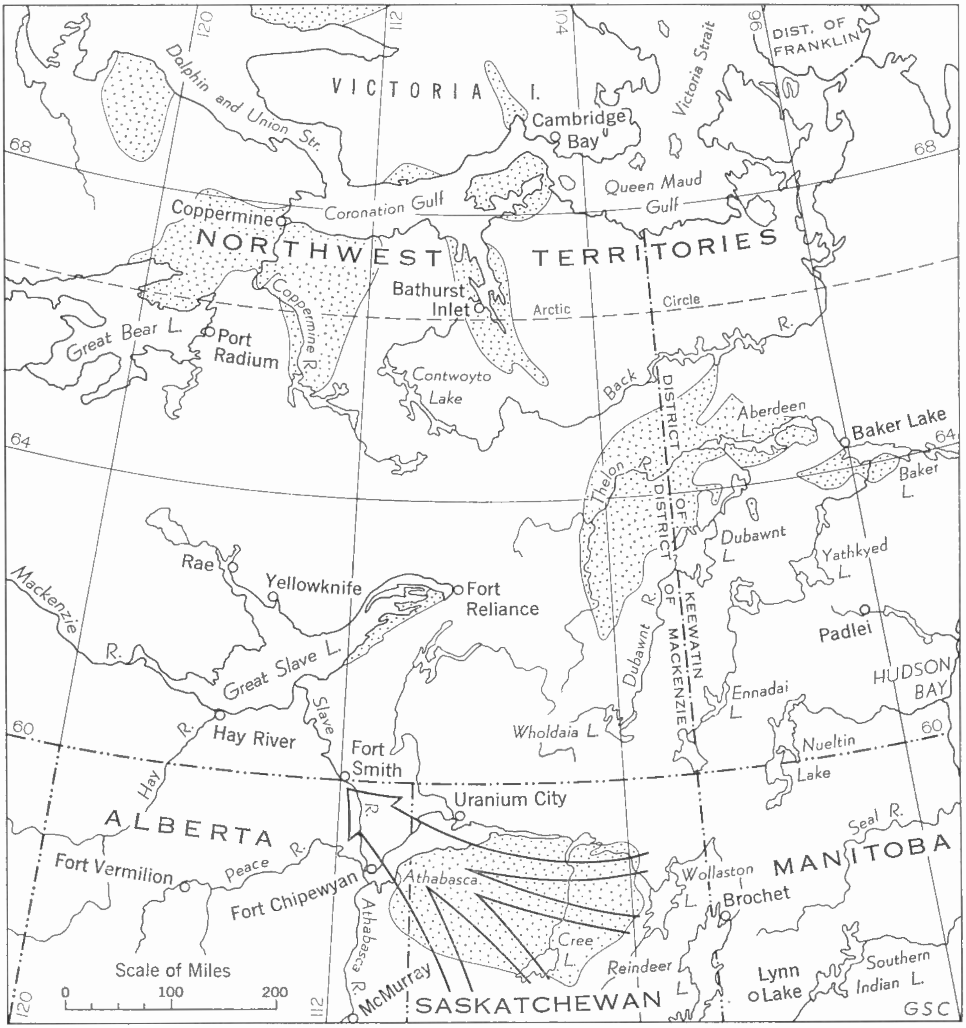

Figure 6. ***The regional distribution of Proterozoic sedimentary and volcanic rocks in relation to sediment transport direction of Athabasca sandstone.***

DEPOSITIONAL ENVIRONMENT OF THE ATHABASCA AND CARSWELL FORMATIONS

All the characteristics of the Athabasca and Carswell formations suggest that together they form a consanguineous association, and as such represent the commonly recognized orthoquartzite-carbonate facies. Features of the Athabasca orthoquartzite such as the high sandstone-shale ratio, intense crossbedding, ripple-marking, shale chip conglomerate, relatively minor thickness, and the features of the Carswell dolomite such as oolites, algal structures, and calcarenite layers are all characteristic of sedimentation in a stable platform area. The postulated sequence of Carswell carbonate rocks overlying Athabasca orthoquartzite is the most commonly observed stratigraphic relationship for deposition in this tectonic environment.

Both marine and continental environments have been suggested by previous writers (Alcock, 1920; Christie, 1953; Blake, 1956) to explain the characteristics of the Athabasca sandstone. The older discussions are confusing because of the practice of considering the Martin formation and Athabasca formation as a single unit (*see* Alcock, 1920). However, Blake (1956) discussed the environments of the two units separately and suggested that the Athabasca may be marine and may grade into the continental red beds of the Martin group. On the whole, however, geologists who have worked in the region have postulated a continental, predominantly fluviatile depositional environment for the Athabasca formation.

In the absence of fossils a number of lines of evidence may be followed in reconstructing the depositional environment of the bulk of the sands of the Athabasca formation. None of these individually provides conclusive evidence that the Athabasca is predominantly or entirely a fluviatile deposit; however a summation of the evidence is believed to indicate that this is so.

The lower strata of the Athabasca formation and the underlying unconformity have previously been described. It is noteworthy that at some points, probably depending mainly on the composition of the underlying Archæan rocks, a regolith has been developed and preserved. Furthermore, Athabascan orthoquartzite consisting of well-rounded and sorted material containing angular boulders of Tazin quartzite, was observed at several points (*see* Plate III). The association of underlying regolith and mature sand with angular quartzite boulders suggests that the maturity of the orthoquartzite is not the result of vigorous beach action. It follows that the lower Athabasca beds are probably fluviatile rather than marine or beach deposits.

Many of the sedimentary structures of the Athabasca are believed to be more characteristic of fluviatile deposition on a coastal plain than they are of deposition in a beach zone. The crossbedding which is shown on Figure 2 indicates a consistent regional pattern over a known area of about 40,000 square miles. The limited variability in the direction of crossbed dips implies a stable system of depositing currents and probably is more characteristic of stream currents than of currents in the littoral zone, and the greater deviation of crossbed measurements from the median in the down-paleoslope direction has been readily explained in terms of fluvial deposition. Furthermore, most of the crossbed units are in the form of narrow 'troughs' and probably indicate intense local scour and fill action, conditions that are consistent with deposition in a stream bed. The previously described overturned crossbedding and other slump features must be indicative of rapid sedimentation under considerable paleoslope, again more typical of stream environment than of shallow marine deposition. Alcock (1936) noted rain-prints in Athabasca formation south of Fond du Lac River, and Christie (1953) refers to mud-cracks in finer grained bands of Athabasca rocks on an island in Lake Athabasca. The writer observed desiccation cracks at one locality south of Carswell Lake. Although rain-prints and obvious desiccation cracks are not common in the Athabasca they do indicate local shallow-water conditions.

With regard to desiccation cracks, the previously described shale chip fragments are of interest. The shale pits on many surfaces are close together and frequently are angular in plan (*see* Pl. II). This indicates little movement of the chips and may signify that the thin shale layers were broken up by desiccation. If such were so, the shale chip layers indicate extremely shallow-water conditions with repeated, temporary withdrawals.

Most of the coarser grained sediments of the Athabasca formation megascopically show poor sorting and pronounced lensing of coarser with finer materials. In some cases pebbly lenses and individual pebbles are distributed irregularly in a crossbedded, predominantly sandy, matrix. Such material probably represents deposition in the beds of rapidly fluctuating streams. Much of the pebbly material contains a mixture of rounded to subangular particles and is unlikely to have been laid down as a typical beach gravel.

The sorting of the sandstone has previously been described. Most of the material analyzed (Fig. 3) exhibits only fair sorting and the size distribution is consistent with and more typical of fluvial deposits than it is of beach or marine orthoquartzite deposits (*see* Pettijohn, 1957, p. 289).

Red beds form a minor part of the Athabasca formation but they were observed at many points and at a number of stratigraphic levels within the sequence. Some thin layers of sandstone are thoroughly cemented with hematite and are brick-red. It is probable that the sands that now constitute these red beds were deposited in a subaerial environment, as the later alteration has been reduction of the iron rather than oxidation (Pl. IV).

The Carswell formation is undoubtedly the product of marine deposition. The position of the dolomite above clastic sediments that are probably in part continental suggests that a deepening took place after the initial period of sand deposition. A gradation from continental to marine sedimentation would be expected and possibly the finer grained sandstone southeast of Lake Athabasca represents a gradational phase, which is in part marine.

POST-ATHABASCA WARPING

Some idea of the end result of differential crustal warping since the deposition of the Athabasca sands may be gained from a knowledge of the trends of paleocontour lines, as these represent lines of zero or low slope at the time of Athabascan sedimentation. An estimate of the trend of Athabascan fall lines can be gained by drawing lines perpendicular to paleocurrent directions. The result is a set of curved lines which are concave to the northwest (*see* Fig. 2).

The four most westerly of these lines intersect Lake Athabasca and the unconformity below the Athabasca formation occurs within a few feet of lake level at many points around Lake Athabasca. The lake level (699 feet) may therefore be used as a reference for the relative rise of the crust along the southern extension of the hypothetical paleocontour lines. The Cree Lake crustal area has risen about 800 feet relative to the Stony Rapids area to the north, whereas crustal rocks of the Richardson Lake area have not risen at all relative to the Athabasca area to the northeast. Relative crustal rise between these two areas increases eastward from Richardson to Cree Lake.

In addition to using paleocontour lines at right angles to paleocurrent directions, the directions of paleoslopes themselves may be used to indicate post-Athabasca warping. The present land surface and probably most of the underlying Archæan-Athabasca erosion surface of the main sandstone area dip to the northwest. This conforms roughly in direction to the paleoslope that existed during the time of Athabasca sedimentation. The area northwest of Lake Athabasca, however, lies down the paleoslope from lower Athabasca outcrops exposed around Lake Athabasca but now lies higher topographically than these outcrops. This area has therefore risen relative to nearby Athabasca formation in the period since the deposition of the Athabasca sediments. If this area of gneiss has undergone a moderate amount of erosion, including glacial erosion during the Pleistocene, then the indicated rise is probably hundreds of feet. This area of uplift extends from about Slave River eastward around the north shore of Lake Athabasca.

If the two lines of evidence for regional warping are integrated, two belts of relative upwarping appear, with an intervening zone of relative downwarping. These are illustrated in Figure 7.

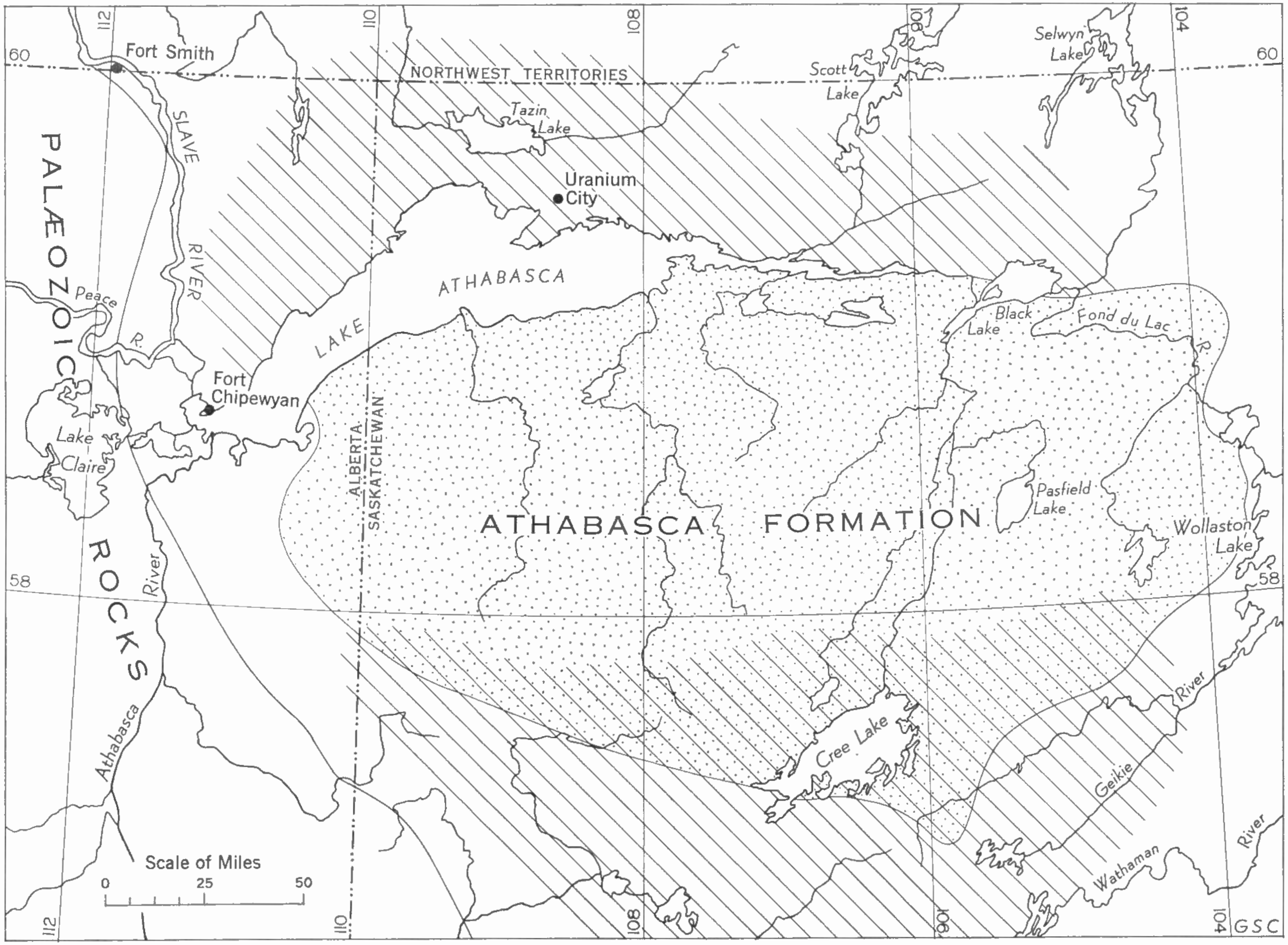

Figure 7. *Zones of post-Athabasca positive movement (shown by ruling) relative to an intervening zone.*

PROVENANCE OF THE ATHABASCA SANDSTONE

The composition of the terrain at present exposed in the area south and east of the Athabasca formation is believed to be essentially the same as that which was exposed in this area at the time of deposition of the Athabasca sands. The erosion surface of the gneisses passes, with no abrupt change in slope, into the gentle intracratonic basin occupied by the Athabasca formation and so it is unlikely that profound erosion has taken place in the area of gneiss to the east and south since Athabasca time. The rocks now exposed must therefore be very similar to the ones exposed there during Athabasca time.

This statement is true of a large area lying in the direction from which the Athabasca sands were derived. However, because the Athabasca sands may have been derived from source rocks lying at a great distance, this knowledge may add little to our understanding of the provenance of the sandstones. In addition, the sands of the Athabasca are rounded to well rounded and the postulated predominantly fluviatile environment could not have provided the rigorous abrasion necessary to round sands derived from a gneissic terrain.

The composition of the Athabasca sands, containing as they did only the most stable heavy and light constituents including a considerable amount of chert, coupled with the high degree of roundness of the particles suggests that the Athabasca was a multicycle product derived from a largely sedimentary terrain.

Evidence has been presented to indicate that the sands were deposited in a coastal plain environment by fluctuating streams rising predominantly in the east and south. These streams converged as they passed northeastward across the area now covered by the western part of Lake Athabasca.

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