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DEPARTMENT OF ENERGY, MINES AND RESOURCES

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GEOLOGICAL NOTES ON THE CARSWELL CIRCULAR STRUCTURE, SASKATCHEWAN (74 K)

(Report and 24 figures)

K. L. Currie

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ABSTRACT

The Carswell circular structure comprises a nearly circular downdropped block about 25 miles (39 kilometres) in diameter, set in undisturbed clastic sedimentary rocks of the Athabasca Formation. Inside the circular block, the Carswell dolomite, 610 feet (185 metres) thick, is exposed in a marginal ring syncline intricately folded and deformed. The Athabasca Formation, relatively flat lying and undeformed is exposed in a ring between the Carswell Formation and a central core of basement complex about 11 miles (18 kilometres) in diameter. The basement complex is characterized by deformation lamellae on quartz, ascribed to high shearing stress under high confining pressure, and by local potash metasomatism and iron depletion. Both of these features are associated with fault zones in which lenticular masses of Cluff breccia are found. Breccias of similar style are also found in fault zones in the Athabasca and Carswell Formations.

An hypothesis of origin by extraterrestrial impact is considered and rejected. The cause of the structure is considered to be diapirism of the basement caused either by igneous intrusion, or more probably, by concentration of volatiles at depth. The rising diapir dragged up the Athabasca Formation along its flanks, reducing it to a series of concentric fault slivers. The Carswell Formation at first domed over the rising diapir, then slid down the flanks of the dome accumulating in folds concentric to the dome. The last stage of activity was marked by escape of volatiles, producing metasomatized breccia zones along the edges of the diapir, and causing eventual collapse of the structure. This stage culminated about 475 million years before present.

The Carswell circular structure is structurally similar to other circular structures displaying central uplifts and shock metamorphism, but differs from them in the lack of igneous phenomena.

Frontispiece. Scarp in the Carswell Formation facing outward over the Athabasca Formation which is exposed across the valley. Note the dip of 40 degrees in the strata. (GSC 120157)

GEOLOGICAL NOTES ON THE CARSWELL CIRCULAR STRUCTURE, SASKATCHEWAN

INTRODUCTION

Location and Access

The Carswell circular structure in northern Saskatchewan, is centred approximately at 58°27' north, 109°30' west. Carswell Lake lies about 70 miles (110 kilometres) south of Uranium City, and 325 miles (515 kilometres) northwest of Prince Albert. Carswell and Cluff Lakes are readily accessible by float equipped aircraft, which can be chartered at Uranium City, and several of the smaller lakes can be used by light float equipped aircraft under favourable weather conditions. Carswell Lake is also accessible by canoe from Lake Athabasca via William River.

Physical Features

The Carswell structure is on a surface of low relief rising gently from Lake Athabasca to the southeast. Although there is some swamp, particularly to the north of the structure, the surface is generally sandy and supports a rather sparse forest of jack pines and spruce with little underbrush.

The structure itself consists of four distinct parts: (1) the rim, (2) the marginal depression, (3) the inner slope, and (4) the central highland.

The rim is marked by an inner ring of cliffs about 18 miles (29 kilometres) in diameter, varying from 50 to 210 feet (15 to 65 metres) in height, and an outer ring of less precipitous cliffs some 25 miles (39 kilometres) in diameter (Frontispiece). This annular highland, about 7 miles (10 kilometres) wide, has abundant outcrop and is topographically rugged, with 145 to 210 feet (45 to 65 metres) of abrupt local relief. The only major breaks in the rim are a 7 mile (10 kilometre) gap in the west rim between Points Lake and Badwater Lake, a 3 mile (5 kilometre) gap near the junction of Beaver Creek and Douglass River, and a split in the north rim occupied by Carswell Lake. Just inside the bounding cliffs is a pronounced marginal ditch 0.6 to 2 miles wide (1 to 3 kilometres wide). This depression is marked by a continuous chain of lakes and swamps, on the inner side of which the ground rises gently, exposing considerable rock outcrop partially veneered by sand plains. The central core of the structure, about 11 miles (18 kilometres) in diameter, is 100 to 200 feet (30 to 60 metres) higher than the rim, but little outcrop is exposed, much of the area being covered by swamp.

Manuscript received: March 8, 1967

Geological Work

The dolomite which outlines and characterizes the structure was discovered by Blake (1956), who examined the prominent cliffs extending some miles east and west of Carswell Lake. Blake recognized the intricately deformed character of the rock, and its structural complexity. W.F. Fahrig (1961), in the course of an examination of the Athabasca Formation, made an additional reconnaissance study of the dolomite, naming it the Carswell Formation. Fahrig discovered that the dolomite outcropped in an almost complete circle some 25 miles (39 kilometres) in outer diameter, and that the outcrop had the general form of a synclinorium. Fahrig mentioned, but did not observe, outcrops of pre-Athabasca basement complex. These were examined in the course of a gravity survey of the structure in 1962 (Innes, 1965). This survey also discovered outcrops of unusual breccias east of Cluff Lake.

The present study is based on 3 months of field work in 1964, during which time all parts of the structure not covered by swamp were traversed by pace and compass methods at intervals of about half a mile. Particular attention was paid to (1) the disposition and structure of the Carswell Formation, (2) the relation of the Carswell Formation to the Athabasca Formation and the crystalline basement, and (3) the fabric of the circular structure.

Acknowledgments

The author wishes to acknowledge efficient assistance in the field by R. McLaughlin. Discussions with W.F. Fahrig and M.R. Dence clarified many points in the author's mind concerning the structure. The manuscript has been greatly improved by the critical reading of J.E. Reesor.

GENERAL GEOLOGY

Introduction

The Carswell structure lies in the midst of a great sheet of nearly flat-lying clastic, sedimentary rocks, the Athabasca Formation. Four major rock units outcrop within the Carswell structure. Steeply dipping granite gneisses, lit-par-lit gneisses and related rocks, presumed to be of Churchill age, form a central core, overlain with great unconformity by a concentric ring of conglomerate, grit, and sandstone, the Athabasca Formation. In this area the Athabasca Formation can be divided into two units on the basis of slight differences in grain size and colour. These units are overlain possibly with slight unconformity, or thin intervening formations, by the Carswell dolomite which may be divided into two units on the basis of slightly differing physical characters. All of these rocks are cut by dyke-like bodies of Cluff breccia filling transcurrent faults. Relatively thick deposits of unconsolidated material, principally glacial tills and outwash, obscure the bedrock over most of the area. Bedrock exposure is estimated to be less than 1 per cent of the map-area, except on the rim where it is 10 to 20 per cent.

Basement Complex (Unit 1)

Distribution The basement complex consists chiefly of steeply dipping granitoid gneisses with generally southeasterly strikes. These rocks outcrop around the edge of a roughly circular central core about 11 miles (18 kilometres) in diameter, and are best exposed north and east of Cluff Lake. A single outcrop is known from about 1 mile west of the central core. Outside the Carswell structure, the nearest outcrops of comparable rocks are on the north shore of Lake Athabasca, about 60 miles (100 kilometres) away.

East of Cluff Lake, an outlier of the lower Athabasca Formation is found resting unconformably on the basement rocks. The boundary of the central core is poorly exposed, but where it is exposed east of Cluff Lake, it is a fault contact between the basement complex and the Athabasca Formation.

Macroscopic character Outcrops of the basement complex consist of lit-par-lit gneiss, hybrid gneisses, granite gneiss, and massive granite or pegmatite in varying proportions. Boulders of amphibolite occur south of Carswell Lake. Most of the rocks are bright red due to iron staining.

The gneisses are composed of very regular, even layers 0.08 inch to 32 feet (2 millimetres to 10 metres) in width. They show strong fissility along gneissosity planes, and the parting planes display complex slickensides. The mafic minerals are soft, green, and altered in appearance. Granitic material may be present as thin, well-defined beds, boudins, irregular breccia fillings, or intimately mixed irregular bodies. This type of hybrid material is locally replaced by more homogeneous gneissic biotite granite, or massive pegmatite. This material forms small pods or lenses within a generally hybrid terrane.

Lithology and composition The basic bands in the gneisses consist of plagioclase (An_{30}), generally creamy from alteration, and in places almost opaque, together with severely chloritized hornblende ($z \wedge c$ 0-8°) and a little magnetite and pyrite. Garnet is locally present as pale pink allotriomorphic grains, and in some instances the rock is a quartz-garnet-plagioclase gneiss. Here and there quartz is abundant in polycrystalline lenticles and mosaic patches and may show multiple sets of deformation lamellae. The granitic fraction comprises 25 to 60 per cent quartz, 30 to 50 per cent microcline in the form of large, irregular grains, 10 to 25 per cent albitic plagioclase, and minor biotite. In the granitic rocks the potash feldspar is generally so iron-stained as to be virtually opaque. Alteration of most specimens by formation of sheaves of chlorite, rarely epidote, and cryptic brownish or creamy alteration products is far advanced. Modal analyses of some selected specimens are given in Table I.

In view of the high degree of alteration of the basement rocks, chemical analyses may yield information on the geochemical processes at work. In Table I are tabulated analyses of four channel samples of the basement aggregating about 50 pounds each and covering the range of compositions encountered. As there is no priori reason to give more importance to one specimen than to another, the four specimens have been averaged to yield a crude estimate of the average composition of the basement rocks. The magnitude of the standard deviations shows this estimate to be, at best, very approximate.

Discussion and conclusions The deeply altered character of the basement rocks, together with the rubbly, fractured character of the outcrops could be due to disruption during the formation of the Carswell structure. However, Conybeare and Campbell (1951) describe essentially identical rocks from near Uranium City and a brief examination of these rocks by the author confirmed the similarity in degree of alteration, iron staining, and fissility.

Examination of the average composition of the basement in Table II reveals no marked peculiarities except an unusually high content of potash. No chemical analyses of the granitoid gneisses in the Uranium City area are available to the writer, but Conybeare, quoted by Christie (1952, p. 45) measured the modal composition of ten of these rocks, obtaining a mean microcline content of 21.1 per cent and a mean muscovite content of 5.6 per cent, corresponding to roughly 4.3 per cent of potash. However, if two analyses which showed no potash-bearing mineral at all are discarded, the microcline and muscovite contents rise to 26.5 and 7.0 per cent respectively, equivalent to slightly over 5 per cent potash. Reesor (1965, pp. 8-11) considered the average composition of a 'veined gneiss' complex in southern British Columbia, under various assumptions as to the relative abundance of

Table I

Chemical analyses of rocks from the basement complex

(Analyst: S. Courville, analyses by rapid method)

Specimen Number	35	77	82	119	Average	Standard Deviation
SiO_2	63.0	74.5	70.0	59.5	66.75	5.82
Al_2O_3	20.0	11.6	17.4	18.8	16.95	3.21
Fe_2O_3	1.6	3.2	1.3	2.7	2.20	0.77
FeO	1.1	6.7	0.2	4.9	3.22	2.59
CaO	0.6	0.6	0.3	3.1	1.15	1.14
MgO	0.8	1.0	1.1	1.6	1.12	0.59
Na_2O	2.9	1.0	2.3	2.5	2.17	0.71
K_2O	8.33	0.50	7.53	4.30	5.17	3.16
MnO	0.05	0.25	0.11	0.01	0.11	0.07
TiO_2	0.25	0.11	0.02	0.88	0.32	0.31
P_2O_5	0.05	0.11	0.07	0.22	0.11	0.06
H_2O	0.5	1.1	0.9	1.9	1.10	0.5
CO_2	0.2	0.1	0.1	0.1	0.11	0.03
	99.88	100.77	100.33	100.51	100.08	

Modal analyses of rocks from the basement complex

(based on 2000 points counted on two thin sections on a grid 0.3 by 0.9 mm)

Specimen Number	35	77	82	119
quartz	28.2	57.2	40.3	32.1
plagioclase	16.8	-	12.9	29.1 (An 28)
microcline	43.1	7.1	28.6	11.2
hornblende	4.3	-	-	-
biotite	-	-	8.2	10.1
chlorite	3.1	2.2	1.0	14.8
garnet	-	21.3	-	-
zircon, apatite	0.2	tr	0.2	0.3
opaque	-	0.6	0.3	2.3
alteration products	4.5	11.6	8.5	0.2
glass	tr	-	tr	-

Description of specimens

35 Coarse-grained, red, gneissic granite, with shearing on gneissosity, 2 km west of south end of Carswell Lake.

77 Coarse-grained quartz-garnet matrix with feldspar porphyroblasts to 1 cm diameter. 5 km northeast of Cluff Lake.

82 Medium-grained, massive leuco-granite with net fracturing, reddish alteration spots. 6 km northwest of Cluff Lake.

119 Finely banded lit-par-lit gneiss of amphibolite and red pegmatite, Badwater Lake area.

the component parts. Assuming equal amounts of the 'vein' and 'gneiss' component, a proportion appropriate to the Carswell Lake rocks, he obtains 4.40 per cent potash for the average composition. Allowing for the fact that the sampling of the rocks in the Carswell structure is probably biased toward high potash content because granitoid rocks were relatively sound and easily sampled, the potash content of the basement rocks probably does not differ significantly from the potash content of either similar rocks in the general region, or complexes of similar rocks in other regions. If enrichment in potash has taken place it must be slight.

The rather unusual physical character and composition of the basement rocks may be due to processes connected with formation of the circular structure, but rocks of similar character and composition outcrop outside the structure. If these characters result from formation of the circular structure, the processes of formation must have much in common with conventional geologic processes.

Athabasca Formation (Units 2, 3)

Distribution The Carswell circular structure occurs within a great sheet of nearly flat-lying, clastic sedimentary rocks, the Athabasca Formation, which covers an area of 245 miles (390 kilometres) from east to west - 130 miles (210 kilometres) from north to south. Within this vast sheet, the only known localities at which other rock types are exposed are within the Carswell structure.

In the vicinity of the Carswell structure the Athabasca Formation is exposed outside the rim, and immediately inside it. The outcrops inside the rim form an annulus surrounding the central core of basement rocks previously described. East of Cluff Lake a large outlier of Athabasca Formation rests on basement rocks with unconformity. At one exposure, light coloured sandstone rests on scoured, relatively unaltered basement rocks, whereas at another exposure about 3,300 feet (1 kilometre) to the south, red to purple conglomerate rests on rotten reddish basement rocks with perceptible sulphide mineralization. Conglomerate, believed to be at or near the base of the Athabasca Formation is also exposed near the basement outcrop southeast of Points Lake.

The thickness of the Athabasca Formation has been studied by Hobson (personal communication) using seismic refraction techniques. These results will be discussed in detail in a later section, but they suggest that the Athabasca Formation is relatively thin in the region surrounding the Carswell structure. Detailed gravity surveys by Innes (1964) within the structure suggest a very variable thickness for this formation, ranging from zero up to possibly 2,700 feet (830 metres). Outcrop is so poor that direct measurement is not feasible.

Within the Carswell structure the Athabasca Formation can be divided into two units on the basis of colour and texture. The lower member (Unit 2) is brightly coloured in shades of red, purple or iridescent black. Pebble beds are common, usually consisting of a single layer of well rounded frosted quartz pebbles up to 0.4 inch (1 centimetre) in diameter. Between the pebble beds the rock is coarse, porous sandstone and most of the grains exceed 1 millimetre in diameter. Graded bedding, crossbedding and scour-and-fill structures are common. This member is readily recognized on aerial photographs because it supports vegetation which imparts a markedly darker hue than the upper part of the Athabasca. This criterion has been used to draw the boundaries on the map. The upper member (Unit 3) consists of white to pale buff, rarely orange, homogeneous orthoquartzite. Pebble beds are rare, and bedding or other sedimentary structures are inconspicuous or absent.

Macroscopic character The lower member (Unit 2) outcrops in rubbly, rounded masses with a great deal of loose sandy material from the decomposition of the rock. Colour banding is normally regular, but in some outcrops is strongly lensoid. In a few outcrops whitish subparallel streaks cut across the colour banding, apparently following minute cracks. One outcrop east of Cluff Lake has a remarkable grid-like surface pattern. Mildly sheared material occurs southwest of Beaver Lake. Hematite forms slickensided films between layers of sandstone. Attitudes are not easy to determine in this rock because of the decomposed nature of the outcrops.

The upper member (Unit 3) outcrops in rubbly knobs (Fig. 2) and less commonly as low scarps. A close examination will generally disclose some orientation of grains defining bedding, but some outcrops appear perfectly homogeneous and massive. The rock has well developed orthogonal joints, giving a characteristic blocky appearance. Signs of shearing have not been found in this rock, but a few outcrops show a pervasive fine fracturing, recognizable in specimens as a fine tracery of white lines. On one outcrop south of Points Lake, the scale of fracturing is larger, and the rock is a breccia of fractured rotated fragments a few centimetres in diameter embedded in irregular masses of finely crushed material. Boulders of similar material were noted by Fahrig (1961, p. 20) west of Carswell Lake.

Lithology and composition The lower member ranges in composition from coarse quartzose sandstone to conglomerate. In thin section the rocks are monotonous, consisting principally of moderately rounded, single or polycrystalline grains of quartz, with very rare grains of potash feldspar or myrmekite. Despite the strong reddish colours, the cement is carbonate in all but one of the thirteen specimens examined which has hematite cement. The degree of rounding of grains is markedly dependent on size. Grains larger than 2 millimetres in diameter are well rounded, whereas those less than 1 millimetre in diameter are markedly angular with many jagged splinters of quartz. The majority of grains are unstrained, but a few polycrystalline grains show mosaic structure, moderate strained extinction and poorly

Figure 2. Typical outcrop of Athabasca Formation east of Cluff Lake. (GSC 120155)

developed Boehm lamellae. Samples from the outlier east of Cluff Lake display numerous grains with radial cracks and strain shadows where adjacent grains are in contact.

The upper member of the Athabasca Formation is composed of remarkably uniform, medium-grained, well rounded, well sorted quartz sand. Over 99 per cent of the grains examined were quartz. A few microcline and tourmaline grains make up most of the remainder. The lack of heavy minerals is noteworthy. As with the lower member the degree of rounding is dependent on size of grain, and some minute angular blades of quartz are present in the cement. The cement may be quartz or carbonate, or rarely carbonate plus hematite. In some cases, sandstones with quartz cements have been changed to quartzite, with the matrix in optical continuity with the grains.

The breccia previously noted is not impressive in thin section. The fragments are identical to the unfragmented rock, whereas the matrix is simply fine, angular, quartz fragments.

A chemical analysis of the upper member is given in Table IV, where the chemical data are discussed.

Discussion and conclusions Fahrig (1961) was unable to subdivide the Athabasca Formation on a regional scale. It is probable, therefore, that the division used in this report is of very local value. The lower member is of uncertain but slight thickness. Its appearance in Jackfish Creek a few kilometres north of the structure confirms that the Athabasca Formation is rather thin in this region. This makes it more plausible that an outlier of the pre-Athabasca basement should appear, but makes the occurrence of the Carswell Formation an acute problem. In any case the general petrographic character of Athabasca Formation suggests that the formation of the circular structure did not produce either violent disruption or strong chemical action in this formation. The character of the breccia is consistent with that of local fault breccias observed elsewhere in the Athabasca (cf. Fahrig, 1961, p. 15).

Fahrig (1961, pp. 32-34) suggests that the probable age of the Athabasca Formation is of the order of 1500 million years. Gussow (1959), however, has claimed that the formation is probably Devonian in age. This latter suggestion is refuted by the age determination of 476 million years for the Cluff breccias which intrude the Athabasca Formation.

Carswell Formation (Units 4, 5)

Distribution Outcrop of the Carswell Formation is mainly confined to the rim of Carswell circular structure, but small outliers are found within the rim. Borings through the Athabasca Formation near Fond du Lac, about 75 miles (120 kilometres) east of Carswell Lake penetrated no carbonates (L.C. Hogg, personal communication), and Fahrig (1961) saw no carbonate rocks in the Athabasca Formation, except in the Carswell structure.

Thin bedded grey dolomite of the Carswell Formation conformably overlies white to yellowish, medium-grained homogeneous quartz sandstone of the upper member of the Athabasca Formation on a low scarp 3.7 miles (6 kilometres) northwest of Eastrim Lake. Ten feet (3 metres) of section are covered at the contact west of Carswell Lake, an outlier of Carswell Formation appears to lie conformably on white sandstone of the upper Athabasca Formation, but the area within 160 feet (50 metres) of the contact is not exposed. On the west shore of Carswell Lake just south of the cliffs of dolomite, 20 feet (6 metres) of decomposed red shale outcrop, dipping beneath the Carswell Formation. This outcrop is mapped as part of the Athabasca Formation by Fahrig (1961) who notes (op. cit., p. 7) that elsewhere in the Athabasca the thickest known shale bed is about 5 feet (1.5 metres) thick. Rubble of similar shale was seen beneath the Carswell Formation south of Badwater Lake.

The Carswell Formation has been divided into two members on the basis of differing physical character. The lower member (Unit 4) is composed of thinly bedded, fissile dolomite with many calcarenite and stromatolite zones. The top of this member is defined as the uppermost stromatolite zone and above this the character of the rock changes rapidly into thickly bedded, massive dolomite assigned to the upper member of the Carswell Formation (Unit 5).

Poor exposure of the base of the Carswell Formation makes it difficult to measure the thickness of the lower member (Unit 4). Using the cliff northwest of Eastrim Lake and marker horizons discussed below, a composite section has been constructed from 10 different localities, totalling 295 feet (90 metres), with an estimated uncertainty of 32 feet (10 metres).

The upper member (Unit 5) outcrops in a narrow band extending almost 12 miles (20 kilometres) west from Carswell Lake, but occurs elsewhere only as lenticular areas less than 1.2 miles (2 kilometres) in length. The exposed thickness of the upper member is difficult to determine reliably because of the high degree of structural distortion of this unit. A continuous section of relatively undisturbed material measuring 322 feet (99 metres) occurs just west of Carswell Lake. The thickness involved in other occurrences is thought to be much less, probably not exceeding 45 feet (15 metres).

Macroscopic character The lower member of the Carswell Formation (Unit 4) is the best exposed bedrock unit in the Carswell structure. Almost continuous jagged cliffs of dolomite mark the inside and outside of the rim, locally reaching 210 feet (65 metres) in height. The lowest exposures of the Carswell Formation consist of tabular, angular, slickensided fragments up to a few inches in diameter, cemented by identical, but massive, brownish grey dolomite. Above the basal breccia zone is a characteristic sequence of oolite-calcarenite beds which form layers a few inches thick interbedded with pale grey non-fragmental dolomite. The calcarenite layers consist of oolites up to 0.12 inch (3 millimetres) diameter and flakes of similar size resulting from brecciation of the thin non-fragmental layers. The brecciated material in the beds consists of thin discs of dolomite a few millimetres in diameter, well rounded in plan. The alignment of the discs on the bedding plane is perfect. These outcrops suggest packed confetti. The amount of fragmental material appears to increase from north to south, but both oolites and fragments are present in all the occurrences of this horizon examined. The distinctive beds are included in a 35- to 50-foot (10 to 15 metre) section of paper-thin bedded dolomite with perfect cleavage (Fig. 3) which can be traced around the structure thus forming an excellent marker horizon.

The beds of pale grey dolomite range in thickness from paper thin to about half an inch and are characterized by a perfect parting between beds, giving the rock a slaty appearance. The thickness of beds changes very slowly, and sections of several feet are composed of virtually identical beds. The average thickness gradually increases with height reaching a thickness of 2 to 3 inches (5 to 7 centimetres) about 325 feet (100 metres) above the base of the formation. At this level the rock is a very regularly bedded flaggy dolomite.

Figure 3. Paper-thin bedded dolomite, Points Lake area.(GSC 120146)

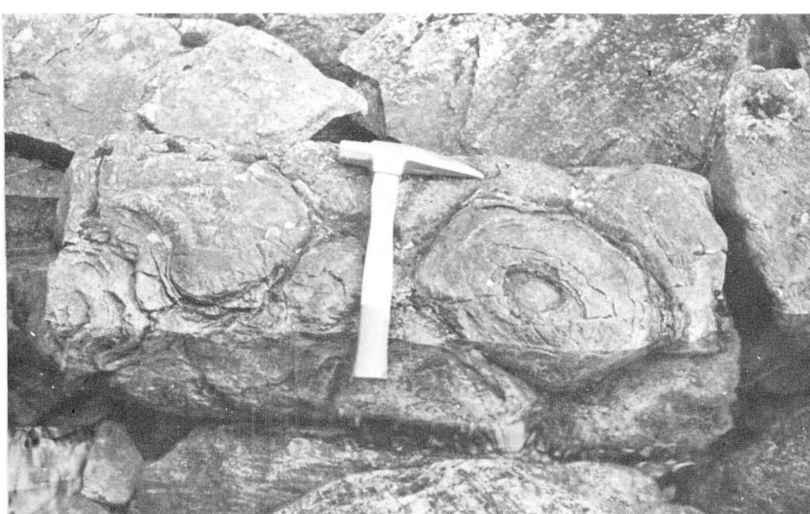


Figure 4. Stromatolites, along west shore of Carswell Lake.(GSC 120147)

Stromatolites (Fig. 4) are distributed irregularly throughout this flaggy material. Where best developed they comprise bun-shaped structures 12 to 20 inches (30 to 50 centimetres) in diameter composed of concentric layers of carbonate one-half to one centimetre thick. The layering of the stromatolites is much thinner than that in the surrounding rocks. Between the layers there are fine seams of dark carbonaceous matter, or fine detrital material. The height to width ratio of the stromatolites tends to be about 1:3 to 1:4. The surrounding beds are deflected around the protuberances, rather than terminating against them. Stromatolites occur in colonies of several dozen, occupying a few cubic metres. The surrounding area may be almost barren. Stromatolites have been used to determine tops of beds, on the assumption that the convex parts points upward, and the stromatolite beds have been used for marker horizons. This latter use is not entirely reliable as a few stromatolites occur lower in the section. These tend to be very much smaller, and show very fine regular banding.

The lower member of the Carswell Formation is characterized by an extraordinary variety and abundance of brecciation (Blake, 1956; Fahrig, 1961, p. 19). The slaty, slickensided material at the base of the formation has already been mentioned. In addition there are numerous areas several tens of square metres in extent where the rock is broken into innumerable blocks 2 to 3 inches (5 to 8 centimetres) on an edge, and each block is rotated 15 degrees or 20 degrees with respect to its neighbour. The blocks are cemented together by a small amount of matrix identical in composition to the fragments. Outcrops of this kind give a remarkable impression of zig-zag strikes. Beds can often be followed across the outcrop as strings of broken and rotted fragments (Fig. 5). This type of breccia may occur anywhere in the Carswell Formation, but appears to be generally related to fold deformation and follows synclinal axes. The ring syncline west of Carswell Lake is a particularly good example. Breccias of this kind can be distinguished from the younger Cluff breccias by the following criteria: (a) the amount of matrix is small, and of the same colour and composition as the fragments; (b) the fragments are extremely angular and of similar size; (c) the brecciated areas are not associated with prominent linears.

The upper member of the Carswell Formation (Unit 5) outcrops in rounded whalebacks, readily distinguished at a distance from the jagged cliff-forming outcrops of the lower member. The colour of the Carswell Formation gradually changes from pale grey at the base of the lower member to brownish grey in the stromatolitic horizons, to buff or fawn shades in the upper member. In the upper member, layers are 10 to 12 inches (25 to 30 centimetres) thick and there is little or no parting between them. Weathering on the bedding planes gives the rock a ribbed or ropy appearance. On weathered surfaces, very fine, regular banding may appear between bedding planes, but when the rock is broken this banding cannot be seen on a fresh surface, and specimens appear rather massive.

Figure 5. Limestone breccia south of Eastrim Lake. Note roundness of fragments at point and handle of hammer. The fragment at the point is highly altered basement granite. (GSC 120158)

Figure 6. Small fold in dolomite on west shore of Carswell Lake. Note sharp décollement at the base of the fold, and the loss of bedding in the central core. (GSC 120150)

Intense brecciation of the type common in the lower member does not occur in the upper member but virtually all outcrops show complex small folding. The axial planes of the folds, where they can be discerned, strike in very diverse directions. Intense folding generally has obliterated the bedding planes, and the rock appears massive (Fig. 6).

Outcrops of dolomite can generally be placed in the upper or lower member by their colour. However, many outcrops are neither grey nor buff but various shades of red or purple. This colour is associated with coarse grain size, brecciation, and structural complexity. In many cases the red colour is patchy and irregular. In some exposures it originates at the edge of joint blocks and penetrates only partly into the rock. Reddish outcrops are almost invariably associated with veinlets, seams and patches of red calcite crystals which are accompanied by haloes of red discoloration. The red colour is not primary, but accompanies deformation and recrystallization.

Lithology and composition Microscopically the Carswell dolomite consists of uniform, finely crystalline to cryptocrystalline carbonate charged with minute opaque flecks. Except for oolites and fragments, little or no structure can be seen. The oolites are composed of numerous concentric layers 0.1 millimetre or less in thickness, usually around a minute rusty nucleus. Cracks radiating from the centre are common, but rarely reach the surface of the oolite. Most oolites are spherical, and do not touch each other, but in some cases flattened spheres result from mutual contact. The coarser grained material resulting from recrystallization is calcite, which is also present in gash veins in many specimens.

Chemical analyses of three specimens of the Carswell Formation, covering the range of physical properties observed, are presented in Table II. In terms of the stoichiometric formulae for dolomite and calcite, they all correspond to about 70 per cent dolomite and 30 per cent calcite.

Discussion and conclusions The relations of the Carswell Formation to the underlying Athabasca Formation are of critical importance to the understanding of the Carswell circular structure. Blake (1956) believed the Carswell Formation to underlie the Athabasca, on the grounds that the Carswell Formation was severely deformed and the Athabasca was not. This hypothesis is refuted by discovery of the Athabasca pre-Athabasca contact within the structure, which demonstrates that no formations lie between the Athabasca Formation and the basement complex. In the Dubawnt Formation, which is strikingly similar to the Athabasca in lithology and mode of occurrence, carbonate rocks are found as a lens within the clastic sedimentary rocks (J.A. Donaldson, personal communication). This is a possible mode of occurrence of the Carswell Formation but none of the Athabasca Formation now exposed is likely to be younger than the Carswell Formation. Otherwise a carbonate formation more than 500 feet (150 metres) thick, forming erosionally resistant scarps should surely have been discovered, on surface or in drill holes, elsewhere in the area covered by the Athabasca Formation.

Table II

Chemical analyses of rocks from the Carswell Formation

(Analyst: S. Courville, analyses by rapid method)

Specimen Number	26	29	133
SiO_2	1.0	0.8	1.0
Al_2O_3	1.2	0.9	0.6
Fe_2O_3	0.1	0.1	0.1
FeO	0.2	0.3	0.2
MgO	16.2	16.6	17.2
CaO	35.7	35.7	35.1
Na_2O	0.1	0.1	0.1
K_2O	0.20	0.12	0.07
TiO_2	0.02	0.02	0.02
P_2O_5	0.01	0.01	0.01
MnO	0.01	0.01	0.01
CO_2	45.4	45.1	45.8
H_2O	0.5	0.4	0.2
	100.64	100.16	100.41

Description of specimens

26 Thinly bedded pearl grey dolomite (lower Carswell member), from rim 3.7 miles (6 kilometres) west of Carswell Lake.

27 Near massive, thick bedded, buff dolomite (upper Carswell member), from rim 5 miles (8 kilometres) west of Carswell Lake.

133 Aphanitic red dolomite with fine calcite gash veins, 1.9 miles (3 kilometres) northeast of Points Lake.

It is therefore concluded that the Carswell Formation is younger than any part of the Athabasca Formation now exposed. The conformable nature of the single contact exposed between the two formations, and the presence of shale between them at several places suggests that deposition may have been continuous, with the environment gradually changing from continental to marine. This conclusion is in accord with Fahrig's (1961) results from his study of the sedimentation of the Athabasca Formation.

Fahrig (1961, p. 39) concludes that the Athabasca " ... sands were deposited in a coastal plain environment by fluctuating streams ...". The relief on such a coastal plain must have been low, probably not exceeding a few metres. This conclusion is supported by the great area of the Athabasca Formation, and the regularity of its margins. If there had been any great relief on the paleosurface the present outcrop pattern of the formation would be much more irregular. If deposition was continuous between the Athabasca and Carswell Formations a near maximum thickness of Athabasca Formation must be preserved beneath the Carswell Formation. In contrast to the rest of the Athabasca Formation, the top is not eroded in this area, and the thickness occurring is less than the maximum by only the amount of the relief on the surface of the basement complex when the Athabasca Formation was laid down. As we have seen this relief was small, probably less than 300 feet (100 metres).

Cluff Breccias

Distribution The Cluff breccias form series of dykes and veinlets cutting all other formations at six localities in this area. They are exposed on low scarps or great cliffs. One mile east of Cluff Lake, breccias are exposed in a series of low, east-trending linear bluffs that can be traced for about a kilometre. These bluffs mark a fault juxtaposing the basement and the upper part of the Athabasca Formation. Two kilometres south of Points Lake, breccia is exposed on two low scarps about a kilometre apart. At one locality the scarp marks a fault bringing the upper and lower members of the Athabasca Formation into contact. At three localities, about 9.5 miles (15 kilometres) west of Carswell Lake, linear swamps cut obliquely across the 210 foot (65 metre) relief in this area. The swamps are bounded by cliffs faced with breccia, most of the breccia being on the north side of the swamp. A few hundred metres east of most easterly of these localities veinlets of ultramylonite(?) cut apparently undisturbed strata of the upper member of the Carswell Formation. On Douglass River, in the extreme southeast corner of the area breccia is found on a large cliff in the Carswell Formation. Finally many fragments of breccia have been found in the float south of Tuma Lake, northeast of the structure. This concentration of fragments coincides with a pronounced magnetic anomaly, and may mark the site of a pipe of breccia.

Macroscopic character The character of the breccias varies considerably, depending on the character of the rocks they cut. However, they are distinguished generally by (a) relatively large amount of matrix, (b) brilliant colour, ranging from red through yellow and yellow-brown to green, (c) variety of shape and composition of fragments, (d) strong deformation of fragments, and (e) close association with linear zones.

Spectacular exposures of brecciation of the basement can be seen 0.6 mile (1 kilometre) east of Cluff Lake. The breccias may be subdivided into: (a) intensely altered and distorted, but coherent, basement rocks, (b) fragmental breccias with particulate matrices, and (c) breccias with aphanitic or vitric matrices.

The altered basement rocks appear earthy red in hand specimen. Recognizable mineral grains show remarkable plastic distortion. Locally the rock is disaggregated and somewhat 'jumbled'. This type of material grades rather rapidly into the usual red stained, rubbly basement rocks. The fragmental breccias consist of fragments, rarely more than a centimetre in diameter, embedded in a fine paste of crushed fragments, or vitric material. The fragments are of intensely distorted basement rocks, together with apparently unaffected grains and fragments of the Athabasca Formation. The colour varies from reddish-brown to green. This material forms a zone, parallel to the trend of the outcrops, which locally grades into disaggregated basement, but more commonly displays an intricate intrusive, crosscutting contact with some well-defined dykes up to a metre across. In the contact zones are local lenticular masses of strongly colour-banded rocks with an aphanitic matrix and characteristic conchoidal fracture, and rare, minute, rounded inclusions. Bands of fragmental rocks up to a centimetre in width are commonly intercalated. Flow texture is usually prominent, contorting the banding.

Breccias possibly referable to the Cluff breccia occur in the Athabasca Formation 1.2 miles (2 kilometres) south of Points Lake. The rock involved is an ivory homogeneous sandstone of the upper member of the Athabasca Formation. Rounded sandstone fragments of diverse sizes float in a matrix of crushed white quartz. The fragments are notably diffuse at the edges, as though dissolving into the matrix. Vague red to purplish coloration of the matrix is characteristic, as is a curious opaque quality reminiscent of argillaceous alteration. Parts of the matrix are extremely fine grained and after manual disaggregation pass through a 320 mesh sieve. The matrix is cut by anastamosing veinlets of porcelain-like quartz.

The Athabasca Formation is also involved in the breccia occurrence east of Cluff Lake, and appears in the float from the Tuma Lake area. In both cases, however, the matrix is not composed of sandstone. The Tuma Lake specimens contain small inclusions of Athabasca Formation in a brownish aphanitic matrix, similar to the aphanitic breccias from the Cluff Lake occurrence.

The Cluff breccias cutting the Carswell Formation comprise angular to distinctly rounded fragments ranging from microscopic to a few centimetres in diameter (Fig. 5). Near the gradational contact of the breccia lens with the undisturbed rocks there are larger blocks that range up to several metres in length. The matrix is intensely red or rarely reddish-purple. Typically fragments of both the lower and upper members of the Carswell Formation are found in the breccias. In several outcrops there are fragments up to 1 foot (30 centimetres) across of an older brownish breccia. This breccia has not been found in situ. At two of the breccia occurrences west of Carswell Lake, fragments of severely argillized granitoid rocks were found, presumably brought up from the basement. The largest granitoid fragment was about 10 centimetres across.

East of these occurrences veinlets of porcelain-like material up to 5 centimetres across were observed parallel to the larger breccia occurrences. Fragments of white aphanitic material up to a centimetre across occur in an aphanitic flow banded matrix. The veinlets have a well defined trend, although they are slightly sinuous in detail. These veins were only seen in the upper member of the Carswell Formation, which they cut at almost right angles to the bedding.

Petrography and composition The petrography of the breccia will be discussed in the following order: (1) disturbed basement rocks, (2) fragmental breccias with particulate matrices, (3) fragmental breccias with aphanitic or vitric matrices, (4) breccias of the Athabasca Formation, and (5) breccias of the Carswell Formation.

The strong deformation of the basement rocks is evident from a microscopic examination. Almost all quartz and feldspar grains are cracked and partially granulated at the edges. In many cases they show protuberances suggesting partial intrusion into minute cracks. Sinuous forms are common. Quartz grains may show deformation lamellae (see section on Structural Synthesis). Feldspars are barely recognizable under a cloud of argillaceous alteration. Both feldspars and quartz are markedly cloudy and stained by hematite. Mafic minerals are generally converted to chlorite and sieved by magnetite. Chlorite shreds, pseudomorphous after biotite, show intricate deformation. Small amounts of honey yellow isotropic or cryptocrystalline material which passes gradationally into surrounding grains occur in cracks and interstices. This material is charged with minute fragments to such an extent that a reliable refractive index cannot be obtained, although the index is certainly much less than that of quartz.

The fragmental breccias are essentially identical to the above material, but with a much larger proportion of finely granulated matrix material. Figure 7 shows that even minute fragments were further broken down during formation of the rock. The honey yellow, glassy(?) material noted above is present in much greater amounts in some specimens and forms a matrix. Where present in substantial amounts it is very finely crystalline, and takes on a pale green hue, probably due to development of chlorite. A

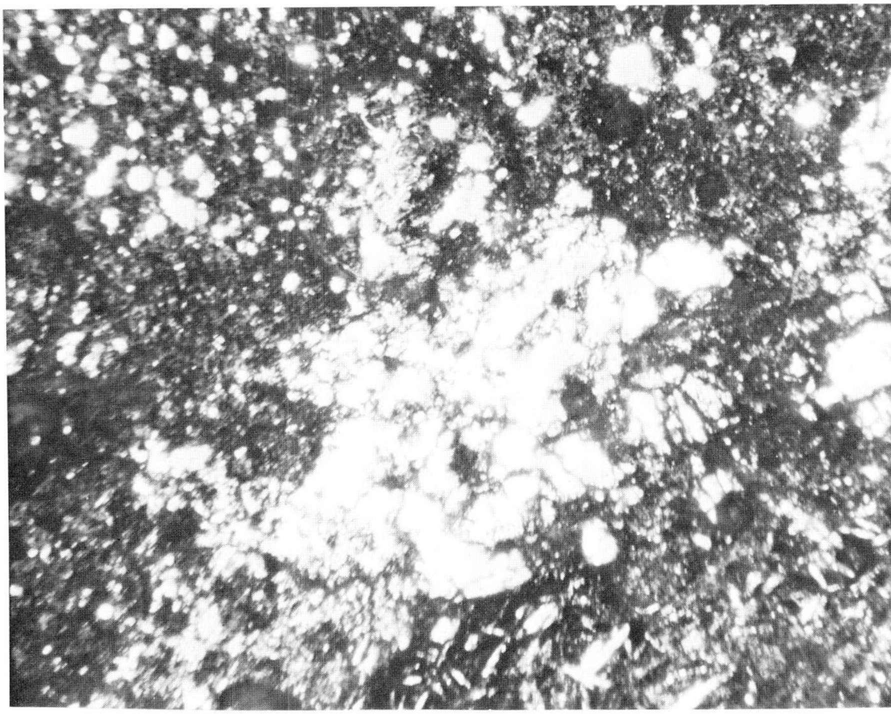


Figure 7. Photomicrograph of Cluff breccia, east of Cluff Lake (x480, crossed nicols). The fragment of quartz appears to be in the process of absorption by the matrix. The laths in upper part are probably potash feldspar. (GSC 113385-C)

specimen of this material yielded a very weak X-ray powder pattern of chlorite, suggesting that the original substance was glass, now weakly chloritized.

The aphanitic or vitric rocks contain even larger amounts of this material charged with a myriad of minute angular quartz inclusions. Contorted flow structure is very evident. In both the vitric and particulate breccias the difference in degree of alteration between the basement fragments and those of the Athabasca Formation is remarkable. The basement fragments display very strong, unusual deformation. The Athabasca fragments appear quite unaltered. Even internal cracking of quartz grains is uncommon.

The presence of quartz fragments in glass-bearing breccias with lamellar deformed quartz suggested that coesite or stishovite might be present. Forty grams of glassy material rich in quartz inclusions was submitted to J.A. Maxwell of the Analytical Chemistry Section of the Geological Survey. After reduction of the sample by the method of Fahey (1964) no coesite or stishovite was found by X-ray examination, even after reduction of the sample to 25 milligrams.

Breccias of the Athabasca Formation south of Points Lake are not impressive under the microscope. They consist of unaltered fragments of quartz sandstone set in a matrix of angular fragments of the same material. A few veinlets of extremely fine grained or cryptocrystalline quartz(?) cross the matrix. The material from Tuma Lake is composed of single grains of the Athabasca sandstone, variously fractured and embayed, in a matrix of devitrified material. In some places small fragments of sandstone have been impregnated with this material. A later generation of similar devitrified material forms veinlets cutting the specimen (Fig. 8).

Microscopic examination of the breccias in the dolomite yields little additional information. The fragments are virtually unaltered, except for the rare granitoid fragments which are composed of quartz, a little recognizable microcline, sericite, argillaceous material and trace epidote. The matrix is charged with minute particles of carbonates, but the matrix itself is a reddish, cryptic mass.

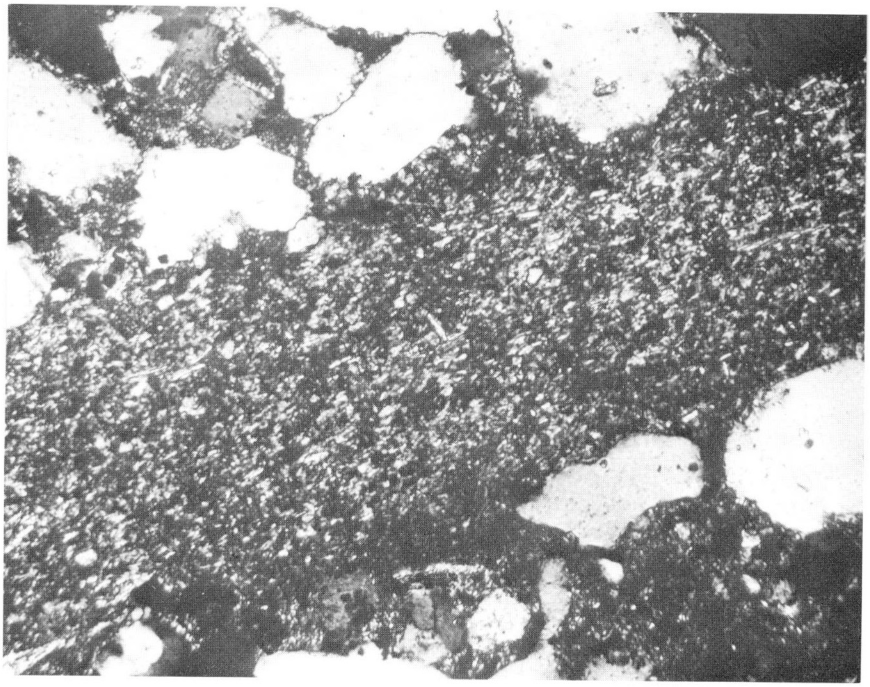


Figure 8. Veinlet of aphanitic material crossing sandstone impregnated with earlier glassy or aphanitic material (x65 crossed nicols). Note alignment of microlites in the veins. (GSC 113384-F)

Table III

Chemical analyses of rocks from the Cluff breccias

(Analyst: S. Courville, analyses by rapid method)

Specimen Number	80a	80c	80g	124	136	160	206
SiO_2	79.2	70.7	68.0	94.2	92.2	1.0	84.1
Al_2O_3	12.0	15.1	16.0	4.2	4.7	1.7	9.0
Fe_2O_3	0.7	1.7	2.2	1.3	0.5	0.4	1.3
FeO	0.2	0.3	1.3	0.1	0.2	0.3	0.2
MgO	0.5	0.5	0.5	0.5	0.5	17.4	1.6
CaO	0.2	0.1	0.2	0.1	1.0	34.9	0.1
Na_2O	0.7	0.2	0.2	0.1	0.1	0.1	0.1
K_2O	5.79	10.10	7.66	0.01	0.05	0.34	0.81
TiO_2	0.26	0.02	0.21	0.02	0.02	0.02	0.13
P_2O_5	0.05	0.05	0.11	0.01	0.01	0.01	0.03
MnO	0.01	0.01	0.04	0.01	0.01	0.01	0.01
CO_2	0.1	0.3	0.1	0.1	1.0	44.1	0.1
H_2O	1.0	1.3	3.3	0.1	0.7	0.3	2.6
	100.71	100.38	99.82	100.74	100.99	100.48	100.08

Description of specimens

80a Aphanitic flow banded buff matrix with rare fragments of sandstone and granitic rocks, 0.62 mile (1 kilometre) east of Cluff Lake.

80c Earthy red to buff, coarse-grained granitoid rock with distorted grains, 0.62 mile (1 kilometre) east of Cluff Lake.

80g Polymict breccia with subrounded distorted fragments in greenish silty matrix, 0.62 mile (1 kilometre) east of Cluff Lake.

124 Sandstone breccia, Points Lake area.

136 Flow banded, siliceous porcelain veinlet cutting Carswell Formation, 3.7 miles (6 kilometres) northeast of Points Lake.

160 Coarse breccia of dolomite in cryptic red matrix, Points Lake area.

206 Buff breccia of sandstone in aphanitic matrix. Boulder from Tuma Lake occurrence.

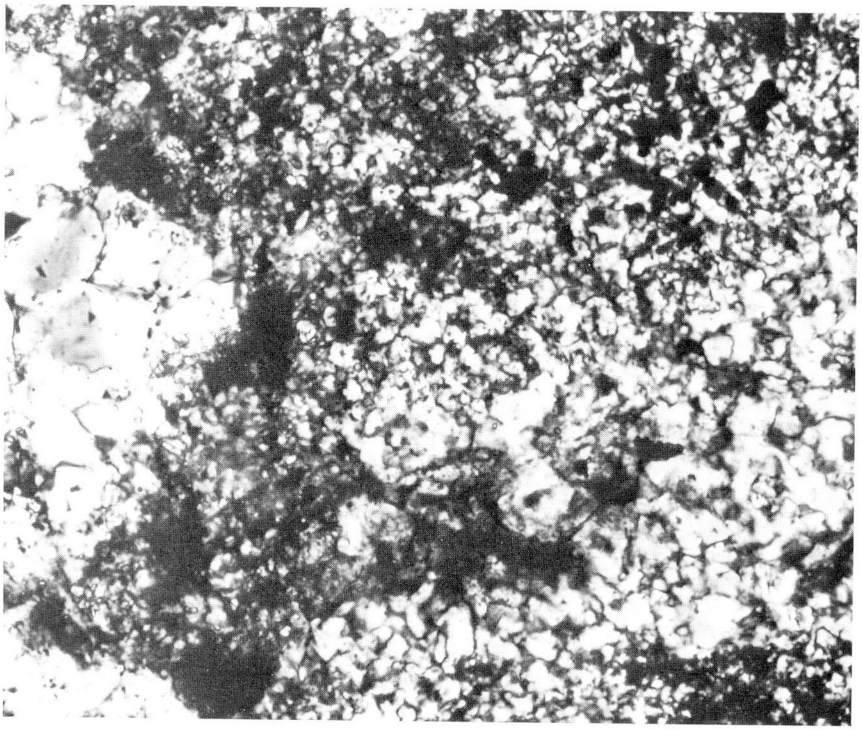


Figure 9. Photomicrograph of siliceous vein cutting dolomite in the Points Lake area (x 150). Note the curving fracture pattern on the quartz grain at left, and the gradual increase in matrix grain size away from the grain. (GSC 113385-H).

The small veinlets cutting the upper member of the Carswell Formation are composed of rounded, curiously fractured fragments of quartz in a fine-grained to aphanitic, non-clastic matrix of quartz (Fig. 9).

Chemical analyses of the Cluff breccias made by S. Courville, are displayed in Table III. These analyses were selected to show the compositional variation displayed by the breccias.

A specimen from the Cluff Lake locality composed of glass plus quartz fragments was submitted for age determination by the whole rock potassium/argon method. Because the specimen was obviously inhomogeneous it was divided into two parts representing different colours. One portion analyzing 2.15% K yielded an age of 486 $\pm$ 55 million years, while the other part, analyzing 4.89% K yielded an age of 469 $\pm$ 28 million years.

Discussion and conclusions The occurrence of Cluff breccias within the structure is clearly controlled by faulting, or at least fracturing. The character of deformation of the fragments, however, is not that normally associated with tectonic deformation. Heterogeneous glass, lamellar deformation of quartz, and multicrystalline quartz are features usually quoted as definitive of shock metamorphism (Short, 1966b). In the case of the Cluff breccias, these features appear only in the basement complex. They do not appear in the Athabasca Formation, either in situ, or in fragments included in the breccias. A possible exception to this rule is the veinlets in the Carswell Formation. Comparison of the analyses shows that this material is derived from the Athabasca Formation. Peculiarly fractured and recrystallized quartz does occur in these veins.

Although the breccias are characteristically polymict, the direction of transport of fragments seems to have been always upward. Fragments of both the basement and the Athabasca Formation can be found in material cutting the Carswell Formation, but fragments of the Carswell Formation are never found in breccias cutting lower units, and Athabasca fragments are found in conjunction with the basement only where the two units have been tectonically juxtaposed.

Whatever the mode of deformation of the breccias, their emplacement was a very late event in the development of the structure. Although they occupy fault zones, the breccia matrix is never found sheared. Evidently the emplacement of the breccia matrix was the last activity along the zone.

An examination of the analyses in Table III shows that with rather slight deviations, breccias in the Carswell and Athabasca Formations have the composition of the host rock. An exception to this rule is the veinlet in the upper Carswell Formation. This veinlet is clearly a mobilized portion of the upper Athabasca sandstone injected and recrystallized. It is very difficult to conceive how this material could have been shot upward through the 295 feet (90 metres) of the lower Carswell Formation and emplaced in fine veinlets. However, the analysis does not suggest any material was added to the sandstone during the passage.

The concept of comminution and mixing is inadequate to explain the breccia occurrences at Cluff and Tuma Lakes. The pre-existing materials there are the Athabasca Formation and the basement complex. In Table IV are listed the analyses of breccia, the average analysis of the basement from Table I, and an average analysis of the Athabasca Formation obtained by analyzing a bulk sample taken from the large outcrop facing the breccia occurrence east of Cluff Lake. In Figure 10 the results of mixing the basement and the Athabasca Formation are displayed graphically. The content of silica, alumina and titania in the breccias can be conveniently explained by mixing, and the amounts of sandstone required are consistent with modal analyses, but the content of the other major oxides cannot be explained by mixing. In view of the extreme heterogeneity of the breccia, and the limited

Table IV

Chemical composition of rocks in the breccia occurrence east of Cluff Lake

Specimen Number	I	II	III
SiO_2	66.7	72.6	94.2
Al_2O_3	17.0	14.3	4.1
Fe_2O_3	2.2	1.5	0.9
FeO	3.2	0.6	0.1
CaO	1.2	0.2	0.4
MgO	1.1	0.5	0.5
Na_2O	2.2	0.4	0.1
K_2O	5.17	7.85	0.01
TiO_2	0.32	0.16	0.02

Description of specimens

I Average basement (from Table I).

II Average Cluff breccia (average of analyses 80a, 80c, 80g, Table III).

III Average Athabasca Formation (analysis of bulk sample from outcrop adjacent to breccia occurrence), analyst S. Courville.

sampling, it is doubtful if the figures for soda, magnesia and lime can be given great weight. However, it is clear that the breccias are greatly impoverished in iron, and in two cases greatly enriched in potash. It is possible that the Tuma Lake specimens represent a potash poor phase of a rock with a generally higher potash content, such as was observed in the specimen submitted for absolute age determination.

Figure 10 suggests that the degree of enrichment in potash and impoverishment in iron is related to the amount of the basement component in the breccia. If this is correct, it presumably results from alteration of the rocks surrounding the breccia zone, and their subsequent incorporation in the breccia. The sequence of events in this case would be the development of the fault (or at least some feature to localize the later metasomatism), metasomatic alteration of the wall rocks, and lastly, brecciation.

The occurrence at Tuma Lake is of particular interest. The glassy material comprising approximately one-third of the rock seems to be derived by melting of the basement. With the exception of the comparatively low potash content, it is comparable to the breccias at Cluff Lake. To produce and emplace glass in these quantities must have required rather unusual conditions.

The absolute age determined from the breccia seems reasonably dependable. Although it is a K/A whole rock age, determined from an altered, highly heterogeneous rock, the ages determined from the most differing portions of the rock are congruent, the material used had been almost completely melted and recrystallized, and the potash content was in a range favourable for the method. The average age obtained, 478 million years is approximately the same as the most reliable Pb/U age of 432 million years obtained by Fahrig (1961) from pitchblende veins cutting the Athabasca Formation about 80 kilometres north of Carswell Lake. This age (Middle Ordovician on the stratigraphic time scale) refutes Gussow's (1959) suggestion that the Athabasca Formation is Devonian in age.

Unconsolidated Deposits

Overlying all the older rocks are two distinct kinds of unconsolidated deposits. Ordinary glacial deposits include till, drumlinoid ridges and eskers. In some places drift ridges suggest a thickness of over 100 feet (30 metres) for the till blanket. Southwest of the crater the superficial material is crudely stratified fine sand. This material appears to lap onto the till blanket southwest of Badwater Lake, and is presumably younger than the till. Both types of loose material represent decomposed Athabasca Formation, and boulders of other lithologies are rare. Boulder accumulations of dolomite or pre-Athabasca rocks can be mapped with some confidence as representing nearby bedrock.

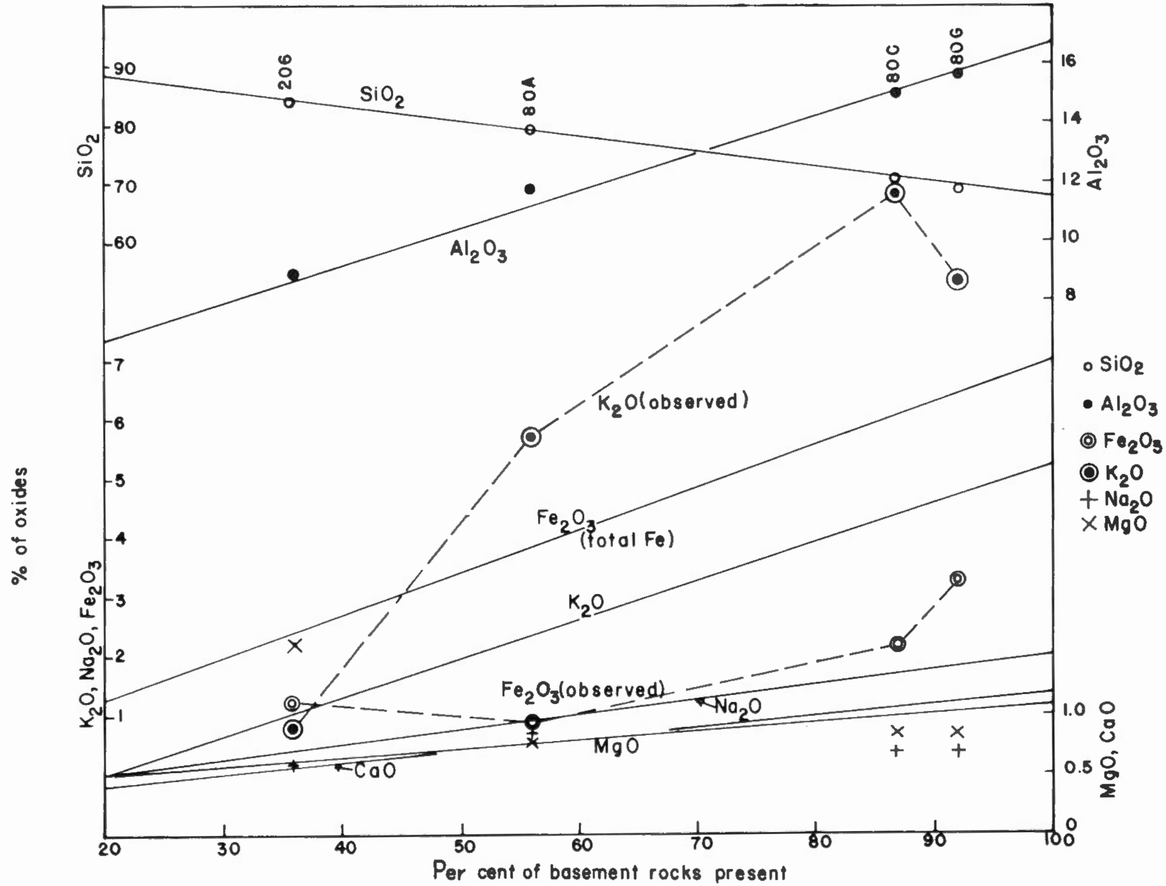


Figure 10. Variation in composition of Cluff breccia compared to composition of mixtures of the basement and Athabasca Formation

Figure 11. Linear sand 'dune' west of Carswell Lake. This streak of sand can be followed more than 25 kilometres. (GSC 120144)

The most curious superficial features of this area are streak-like deposits of white sand running in a southeasterly direction. They are readily visible on air photos, and follow remarkably straight courses for 12 miles (20 kilometres) or more. A few cross the boundary of the structure, and all seem to cross lithological boundaries without deflection. The deposits consist of sand ridges 6.5 to 20 feet (2 to 6 metres) high and 50 to 210 feet (15 to 65 metres) wide (Fig. 11). The direction of latest glaciation is southwest in this region and in any event the ridges are too straight to be glacial features. This consideration likewise makes an aeolian origin implausible. Gussow (1959) supposes them to result from deposition in cracks on the continental glacier. If they have a structural control, both the control and method of formation are unknown.

RÉSUMÉ AND INTERPRETATION OF GEOPHYSICAL DATA

Introduction

In the absence of abundant outcrops, the fixing of the boundary between the basement complex and the Athabasca Formation, and the determination of the thickness of the Athabasca Formation are not possible by ordinary geological mapping but both problems can be treated by geophysical methods. Data which are available are regional magnetic and seismic refraction surveys, and a gravity survey of the Carswell structure.

Magnetic Data

The Carswell Lake area and surrounding regions are covered by magnetic maps at 1 mile to 1 inch (Geological Survey of Canada, Maps 2684G, 2685G, 2700G and 2701G) and by a 4 mile to 1 inch compilation (Map 7019G). A portion of this latter map is reproduced as Figure 12. In the region of Carswell Lake magnetic contours over the Athabasca Formation are smooth and relatively parallel, with gradients rarely exceeding 40 gammas per mile. Local southeast-trending anomalies are attributed to diabase dykes. The central core of the Carswell structure exhibits an area of small, disorganized highs and lows reaching 220 gammas. There is a large anomaly just northeast of the Carswell structure of almost 600 gammas.

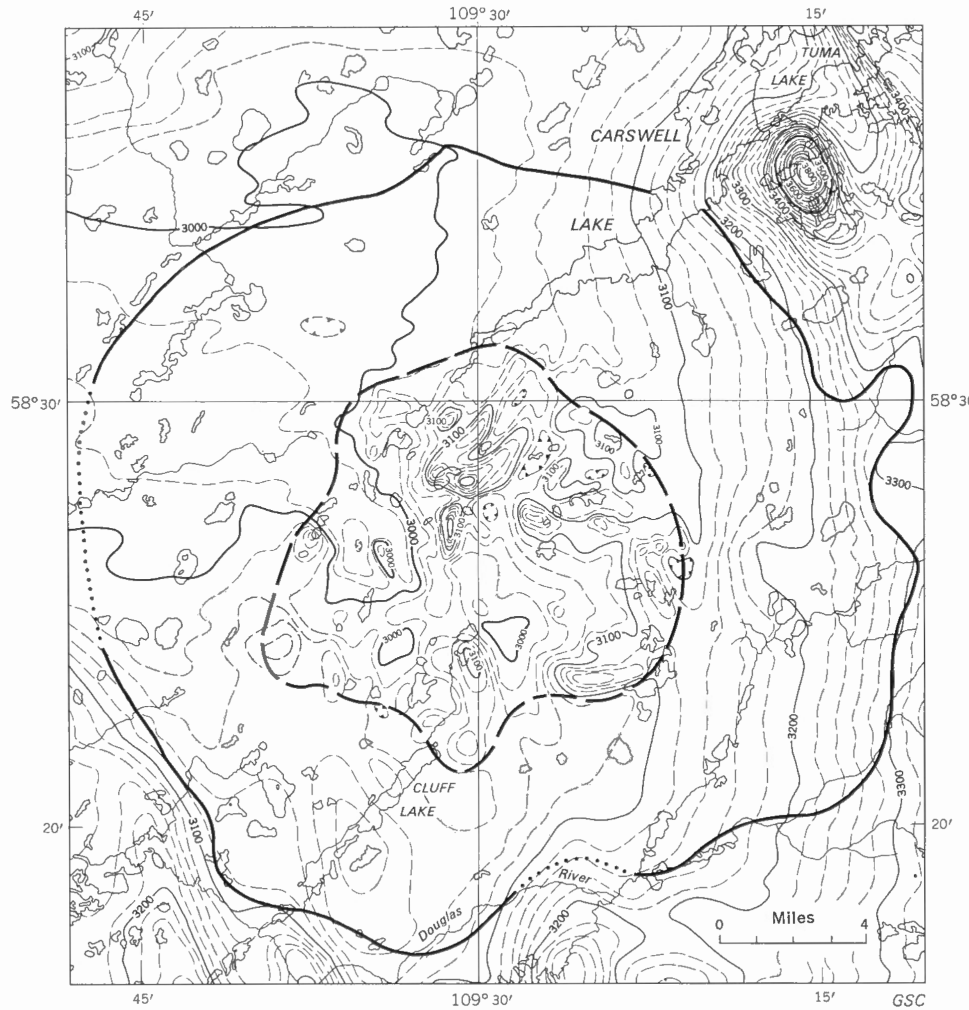
The area of hummocky anomalies is interpreted as being underlain by basement complex rocks. Innes (1964) suggests that the magnetic pattern on the basement complex is abnormal and indicates brecciation. However, comparison with the area just west of Lobstick Island, Lake Athabasca (Tazin Lake, Map 7020G) shows a virtually identical pattern of low anomalies on unaltered pre-Athabasca rocks.

In the author's opinion the pattern simply indicates basement complex, and no conclusion can be drawn as to its physical properties.

In the magnetically 'smooth' region outside the core there is a slight but noticeable tendency for the magnetic lines to parallel the edges of the structure. The large anomaly south of Tuma Lake cannot be identified with a known geologic feature. However, float of Cluff breccia is found there and is the only known occurrence of such boulders. It is tempting to suppose that the anomaly results from a breccia pipe penetrating the Athabasca Formation. Weighing against this interpretation is the lack of anomaly associated with the petrographically similar breccias in the Cluff Lake area.

Seismic Data

Some unpublished data of a regional seismic refraction survey are shown in Figure 13 (after G.D. Hobson). These data show that the circular structure lies on the axis of an east-trending arch in the basement, and that



The broken line marks the boundary of the pre-Athabasca basement, and the outer line shows the boundary of the Carswell circular structure, dotted where uncertain. Note the hummocky pattern of the basement anomalies, and the general concurrence of the ring boundary with the magnetic lines.

Figure 12. Magnetic map of the Carswell circular structure (part of Map 7019G, William River).

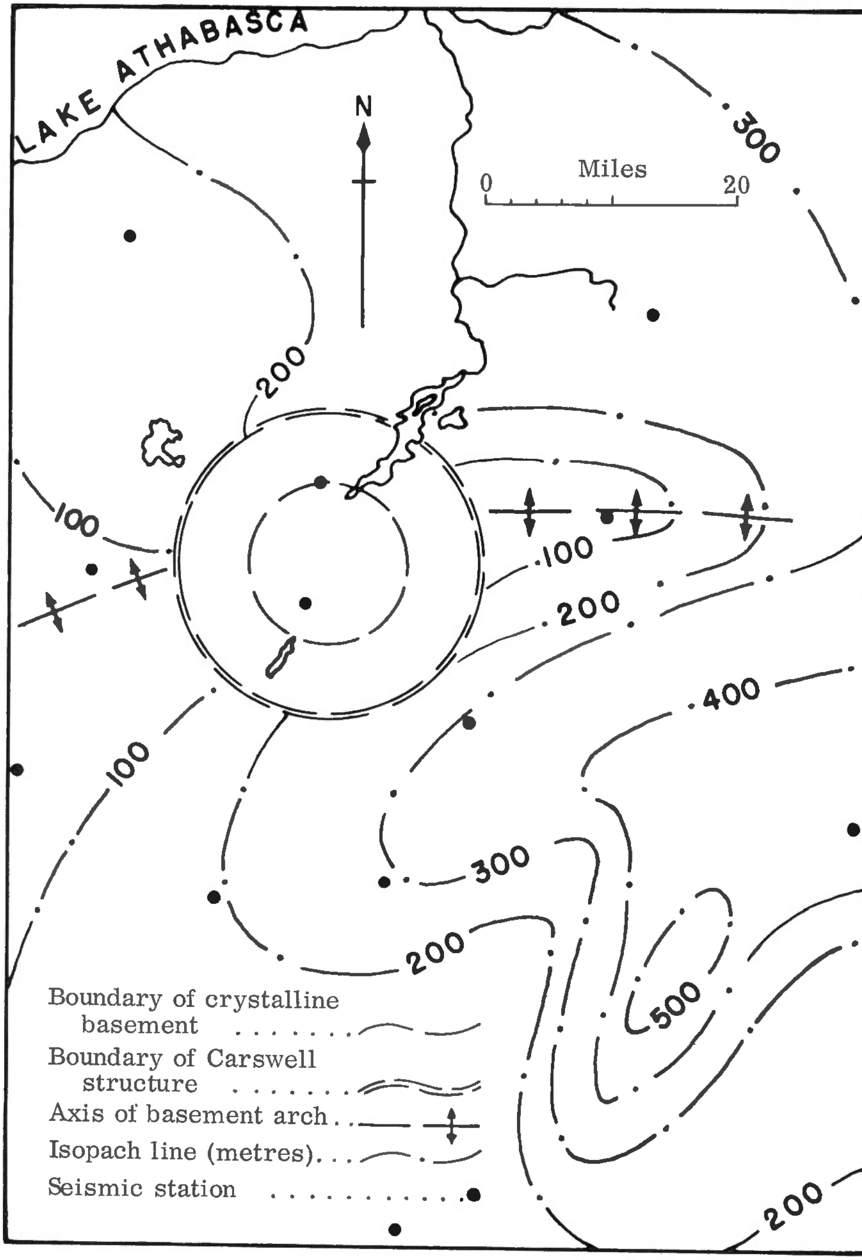


Figure 13. Isopach map of part of the Athabasca Formation (seismic data by G. D. Hobson)

the thickness of the Athabasca Formation on the crest of the arch is 100 feet (30 metres) or less in the vicinity of the circular structure. On the other hand thicknesses in excess of 1,650 feet (500 metres) are known about 55 miles (90 kilometres) south of Carswell Lake. Only two stations of the seismic network were located inside the Carswell structure. One of these stations was located on the Precambrian basement, yet according to the model used, yielded a thickness of over 650 feet (200 metres) of "Athabasca Formation". The other station did not give usable records. In view of the known inadequacy of seismic methods in exploring circular structures (Willmore, 1963), and the anomalous result obtained from the single station, seismic data are given no weight in determining the thickness of the Athabasca Formation within the structure.

Gravity Data

A gravity survey of the Carswell structure has been published by Innes (1964). The data show a toroidal negative Bouguer anomaly with a minimum of -11 milligals near the inner dolomite-sandstone contact. Only three geological formations are exposed in the area of the anomaly, the Carswell Formation, the Athabasca Formation and the basement complex. The Carswell Formation is the most dense (specific gravity 2.78) and no anomaly is observed over the outcrops of basement complex. Thus the anomaly must be due either to the configuration of the Athabasca Formation or to the presence of rock types not exposed at the surface. The attribution of the gravity anomaly to the Athabasca Formation can be semiquantitatively justified by computation, and these computations also show the implausibility of attributing it to unexposed material.

Suppose the Bouguer anomaly to be represented by a toroidal anomaly 15 kilometre inner radius and 30 kilometre outer radius, and parabolic cross-section with minimum -11 milligals (Fig. 14). The anomalous mass may be calculated from the formula

$$dM = \frac{1}{2 \pi \gamma} \int \int dg\, ds \qquad (1)$$

(Hammer, 1945), where γ is the gravitation constant, dg the Bouguer anomaly and ds the area. Since the anomaly is radially symmetrical, consider a strip 1 centimetre wide acrcss one side of the toroid. The mass anomaly in this sheet is 2.62×10^{10} grams. Taking the basement density to be 2.70 gm/cm^3 and that of the Athabasca Formation to be 2.49 gm/cm^3 (Innes, 1964), this is equivalent to 1.25×10^{11} cm^3 of sandstone. This material is assumed spread evenly along the strip considered, 15 kilometres long by 1 centimetre wide, and is thus equivalent to 830 metres of sandstone across the width of the anomaly. Thicknesses approaching 800 metres are indicated elsewhere in the

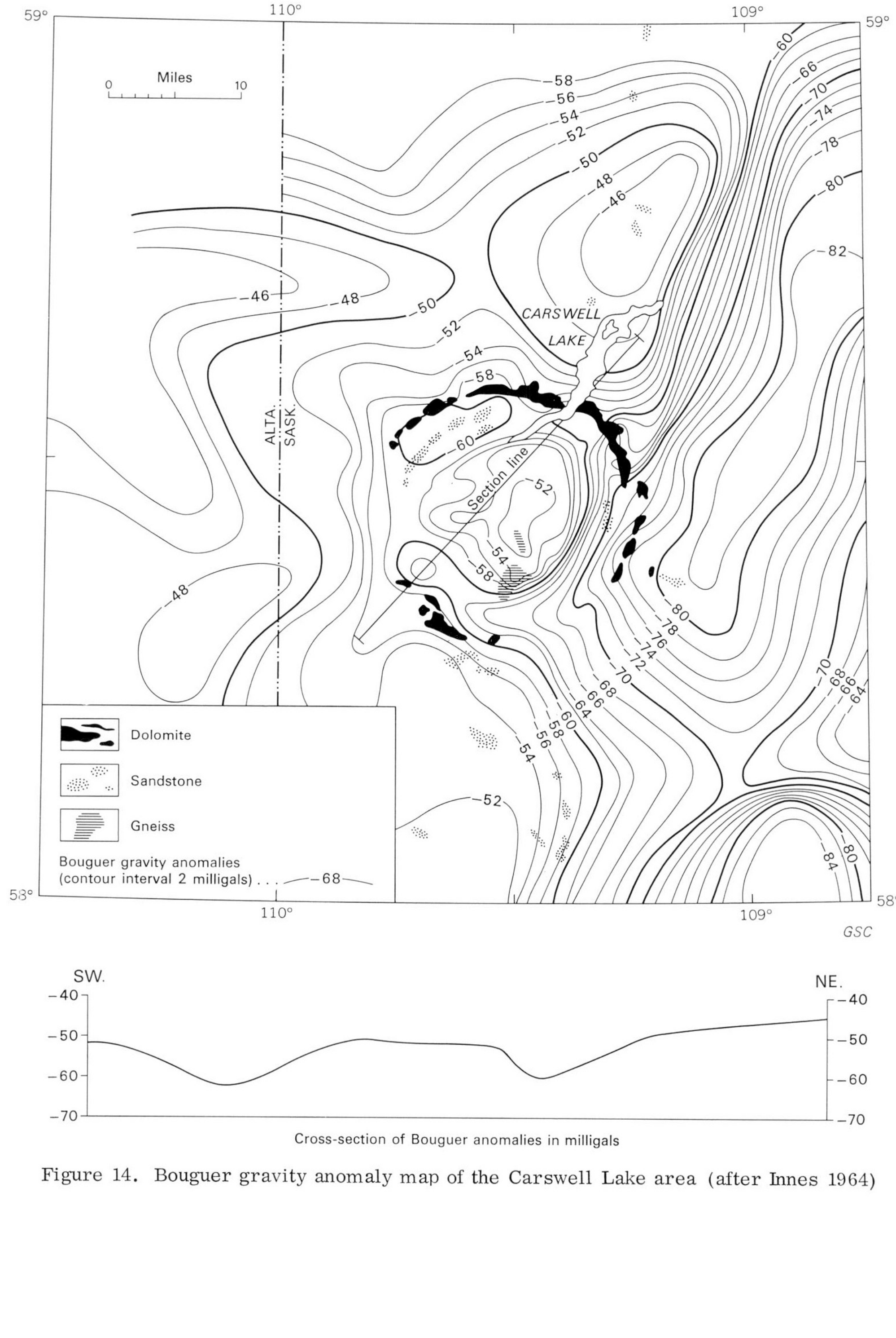


Figure 14. Bouguer gravity anomaly map of the Carswell Lake area (after Innes 1964)

Athabasca Formation by seismic measurements (Hobson, personal communication), thus this value is compatible both with the maximum thickness of the Athabasca Formation in this region, and with the geological deduction that the maximum thickness of the Athabasca Formation should be found beneath the Carswell Formation.

Outside the Carswell structure there is a vague tendency for the gravity contours to trend northeast, parallel to the basement high suggested by seismic data, and for the negative Bouguer anomalies to increase away from the structure. This is the pattern to be expected if the light Athabasca Formation gradually thickens away from the basement high crossing the Carswell structure. If the gravity anomaly is due to rocks not exposed at the surface, for example a large ring dyke, these rocks must have a rather large volume and low density, together with magnetic properties identical to that of the sandstone. For example, a vertical dyke would have to be more than 0.6 mile (1 kilometre) in width if it had the (unusually low) density of the sandstone. Such a concatenation of circumstances seems implausible. The cause of the gravity anomaly is therefore assigned to an unusual thickness of the Athabasca Formation beneath the Carswell Formation.

STRUCTURAL GEOLOGY

Introduction

Study of the fabric of the Carswell structure is hampered by lack of outcrops. In part this can be compensated for by careful study of the available outcrops, and use of geophysical data. However, the fabrics of the three major units involved in the Carswell structure are so diverse that the extension of structural features from one to another is highly speculative. For this reason the structural elements of each unit are considered separately.

Basement Complex

Foliation   Foliation is well developed in the basement complex, and on the scale of an outcrop is regular and even. The thirty-one measurements all have azimuths between 325 degrees and 45 degrees. Dips are vertical or steeply east with a minimum of 55 degrees. On the scale of an outcrop, a few distortions of bedding are present in the form of boudins up to 3.2 feet (1 metre) long and 8 inches (20 centimetres) wide. Folding of the basement rocks was not observed, with the exception of rare isoclinal drag folds a few centimetres in width.

Lineation   As already noted, the gneissic parts of the basement complex are highly fissile, and outcrops are composed of a large number of thin sheets, or lenticular fragments. Adjacent sheets fit together, and there is no matrix of crushed material, so the rock cannot be called a breccia. Each surface along which the rock has split is lineated by slickensides, usually in soft, greenish decomposed mafic material. The slickensides have diverse plunges on successive parting planes and here and there two or more sets are present. On the lenticular fragments, intersecting sets of slickensides occur along the edges. A few curved surfaces with sets of intersecting slickensides were observed east of Cluff Lake.

Fractures   The basement complex is commonly disintegrated into planar fragments by slickensided parting planes parallel to the gneissosity. Despite this pervasive fracturing, no recognizable faults were found within the basement complex, although several faults either cross from the basement complex into the surrounding units, or divide the basement from the surroundings.

Some of the parting planes may represent joints along which slight movement has taken place. A few joints at approximately right angles to the gneissosity were noticed.

On some fracture surfaces the markings have a plumose character. Rarely the fracture surface may be curved. A fragment of this kind has been identified as a shatter cone (Innes, 1964). The author examined the locality east of Cluff Lake from which the 'shatter cone' was recovered and found many similar surfaces. A few additional examples were seen on the outcrop southwest of Carswell Lake. In all cases the fragments are characterized by slightly curved surfaces that rarely subtend more than 20 degrees of arc; complex, poorly defined, striations on the surface; and detachment from the rock. In no example were definitely radiating markings seen nor were any secondary markings seen on the specimen.

Microscopic features The most unusual features of the basement complex are seen under the microscope. These may be divided into: (1) microbrecciation, (2) planar features and kink bands, (3) isotropic material.

(1) Some basement specimens show a variety of microbrecciation akin to mortar texture. In the hand specimen it can sometimes be seen as a fine tracery of white lines. In thin section these are composed of zones of finely granulated material amid otherwise undamaged grains.

(2) Planar features and kink bands are erratically distributed in the rocks of the basement complex at Carswell Lake. Planar features on quartz were found on 9 of 20 thin sections examined, of which 7 came from within 200 metres of the assumed location of the ring fault bounding the basement. Two distinct types of planar features occur, namely deformation lamellae and cleavage-like fractures. In each of the 9 sections 50 quartz grains were selected at random. Of these 450 grains, 251 showed deformation lamellae, the number per section ranging from 14 to 44, and 118 showed cleavage cracks. The lamellae show the following characteristic features: (a) they are closely spaced planar features which do not transgress grain boundaries, but sometimes terminate within grain boundaries, (b) they are visible in both plane polarized light and under crossed nicols, (c) they may contain minute cavities or inclusions, (d) they are asymmetric, being dark on one side and bright on the other, the dark side having noticeably higher index and birefringence than the host. In some cases the lamellae are kinked within grains (Fig. 15).

On the universal stage, the angle between the c-axis of quartz and the poles to deformation lamellae planes was measured for 178 grains. Of this number, 41 grains displayed one set of lamellae, 98 displayed two sets, and 39 displayed three sets, a total of 354 measurements. The results are plotted in Figure 16, and show a strong maximum between 18 degrees and 20 degrees.

Deformation lamellae were seen on a few perthite and microcline grains. They tend to be rather diffuse, and heavily decorated with inclusions and opaque dust. The 11 examples measured all fell within 10 degrees of the plane (100).

Grains that show well developed deformation lamellae do not usually show cleavage cracks. However, other quartz grains often show closely spaced parallel fractures which appear to follow crystallographic planes. Fracture parallel to the basal plane (0001) is most easily recognized, but another fracture inclined about 23 degrees to c, and possibly on (1013) (Short, 1966b; Carter, 1965) is also common.

Kink banding appears as bends in close spaced planar elements such as cleavages or fracture sets. The hinge lines of the bending define subparallel lenticular zones. In the basement complex kinking is seen in biotite and here and there in planar features in quartz. The orientation of the kink bands appeared to have no significant orientation in the specimens examined.

(3) Small amounts of isotropic material are rarely observed around quartz grains and in perthites. In the quartz grains the isotropic material is water clear, has a lower index than quartz and occurs in, or at the ends of cleavage fractures. In perthite the material appears very similar, but individual lamellae of the material are converted to isotropism, whereas neighbouring lamellae appear normal. Isotropic material was seen in only three sections, all from the vicinity of the breccia outcrops east of Cluff

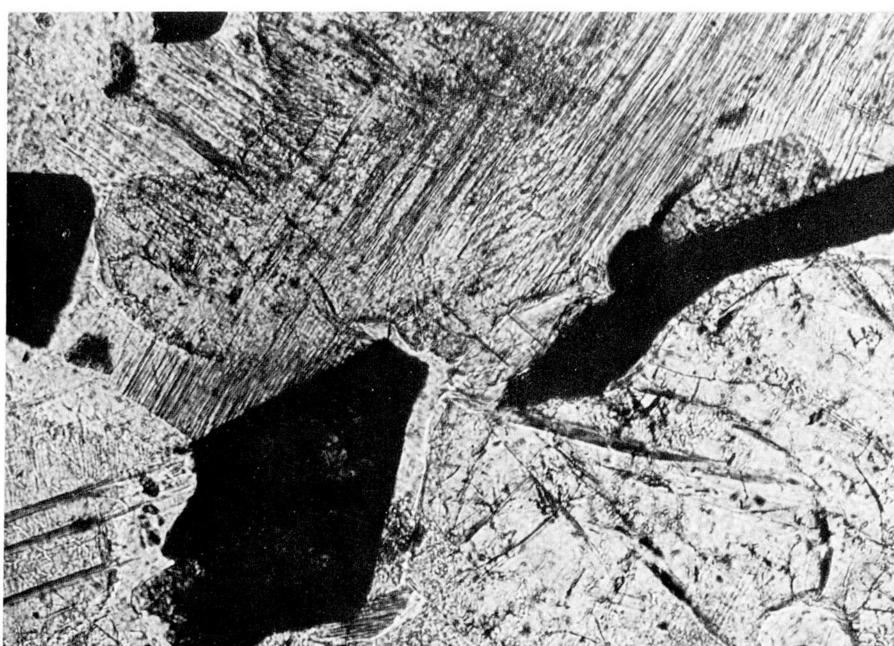


Figure 15. Strongly developed multiple sets of deformation lamellae on quartz-garnet rock northeast of Cluff Lake (x 100). Note kinking of lamellae at upper right. (GSC 113385-A)

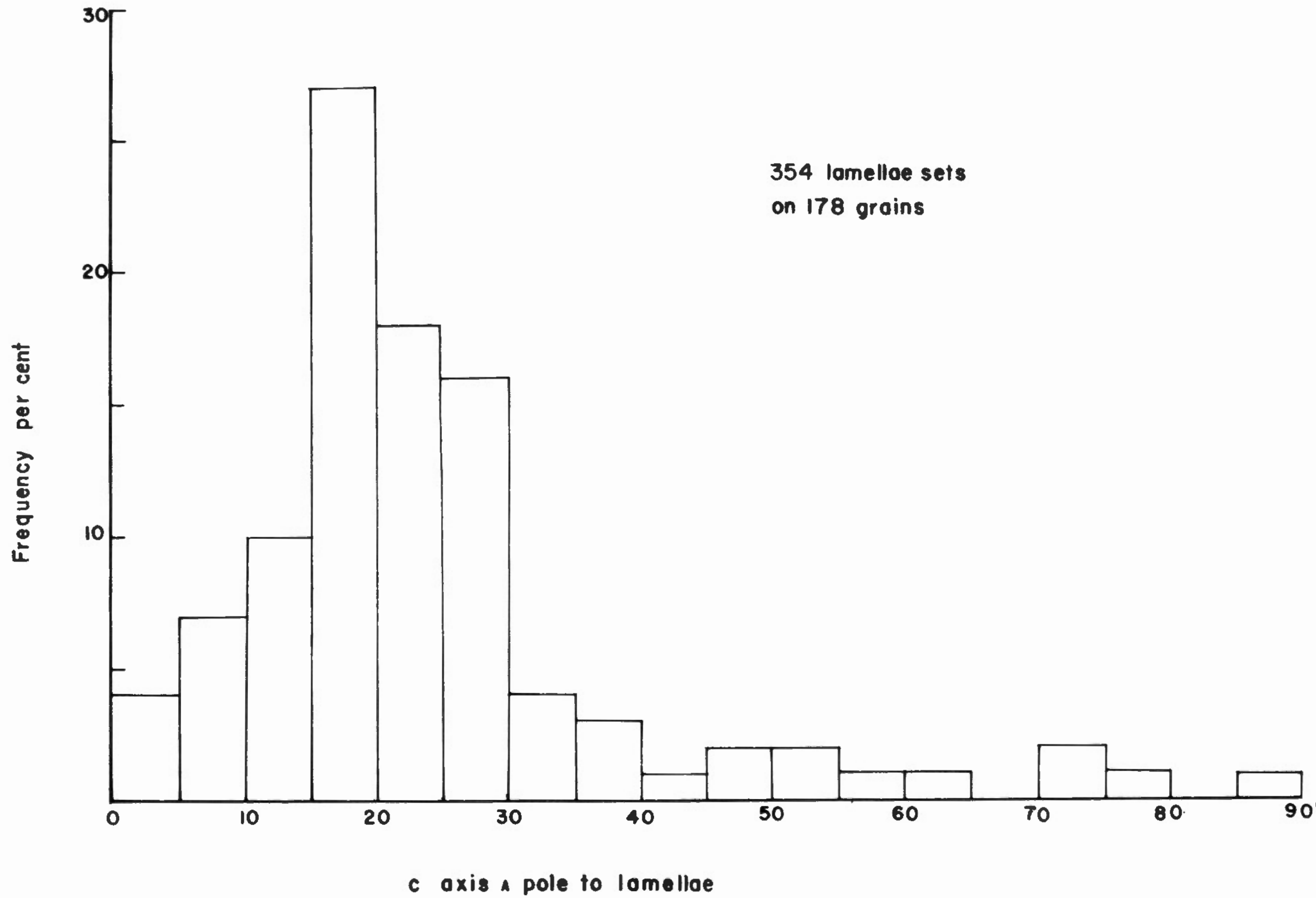


Figure 16. Plot of poles to deformation lamellae against c axis of quartz

Lake. An attempt to concentrate the isotropic material was not successful, and X-ray examination of quartz and perthite concentrates showed only these minerals. It is tentatively concluded that the isotropic material is glass.

Discussion and conclusion Macroscopically the appearance of the basement complex is not striking. The fissility and universal presence of disoriented slickensides show that small scale penetrative movement has been pervasive. However, there is no evidence that this led to any strong relative displacement of various parts of the exposed basement complex, and the pattern of slickensides suggests a general jostling, rather than continued shear.

The alleged shatter cones do not show the radiating striae, and in particular lack the parasitic radiating striae, said by Dietz (1959) to be essential to the identification of shatter cones. The examples studied by the author do not show conical surfaces when broken across the cone axis, another departure from classical shatter cones. Although the objects from the Carswell structure may represent an unusual type of fracture, they are not, in the author's opinion, shatter cones.

Microscopically the rocks display a group of features collectively termed 'shock metamorphism' (Short, 1966a, b). A voluminous polemic literature has accumulated on this subject in the past few years, particularly regarding deformation lamellae (Carter, 1965, and references therein). Unfortunately the differences of opinion are such that it is difficult to use the data to establish quantitative conditions of deformation. Deformation lamellae from tectonically deformed rocks tend to show a maxima in the plot of c against poles to lamellae in the range 10 degrees to 20 degrees with the distribution falling off slowly with increasing angle (Short, 1966a, b). Multiple sets of lamellae on a single grain are rarely observed. Experimentally, Carter et al. (1964) have produced deformations in quartz virtually identical to those at Carswell Lake (including traces of glass in fractures) utilizing quasi-static loading under confining pressures up to 30 kilobars at temperatures above 200 degrees centigrade. Roughly similar results have been obtained by Short (1966a) by implosively loading quartz-bearing rocks. Carter (1965) mentions that basal and inclined lamellae have been experimentally produced under confining pressures as low as 8 kilobars at elevated temperatures, and critical resolved shear stress differences as low as 16 kilobars.

Deformation lamellae on quartz are a well known phenomenon from tectonically deformed rocks (Carter et al., 1964). The lamellae considered here are unusual in that (1) they follow crystallographic planes and do not extend from one grain to another, (2) multiple sets of lamellae are characteristically present on the same grain, (3) the maximum on the plot of poles to lamellae against the c-axis of quartz lies at a greater angle than normal in tectonites (Short, 1966b). These criteria are alleged by Short (1966b) to be diagnostic of 'shock metamorphism' generally ascribed to extraterrestrial impact. Two variations of the impact hypothesis are possible for the

Carswell structure: (1) impact took place after deposition of the Carswell and Athabasca strata, or (2) impact took place before the development of Carswell and Athabasca strata. The first hypothesis is refuted by the observation that deformation lamellae are not found on the quartz of the Athabasca sandstone, even where such quartz demonstrably overlies lamellarly deformed quartz of the basement complex, as at the locality east of Cluff Lake.

This occurrence shows that peak pressures in the underlying basement must have been markedly higher than in the undeformed overlying Athabasca Formation. This is only possible, assuming the shock propagated downward, if the shock impedance of the basement is markedly higher than that of the sandstone. The shock impedance is largely controlled by the density which is virtually identical for the two rocks at this locality (2.51 for the sandstone, 2.53 to 2.55 for the basement). In fact Lombard (1961) shows that the shock propagation characteristics of granite and poorly cemented sandstone are virtually identical in the range below 300 kilobars where deformation lamellae are believed to form (Short, 1966a). The deformation lamellae did not form by propagation of a shock downward from the Athabasca Formation into the basement.

On the other hand if the deformation lamellae formed as a result of impact prior to the deposition of the Athabasca and Carswell Formations, we might expect them to be more or less homogeneously distributed over a region around the point of impact. They are not. Occurrences of lamellae are strongly associated with the edge of the central core. In addition, an hypothesis of pre-Athabasca impacts suffers from the lack of explanation of reactivation of the structure after the long time period required for deposition of the Athabasca and Carswell strata. We might expect moreover, that if the Athabasca in this region had formed over an old impact scar, some marked peculiarities in the sedimentation pattern should be observed. They are not. We may conclude that the presence of deformation lamellae on the basement rocks is not indicative of an impact origin for this structure.

Athabasca Formation

The Athabasca Formation is the only formation known to outcrop outside the Carswell structure for some tens of kilometres. Fahrig (1961) concluded that the Athabasca is essentially undeformed except for " ... gentle tilting toward the central parts ... and locally steeper dips resulting from fault movements in the basement rocks ...". The few outcrops of the Athabasca Formation observed by the author outside the Carswell ring structure entirely support these observations. A probable fault of regional importance passes through the length of Carswell Lake, thence southwest along a pronounced linear, and crosses the rim about 6 miles (10 kilometres) west of Cluff Lake. The eastern part of the ring is offset radially outward about 1.0 mile (1.6 kilometres) on this line. Blake (1956) refers to faulting

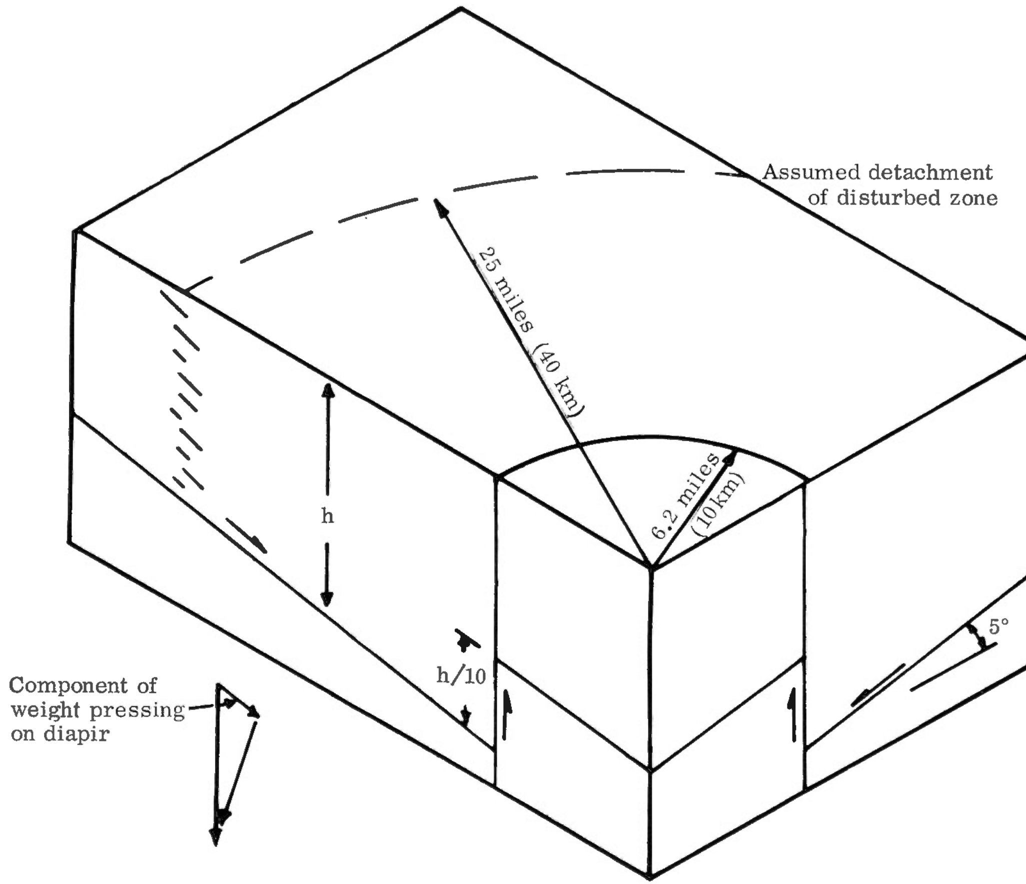


Figure 17. Schematic diagram of development of pressures on a rising diapir by the surrounding rocks

of similar trend cutting the Athabasca Formation in the Black Lake area. Stockwell (1965) shows several faults of similar trend in northern Saskatchewan. From the displacement of Carswell Formation, the movement on the fault is thought to be east side down.

Inside the ring structure the Athabasca Formation is well exposed south of Points Lake and in the area between Cluff Lake and Beaver Creek. Although dips are steeper than those reported by Fahrig (1961) outside the ring, they rarely exceed 30 degrees, and deformation by folding, of the type seen in the Carswell Formation, is not present. Dips in the Athabasca Formation are most commonly toward the centre of the structure. South of Points Lake and west of Beaver Creek slickensided shear zones are exposed showing latest movement in the sense central part up.

Deformation lamellae and cleavage cracks of the type seen in the basement are not seen on the quartz of the Athabasca Formation. Microbrecciation is confined to within 3 feet (1 metre) of shear zones.

The boundary of the Athabasca Formation against the basement complex is a fault east of Cluff Lake, where a zone of shearing can be traced for 1.2 miles (2 kilometres) filled with unsheared Cluff breccia. A probable fault contact between the Athabasca Formation and the Carswell Formation is exposed on Douglass River in the southeast corner of the structure.

Discussion and conclusions The anomaly of the Athabasca Formation is the lack of anomalies! Lying between the intensely microscopically deformed basement, and the intensely macroscopically deformed dolomite, it shows practically no deformation of either kind. The appearance of stratigraphically older beds towards the centre of the structure, combined with the general inward dip of the Athabasca suggests that the formation is cut into a series of concentric fault slices with a net overall movement of centre part up. This is confirmed by the slender observational evidence of faulting of this kind at three localities. The dips of the Athabasca Formation suggest that some slight tilting of the blocks towards the centre may have occurred. On the other hand the gravity evidence strongly indicates that the part of the Athabasca Formation beneath the Carswell Formation is downfaulted. Assuming the calculated thickness of 2,700 feet (830 metres) is correct, this peripheral ring fault has a displacement of roughly the difference between the thickness of the Athabasca inside the structure and the thickness outside, or about 2,600 feet (800 metres). The hypothesis of a fault at the outer boundary of the Carswell Formation is supported by the observations of breccia zones, and antipathetic dips along Douglass River.

Carswell Formation

The Carswell Formation is better exposed than any other unit involved in the Carswell structure. For this reason, more is known about the structure of the Carswell Formation than any of the other units.

Folding Folding on several scales is characteristic of the Carswell Formation. Small scale folding with axial planes nearly parallel to bedding planes is common, though not abundant in the lower, thin-bedded part of the formation. In the upper member the axial planes have no definite trend, and the deformation appears to be of flowage type. Gross discontinuity in the amount of folding between adjacent beds is common, and in the cores of small folds the bedding may disappear entirely (Fig. 6). The folds may pass into irregular patches of autochthonous breccia which appear and disappear without discernible regularity, although there is a slight tendency for brecciated material to be concentrated near the axial planes of folds.

On a larger scale, sinuous trends of ridges of the Carswell Formation (Fig. 18) suggest folds with amplitudes of a few hundred metres. The general annular disposition of the Carswell Formation results from an overturned ring syncline, with axial plane dipping toward the centre of the structure (Fahrig, 1961). A good cross-section through this fold is exposed in cliffs along the west shore of Carswell Lake, where the inner scarp is faced with slaty, overturned dolomite, dipping inward at angles of 50 degrees to 70 degrees. The same strata are found at the northernmost exposures of the Athabasca Formation, upright and dipping inward at 20 degrees to 26 degrees. The axial plane is estimated to dip toward the centre of the structure at about 35 degrees in this region.

Where the Carswell Formation is thin, as for example near Badwater and Cluff Lakes, overturned strata are rare, presumably because the higher, overturned parts of the fold have been lost by erosion.

In the area where the dolomite is thickest, from Carswell Lake eastward to the vicinity of Beaver Lake, there is a tendency for the Carswell Formation to outcrop in two concentric rings. This suggests that the Carswell Formation originally formed two or more ring synclines concentric about the centre of the structure.

Geophysical evidence suggests that the Carswell structure lies on the crest of an east-trending swell in the basement. This swell is expressed in subdued form by the Carswell Formation. The gaps in the Carswell Formation trend roughly southeast, the plunges of the folds in the Carswell Formation are away from this axis, and there is a notable widening of the area underlain by lower Athabasca Formation along this axis. This evidence shows that the swell was still rising after formation of the Carswell structure. On the other hand geophysical evidence suggests that the amplitude of the swell is about 490 feet (150 metres) across the width of the Carswell structure. The uplift of the base of the Carswell Formation is about 300 feet (100 metres) from a projected elevation of 845 feet (260 metres) on Carswell Lake to a projected 1,170 feet (360 metres) on Beaver Creek (see Fig. 14). Considering the uncertainties in the data, perhaps this is satisfactory agreement, but it suggests a possibility that the Carswell structure may have developed after the beginning of the rise of the basement swell.

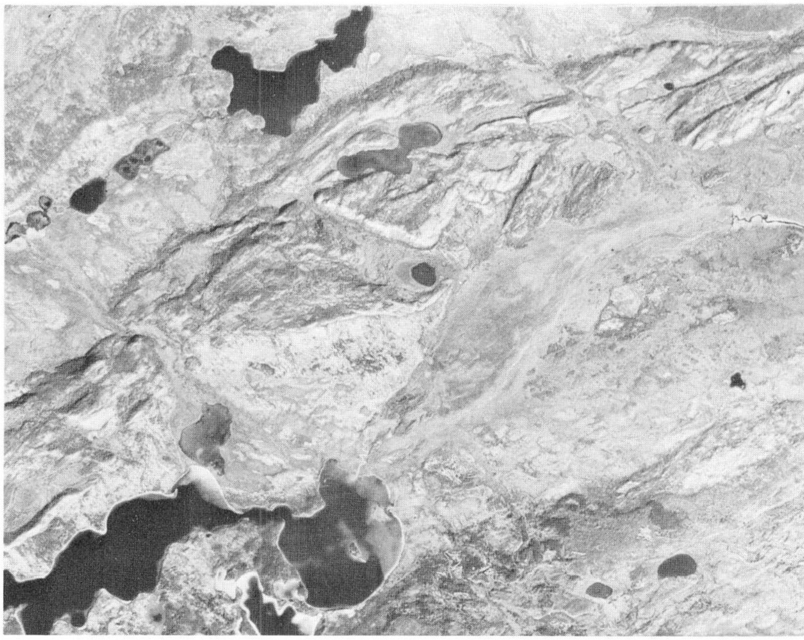


Figure 18. Part of airphoto A14434-109, showing faults crossing the rim, and minor folds in the rim, north of Points Lake. (GSC 113622-C)

Three outliers of the Carswell Formation are known on the Athabasca Formation inside the structure. Their structure is like that of the Athabasca Formation, gently dipping and undeformed by folding.

Faults The presence of a regional fault crossing the Carswell structure through Carswell Lake has already been noted. The offset of the Carswell Formation on this feature is roughly 0.3 mile (1/2 kilometre) in the sense east side radially outward. Assuming that the dip of the axial plane of the ring syncline is 35 degrees as suggested above, this corresponds to a movement of east side down about 975 feet (300 metres).

Faults cutting obliquely across the rim can be identified on airphotos (Fig. 18) and their movement approximately measured by displacement of distinctive beds. The faults are marked by vertical cliffs, faced with Cluff breccia, cutting across the rim at angles of 40 degrees to 50 degrees. Where lateral movement can be identified, it is always in a right-hand sense, and is of the order of tens of metres. The probable existence of a ring fault bounding the Carswell Formation has already been noted.

Discussion The main structural features of the Carswell Formation appear well established. They comprise one or more ring synclines concentric about the centre of the structure. The axial plane of the inner syncline dips toward the centre and the inner limb is overturned, around all, or most, of its circumference. Relatively minor faults cut the rim obliquely, and the formation as a whole is down faulted into its surroundings. The problem is how this deformation can be reconciled with the relatively undeformed underlying Athabasca Formation. Décollements are common on a small scale within the Carswell Formation (Fig. 6), and it seems probable that a major décollement must exist between the Athabasca and the Carswell so that the two units were deformed essentially independently.

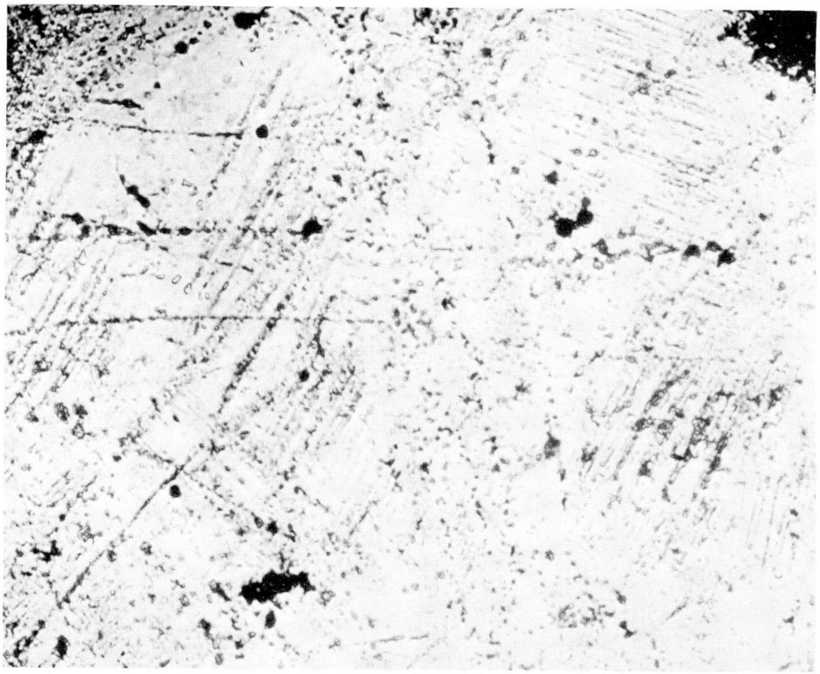


Figure 19. Multiple deformation lamellae from quartz fragment in breccia east of Cluff Lake. Note the lamellae are less distinct than Figure 15, as though slightly annealed. (GSC 113384-J)

Cluff Breccias

The cluff breccias occupy curvilinear zones identified by stratigraphic anomalies as faults. The breccias, however, are not themselves sheared, although some streaky flow-banding occurs in glass-rich material. A microscopic examination of fragments of the basement complex within the Cluff breccias discloses the presence of features identical to those of the basement complex in situ. Reconnaissance measurements of the lamellae by universal stage suggest that the maximum of poles to lamellae against the c-axis of quartz is much the same as in the basement. In some instances the lamellae appear indistinct and discontinuous (Fig. 19), as though partially annealed. By contrast, fragments of the Athabasca Formation in the Cluff breccias are unaltered, except for mechanical disintegration.

STRUCTURAL SYNTHESIS

Résumé and Discussion of Data

The structural elements have been discussed above, and the general disposition of the geological units is evident from the geological map (Fig. 1, in pocket). A cross-section of the structure displaying known and inferred geologic data is given in Figure 20 and the inferred structural elements shown in Figure 21.

The Athabasca Formation is deformed only by faulting, and the deformation of the Carswell Formation is a superficial phenomenon. The key to understanding the Carswell structure lies in the core of basement rocks and the Cluff breccias; the clues to understanding the deformation of the basement complex are the multiple sets of deformation lamellae, and the geochemical and petrographic peculiarities of the Cluff breccias.

The location of the lamellae suggests that they originated as a result of tectonic stresses along the fault zone bounding the central core of basement rocks. Experimental evidence on the origin of multiple sets of lamellae suggests that temperatures greater than 200°C and confining pressures greater than 8 kilobars acted along the fault zones. This pressure is equivalent to that at about 15.6 miles (25 kilometres) depth in the crust. The unaltered character of the sedimentary rocks shows they were never transported to such depths and hence, the pressures must have been produced by some other means.

The cylindrical core of basement has been faulted up into the overlying sedimentary rocks. At the time the upward movement began, the Carswell Lake area may have lain near the axis of a syncline (Fahrig, 1961, p. 38). In such a case the compressive stresses affecting the Athabasca Formation were not only due to the weight of superincumbent rocks, but also involved a component due to lateral compression. When the basement is initially moved upward, it will tend to carry with it the base of the sedimentary sequence, disturbing the equilibrium of the sedimentary rocks and allowing them to slide in against the sides of the rising diapir. This will cause a momentary overpressure equal to the component of the weight of disturbed rocks directed toward the diapir, divided by the area of the diapir intrusive into the sedimentary sequence. For example if the dip toward the centre of the disturbance is 5 degrees, and the height of the diapir is 1/10 the thickness of the sedimentary column, the overpressure is equivalent to a thickness of rock the same as the width of the disturbed zone (see Fig. 17). Assuming a mean specific gravity of 2.70, if a torus of rocks 18.7 miles (30 kilometres) wide began to slide toward the rising diapir it would cause a momentary overpressure of 8 kilobars. Considering the known or postulated scale of gliding phenomena (cf. Engelen, 1964), these conditions do not seem unreasonable. Continued rise of the diapir would cause intense frictional heating along its boundary. Thus conditions of high shearing stress and elevated

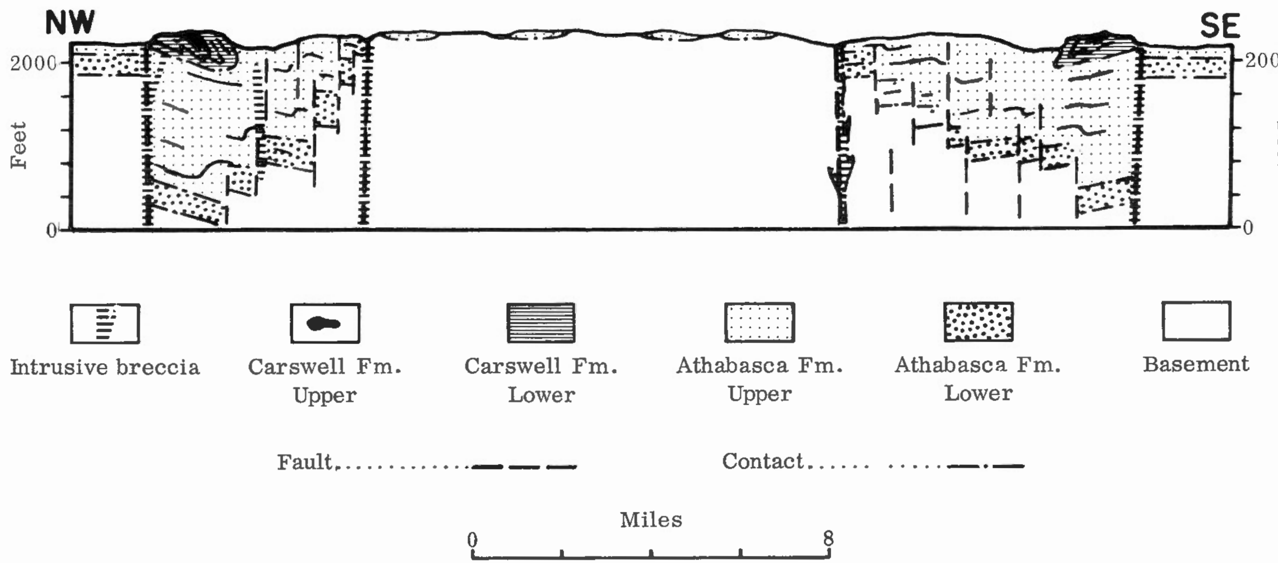


Figure 20. Schematic structure-section across the Carswell circular structure.

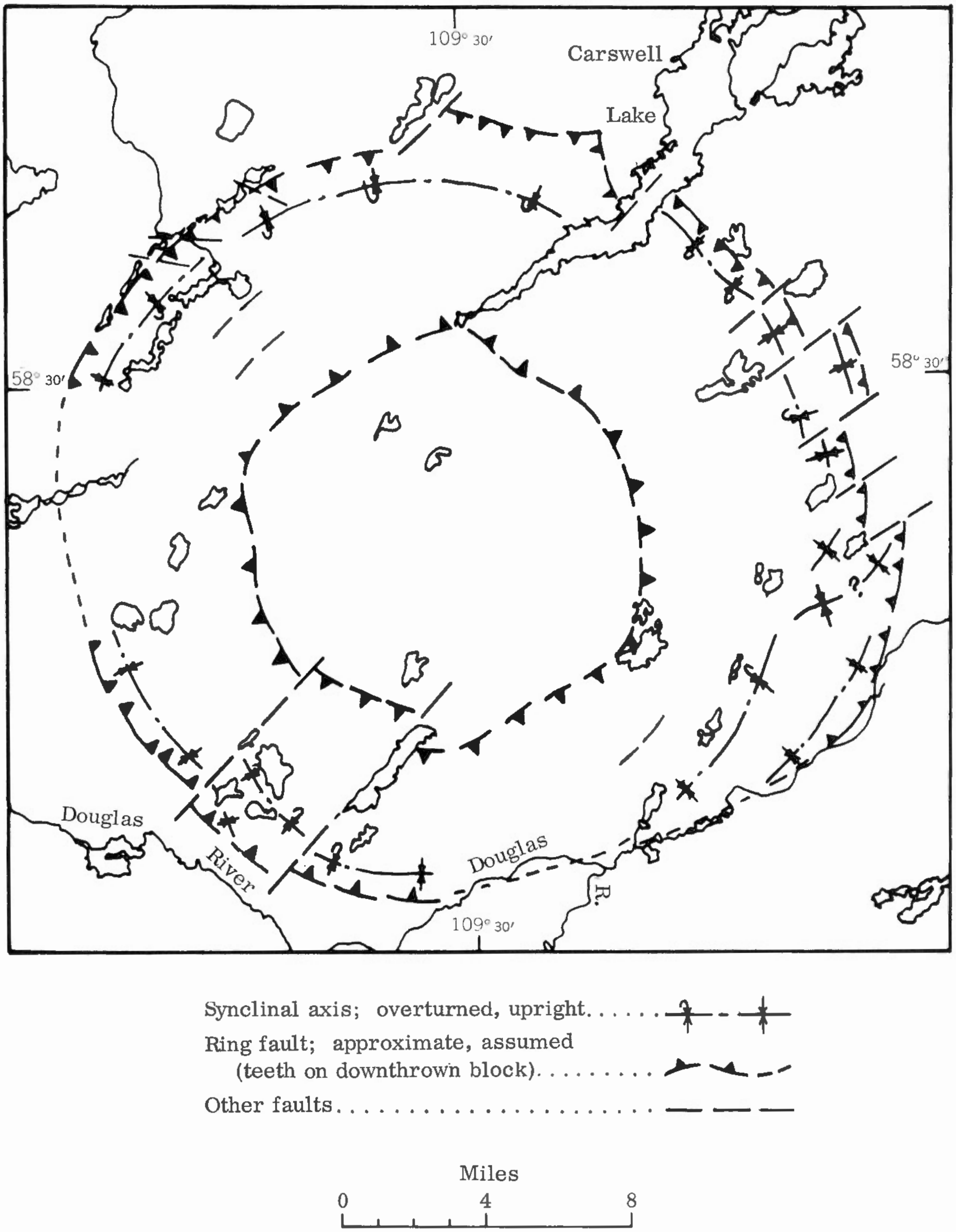


Figure 21. Structural elements of the Carswell circular structure.

temperature under high confining pressure can be created at moderate depths by favourable geometries.

This model predicts that (1) the deformation lamellae will be found only in those parts of the diapir penetrating the sedimentary column, and therefore should rapidly disappear with depth and (2) they will be best developed in the upper part of the diapir because lateral pressures are highest on first intrusion. Both of these predictions are verifiable by core drilling of the structure.

The Cluff breccia zones in contact with the basement are distinguished by the presence of glass, and by enrichment in potash accompanied by depletion in iron. Enrichment in potash and depletion in iron can be confidently ascribed to the action of fluid solutions at high temperatures, whether the process parallels the classical 'granitization' (Reynolds, 1946), or is a late stage igneous phenomenon (Compton, 1960; Turner and Verhoogen, 1960, pp. 241, 266). The presence of glass and devitrification products demonstrates temperatures high enough to melt part of the rock, followed by quenching to preserve the glass. The presence of glass together with the limited extent of the metasomatism shows that the role of solutions was a transient one with an abrupt end. The intervention of solutions occurred after the development of the deformation lamellae, for lamellarly deformed quartz is found as partially annealed fragments in the breccia, and the breccia is not sheared. The formation of the breccia matrix was the last act in history of the fault zones.

Development of the Carswell Structure

A consideration of these data produces a consistent picture of the development of the Carswell structure.

In the deepest part of the basin of sedimentary rocks, uplift of the basement set in. Whether this uplift was originally diapiric, and gradually spread to broad uplift along the axis of the basin, or whether the broad uplift was first and locally intensified into diapirism is uncertain. In any event, diapirism soon developed in the Carswell Lake area. As a result of the rise of the diapir of basement rocks, an area of sedimentary rocks became unstable and slumped in on the rising diapir creating transient high pressures (Fig. 22). As the diapir rose, it carried up with it crescentic slivers of the sedimentary sequence along its flanks. In the initial stages the competent dolomite unit capping the sedimentary sequence arched over the rising dome. Eventually, however, the dolomite, probably broken up to some extent by the stretching and disturbance associated with the intrusion of the basement core, began to slide off the dome, lubricated by a thin sheet of incompetent shale. The first, open folds had axial planes dipping perpendicular to the dome. As gliding continued, the dip of the down-slope limb steepened, and the dip of the axial plane flattened (Fig. 20). Eventually the dolomite piled up at the base

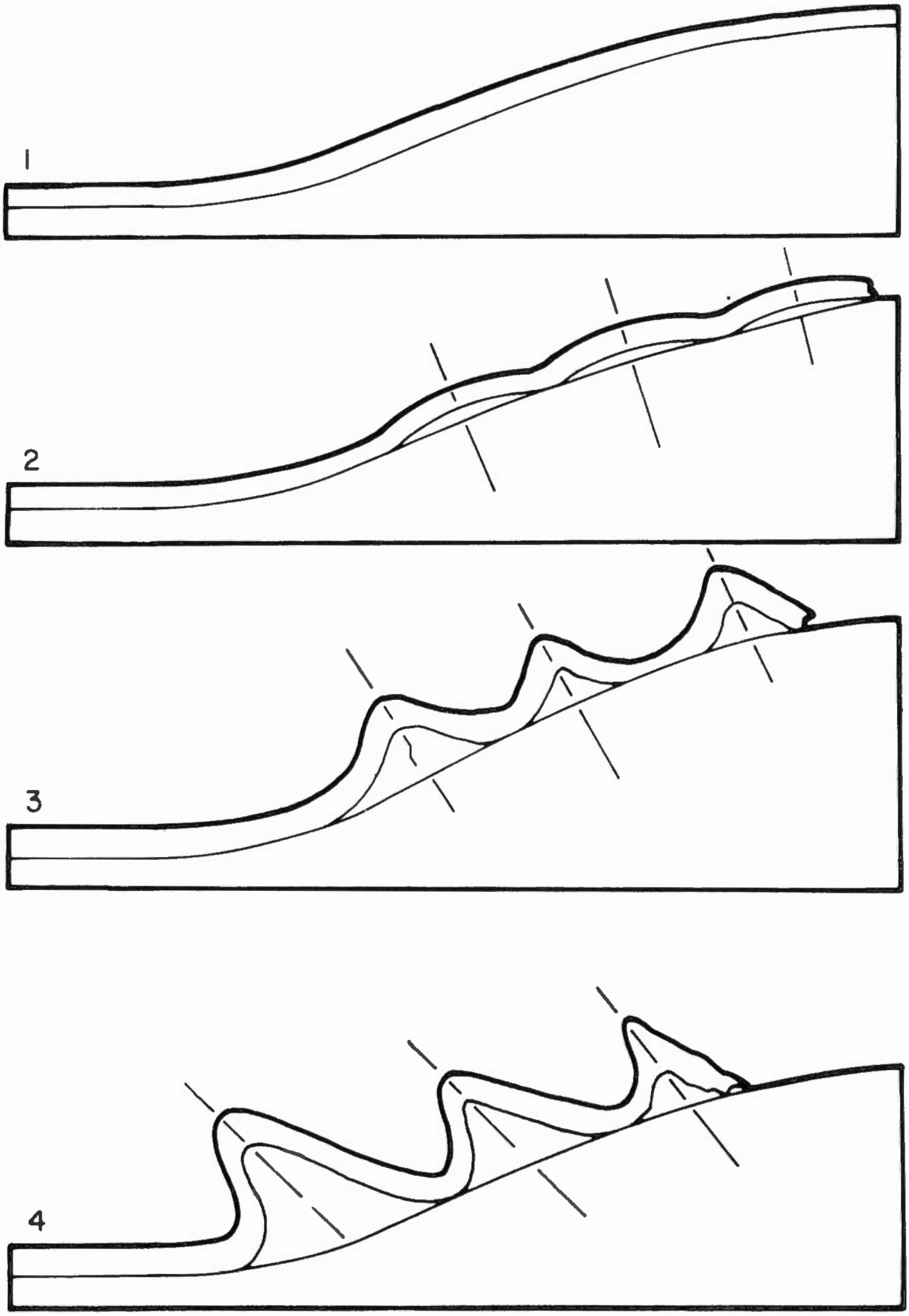


Figure 22. Schematic diagram of development of overturned, inward dipping folds by gliding off a dome

of the dome in a series of folds concentric to the dome. The radial pressures associated with this piling up locally caused shear fractures to propagate across the folds.

By this time, the sedimentary cover had been reduced to fragments, and the rocks of the diapir had been severely fractured by the stresses of intrusion. Solutions which had been trapped beneath the diapir rose along its sides, slowly at first, producing metasomatic alteration, and, combined with frictional heat, locally melting the rocks. When the fracture zones reached the surface, degassing became catastrophic, and the volatiles were vented with explosive violence, causing brecciation along the vents and quenching the pockets of melt to glass.

The exhaustion of volatiles caused the structure to begin to collapse. By this time the vents around the edge of the diapir were becoming plugged, possibly due to emplacement of melted material at depth, and the volatiles began to utilize the outer subsidence fracture and the shear fractures in the dolomite which were cut by the ring fracture. At the last stages even these vents closed, and the volatiles penetrated cracks in the Athabasca and Carswell Formations, fluidizing part of the former and emplacing it in the latter. Possibly at this stage a vent may have been drilled near Tuma Lake emplacing a breccia funnel.

This synthesis accounts satisfactorily for the features of the Carswell structure in terms of known structural process. A schematic diagram of the development is shown in Figure 23. The inward tipping of slivers of the Athabasca Formation parallels the phenomena observed in salt diapirs (Roll, 1949). Combination of diapiric and gliding structures involving competent dolomite beds is known in several localities (van der Fliet, 1953; Engelen, 1964). However, it does leave two problems. What initiated the diapirism of the basement? Where did the assumed volume of volatile materials come from?

The orthodox solution to these problems is to assume magmatic intrusion at depth, causing uplift of the core, and hydrothermal activity at a late stage of crystallization. Some magmatic complexes produce a geometry strikingly similar to that of Carswell Lake (Dougherty, 1964). Fahrig (1961, p. 20) adopted a theory of magmatic intrusion to explain the Carswell structure. In this instance, however, the theory encounters two grave difficulties. First, there is no geophysical evidence of intrusion at depth. That an intrusion capable of producing a structure 25 miles (39 kilometres) in diameter can be emplaced without causing marked anomalies in either gravity or magnetic fields seems rather implausible. Second, the intrusion of a mass at depth results in a net uplift of the column above it. The Carswell structure, however, is a net subsidence. The amount of subsidence depends on the geometry chosen for the Athabasca-basement contact beneath the structure, but Figure 20 shows that no reasonable geometry can negate the conclusion that subsidence is considerable.

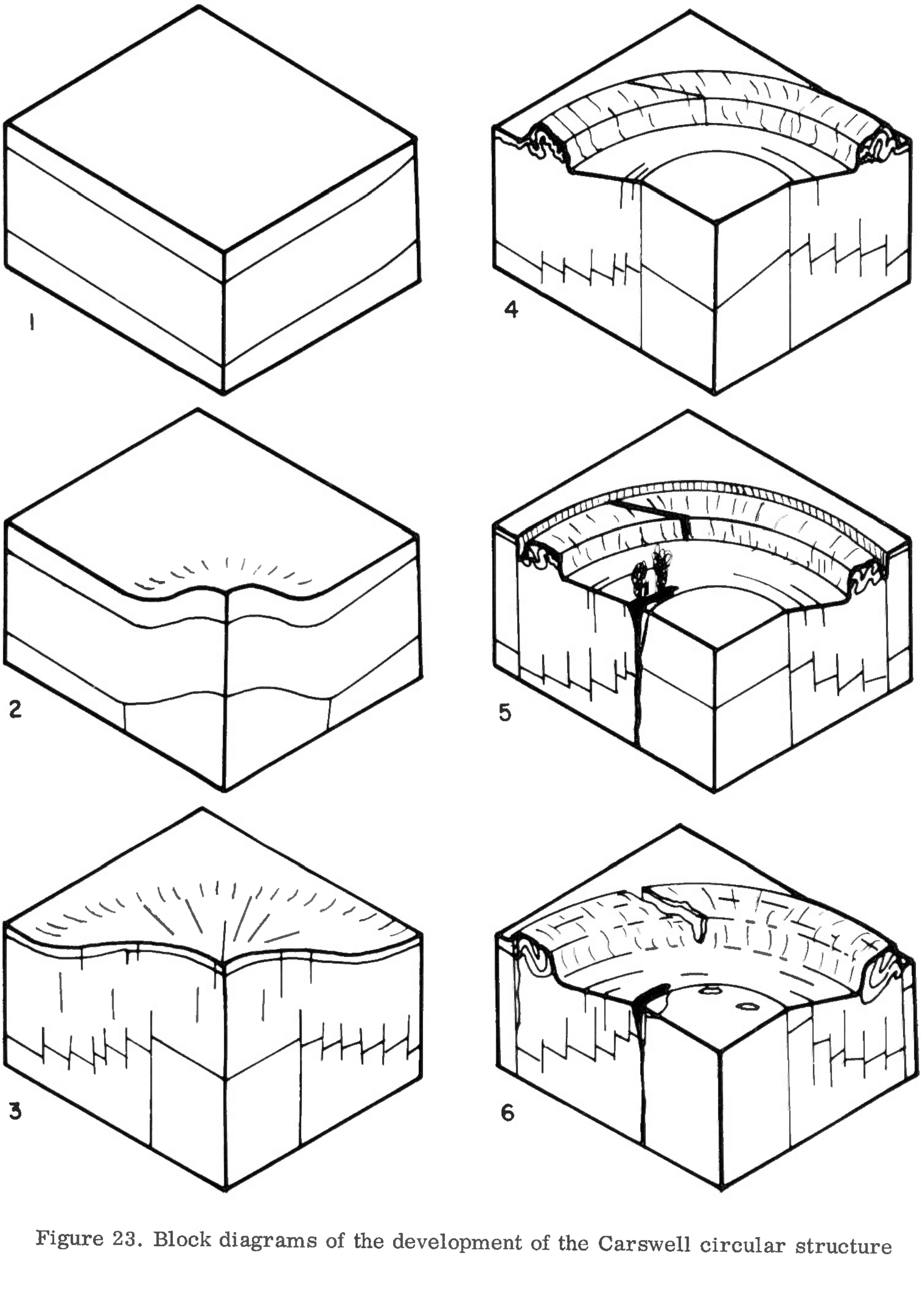


Figure 23. Block diagrams of the development of the Carswell circular structure

The conclusion that the net result of the formation of the Carswell structure was subsidence makes it unlikely that the cause of the structure is ordinary igneous intrusion. The features of the Carswell structure which are incompatible with igneous intrusion suggest the applicability of a theory developed by Currie (1965) to explain other Canadian circular structures. This theory supposes that degassing of the upper mantle is proceeding continuously. In volcanically inactive zones beneath continents, the volatile material is unable to escape to the atmosphere, and accumulates. Such accumulations will migrate toward low pressure areas caused by upwarping of the superincumbent craton. When sufficient volatiles have accumulated, they will begin a diapiric rise due to their buoyancy, carrying upward with them the superincumbent material. Under appropriate conditions they may cause anatectic melting and volcanism during their ascent. Eventually the superincumbent rocks are sufficiently fragmented, or the surrounding fracture zones become sufficiently enlarged so that the gas charge is explosively vented to the surface, and the 'blister' raised by the buoyant volatiles collapses. The process is comparable to the formation of pingoes (Fig. 24). The volume change associated with such a process is small, and often appears to have been negative because of the regional uplift of material around the collapsed zone. The collapse occurs on a ring fault roughly concentric with the diapiric core, but larger in radius. The enlargement in radius of the collapse is assigned to the contrast between the relatively small central, actively rising area, and a much larger area which feeds volatiles to it. The catastrophic loss of volatiles affects the whole feeding area, and thus always has a larger radius than the central uplift. The same effect is observed in the collapse surrounding a salt dome.

The ultimate driving force in the development of these structures is gravity. Brock (1950) has pointed out the key role of gravitational instability in localizing the Vredefort ring, which is strikingly similar to the Carswell structure. Similar considerations very probably apply to most other large circular structures, whether or not their origin is consistent with the speculative theory here outlined.

Carswell Structure compared to other Circular Structures

The Carswell structure has a number of features which set it apart from other geological structures. These include: (1) presence of uplift and downdrop in the same structure, producing juxtaposition of inliers and outliers, (2) presence of 'shock metamorphism', (3) geochemical anomalies, particularly enrichment in potash, (4) presence of polymict breccias with allochthonous matrices. These criteria are shared by a number of structures in Canada, notably Clearwater West (Bostock, 1965), Clearwater East (Dence, 1965), Manicouagan (Currie, 1965), all with diameters greater than 15 kilometres. Several smaller structures including Nicholson Lake, Northwest Territories and Mistassin Lake, Labrador may be of this type. In the United States a large number of 'cryptoexplosion' structures have the same characteristics (Bucher, 1933, 1963), although geochemical work on the

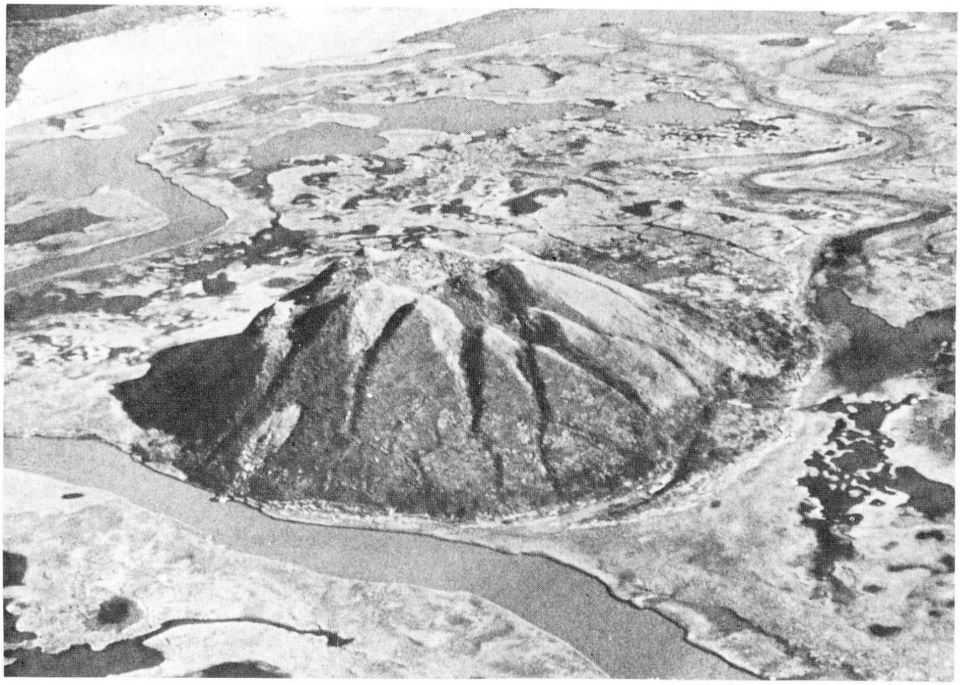


Figure 24. Mature pingo, Mackenzie River delta. The pingo is about 2,900 feet in diameter and 130 feet high. Note tension cracks across the top. (GSC 112643-F)

breccias has not been attempted to the author's knowledge. Structures of this type on other continents are notably few, possibly because of inadequate geologic knowledge. However, the classical example is the Vredefort ring of South Africa. Les Richats, Algeria (Monod, 1965), may be of the same type.

The origin of all these structures is poorly understood. Meteorite impact has been proposed as a causative agent for all, mainly on the basis of their generally circular outline, the presence of lamellar structures on quartz and shatter cones (both of which are usually present), and the presence of 'shock metamorphism' as evidenced by the presence of several types of glass, vesiculation and melting of basement rocks, pseudo-tachylite and other features (Short, 1966b). However, the impact cratering theory (Shoemaker, 1961) does not offer a satisfactory explanation of the geometry of these structures, and it is generally admitted by proponents of impact that a radically different theory of cratering is required (Dence, 1966). A detailed examination of the 'shock metamorphic' phenomena usually reveals further difficulties in theories of impact origin. Thus shatter coning occurrences may be incompatible with impact theories (Manton, 1965, pp. 1044-1045), deformation lamellae may be developed in positions not compatible with a shock origin (see above pp. 38, 39), and the matrices of the breccias may be radically different in composition from the wall-rocks (Shafiqullah and Currie, in press). Considering these discrepancies, theories of impact origin for these structures must be treated with reserve. It is possible that some of these structures are of impact origin; until one of them has been explained in detail and without major discrepancies by an impact theory, attribution of all of the structures to impact origin is obviously premature.

Theories of endogenetic origin of these structures have generally broken down on evidence of high pressures in the structures. The conventional attempt to avoid this problem has been to call on unspecified 'explosive' activity during formation (Bucher, 1963). At Carswell Lake there is evidence that highly reactive volatile solutions acted during formation of the structure. A genuine chemical explosion, as distinguished from explosive release of phreatic pressure, is a real possibility in such circumstances. Jagger (1948) considered such explosions as an important by-product of volcanic activity. Combined with a suitable geometry in the explosion chamber, even weak blasts could give rise to extremely high pressures very locally (Deal, 1962, p. 209).

Such local explosions are a possible source of shock metamorphic phenomena found on fragments in breccias, a frequent occurrence in small craters. However, they cannot explain phenomena such as deformation lamellae which are found on rocks in situ over areas of square kilometres.

A promising way to obtain high pressures on this scale is by manipulation of the geometry of the rocks. A possible mechanism of obtaining transient high pressures has been mentioned above. Jamieson (1963) has pointed out that exceedingly high pressures may be obtained at shallow depths by using suitable geometries. Experimental data to judge the possibilities of high pressures at shallow depths are virtually non-existent.

The great strength of the endogenetic theories is the explanation of the location of structures of the Carswell Lake type. Bucher (1963) has demonstrated that these structures are (1) only formed on the stable craton, (2) follow tectonic features, and hence form linear chains. Exception has been taken to these arguments on the grounds that it is difficult to locate any place that does not have some tectonic feature nearby (Roddy, 1966). However, Currie (1965) answered this argument by showing that on the Canadian Shield, craters are associated only with swells, and that areas without swells are also without craters.

In summary, despite a wealth of petrographic evidence explicable qualitatively by shock metamorphism, circular structures of the Carswell type cannot at present be explained by extraterrestrial impact. Endogenetic theories cannot at present explain the detailed petrographic data, but do explain the general features of the structures. The presence of high pressure phenomena in the structures may be explained by confined explosions, or by geometrical pressure multiplication or by both mechanisms. In short, the processes causing circular structures of the Carswell type remain obscure.

In view of these uncertainties, the data from Carswell Lake add another piece of evidence to the concept that such structures are not caused by extraterrestrial impact and that 'shock deformation' may arise by processes other than impact or explosive shock. The cause of structures of the Carswell type is probably buoyant forces within the crystalline basement.

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