Open File Report 1982-13

CLEAR HILLS IRON DEPOSIT
GEOLOGY, MINERALOGY AND ORE RESERVES

by

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July, 1980

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1.0 SUMMARY

1.1 Geology

The Clear Hills iron deposit is an oolitic iron-rich facies of the Bad Heart Sandstone of Late Cretaceous age. The deposit crops out on the southern and northeastern flanks of the Clear Hills in northwestern Alberta, is essentially flat-lying and extends back from outcrop to underlie a large area of the hills.

Lithologically, the deposit consists of dark brown and green to black, ferruginous oolite, forming a bed up to 10 m thick. The ore bed is thickest in the northeast (Swift Creek) segment of the deposit, thinning westward to zero as the oolitic facies passes into siltstone and argillaceous sandstone. It is overlain and underlain by gray marine shales of the upper and lower Smoky Group.

The deposit has been known to exist for more than 50 years and has received considerable exploratory attention. Substantial reserves are proven, but low grade (35 percent Fe) and complex ore mineralogy have prevented development to date.

1.2 Ore Mineralogy and Petrography

The Clear Hills ore is a minette-type oolitic ironstone, comprising densely packed ooliths, rounded rock fragments and angular grains of quartz and siderite in a soft earthy matrix. The ooliths consist of concentric layers of goethite and nontronite, commonly with a mineral grain nucleus. They constitute from 30 to 70 percent of the rock mass, increasing upward from the base of the ore bed and averaging about 60 percent for the whole.

The matrix consists of illite and nontronite imbedded in a ferruginous opal cement. It averages about 25 percent of the rock mass.

Minor components of the oolite include rock fragments, quartz grains, siderite, and amorphous phosphate. Rock fragments occur commonly as well rounded "pebbles" up to 1 cm in size, composed of matrix-like ferruginous material. They constitute about 10 percent of the rock. The quartz is found mainly as the cores of ooliths but also in the matrix. Siderite occurs as authigenic crystals in the matrix. Phosphate is confined to ooliths, as a diffuse impurity in the goethite and nontronite layers and rarely as grains in the cores.

1.3 Ore Chemistry

Total iron (Fe) content in the Clear Hills deposit averages between 32 and 36 percent. Silica (SiO_2) content is relatively high, between 25 and 30 percent. Alumina (Al_2O_3) is low at around 5 percent. Water content is high (15 percent) due to the abundance of opal.

Iron content varies vertically within the ore bed. From minimum values at the base of around 25 percent, it increases upward to around 40 percent, reflecting the upward increase in ooliths (the main iron-bearing component).

The main ore minerals and the proportion of iron carried by each are as follows:

Goethite ($Fe_2O_3 \cdot H_2O$)		37.9%
Nontronite ($[Fe,Al)_2O_3 \cdot 3SiO_2 \cdot nH_2O$)		39.0%
Ferruginous Opal ($[SiO_2+Fe_2O_3) \cdot nH_2O$)		9.4%
Siderite ($FeCO_3$)		10.8%
	Total	97.1% (of iron in ore bed)

1.4 Physical Character of Ore

Properties of the iron ore are dependent on the depth of weathering in the ore bed. Unweathered, unoxidized ore is moderately hard and compact, and it requires blasting in mining recovery. Weathered ore is soft and friable and can be mined by ripping with bulldozer. The depth of weathering varies, but may extend as much as 3 m into the bed (as in the Swift Creek area).

The ore bed is massive and lacks distinct bedding planes, but is intensely fractured by a vertical joint system, which is an aid in blasting and fragmentation of the rock. Specific gravity determinations of the ore material vary from 2.5 to 2.82. No determinations have been made of compressive and shear strengths, or seismic velocity.

1.5 Ore Reserves

Reserves are defined in four main segments, or "blocks" of the Clear Hills iron deposit. These are referred to as Worsley (block A), Swift Creek (block B), Whitemud River (block C), and South Whitemud River (block D). In blocks A and B the reserves are essentially proven, by extensive test drilling, at 23 million and 182 million tonnes respectively. Blocks C and D reserves are only roughly outlined, at 620 million (probable) and 186 million (possible) tonnes respectively.

Block B, the Swift Creek segment, is the most likely site for future mine development. The ore bed is thickest here and has the best potential mineability. The reserves underlie less than 40 m of overburden, with an average stripping ratio of 3:1, and are ample to sustain a major steel plant.

1.6 Recommendations for Further Work

Further work is recommended in two phases. The first is a complete review of existing data generated from assessment work, various geological studies, coal test drilling and water well drilling. This review will provide a better indication of reserves and a firmer geological base for ore studies to follow.

The second phase involves an extensive coring program, with complete facies analysis and advanced petrographic studies of the cores. The petrographic studies will give enhanced mineralogical characterization of the core, and may lead to a better understanding of, and improvements in, the iron making process. Facies analyses will provide better control on ore grade and thickness variations in the deposit.

A program for evaluation of coal deposits in the Clear Hills is also recommended.

2.0 INTRODUCTION

The Clear Hills iron deposit is a ferruginous oolite bed of Late Cretaceous age that underlies the Clear Hills in the Peace River district of northwestern Alberta. The deposit, known to exist for more than 50 years, has attracted development interest recurrently over the past 25 years because it is the only potentially economic iron ore in the Prairies region. However, the low grade and complex mineralogy of the ore have prevented development to date.

Exploratory drilling on parts of the deposit has outlined ample reserves. Reconnaissance geological mapping has indicated the general limits of the deposit, and detailed mineralogical and petrological studies have helped to characterize the ore quality. However, no comprehensive geological study of the deposit has been made to date. This report constitutes a literature review and consolidation of pertinent geological information on the Clear Hills iron.

2.1. Location and Physiographic Setting

The Clear Hills lie about 485 km northwest of Edmonton and about 80 km northwest of the town of Peace River (Fig. 1). The hills are part of the northern Great Plains region and form a gently rolling upland that rises to 1100 m above sea level, about 100 m above the surrounding wooded plain. Local relief is as much as 300 m along a gentle escarpment on the southern margin of the hills. To the north and east, the hills slope gradually into wide glaciated valleys of the Notikewin and Whitemud Rivers and their tributaries (Fig. 2).

The Clear Hills originated as post-Cretaceous monadnocks, subsequently modified by Pleistocene glaciation. The nearly flat-lying Cretaceous strata underlying the hills are now mantled by unconsolidated glacial and alluvial deposits, but preserve the expression of a former dissected upland.

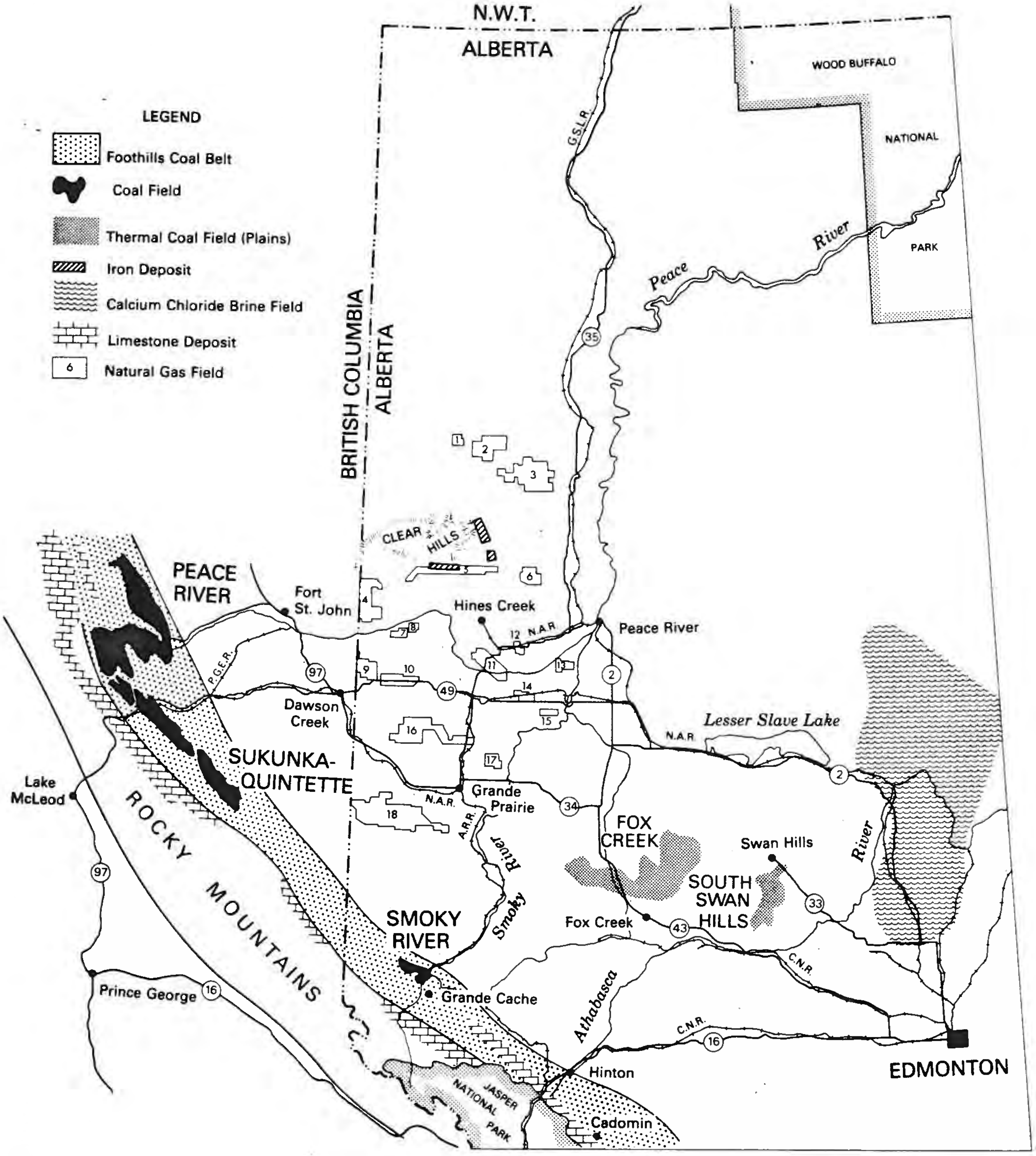

FIGURE 1. Northwestern Alberta, showing locations of Clear Hills iron deposits and other mineral resources in the region.

NATURAL GAS FIELDS AND RESERVES

		1978 Established Reserves ($10^6 m^3$)	
	Field	Initial	Remaining
1.	Chinchaga	573	567
2.	Cranberry	6943	6940
3.	Hotchkiss	4574	3666
4.	Boundary Lake South	3878	1687
5.	Worsley	5382	1467
6.	Dixonville	2120	1824
7.	Balsam	1348	1306
8.	Josephine	2313	2299
9.	Pouce Coupe	5369	2258
10.	Gordondale	2686	871
11.	Dunvegan	29886	23203
12.	Whitelaw	1521	1261
13.	Tangent	1106	1078
14.	Belloy	4412	3961
15.	Eaglesham	1057	1056
16.	Valhalla-Saddle Hills -Webster	5485	5276
17.	Teepee	1645	1614
18.	Elmworth	32618	32663

Source: ERCB 79-18

To accompany Figure 1

2.2 Access and Transportation

Existing access to the Clear Hills iron deposit is from the south (Fig. 2). The southernmost (Worsley) segment of the deposit is about 56 km from the town of Hines Creek and the terminus of a Northern Alberta Railway spur line. Access is provided by an all-weather gravelled road which crosses the Worsley deposit. However, access to the eastern and northeastern segments is possible only in winter when the ground is frozen, along the Notikewin forestry road and winter truck trails and seismic lines. The distance from Hines Creek to the northeastern (Swift Creek) segment of the deposit is about 85 km, the last 50 km on unimproved bush trails which traverse several stretches of muskeg.

Potential access routes from the east, following the Notikewin or Whitemud River valleys, would link the deposit with the Great Slave Lake Railway. The distance is about the same as from Hines Creek (for the Swift Creek segment), but the grades may be more favorable for railroad construction. No terrain analysis studies have been undertaken to determine the best route.

2.3 History of Exploration

The iron deposit was discovered in 1924 by homesteaders in the Peace River area, who staked claims and had some sample assays made in the following year (Bertram and Mellon, 1975). However, the deposit held little economic interest at that time and was all but forgotten for the next 25 years. In 1951 it was "rediscovered" during drilling of a wildcat well by Phillips Petroleum Company Ltd. (Colborne, 1958). The iron bed was intersected in several subsequent wells, thus spurring the formation of the McDougall-Segan Syndicate to explore the iron. In 1954 the Alberta Government issued four iron prospecting permits to the Syndicate.

The Syndicate undertook test drilling on the east flank of the Clear Hills and established the existence of a flat-lying oolitic iron deposit, the reserves of

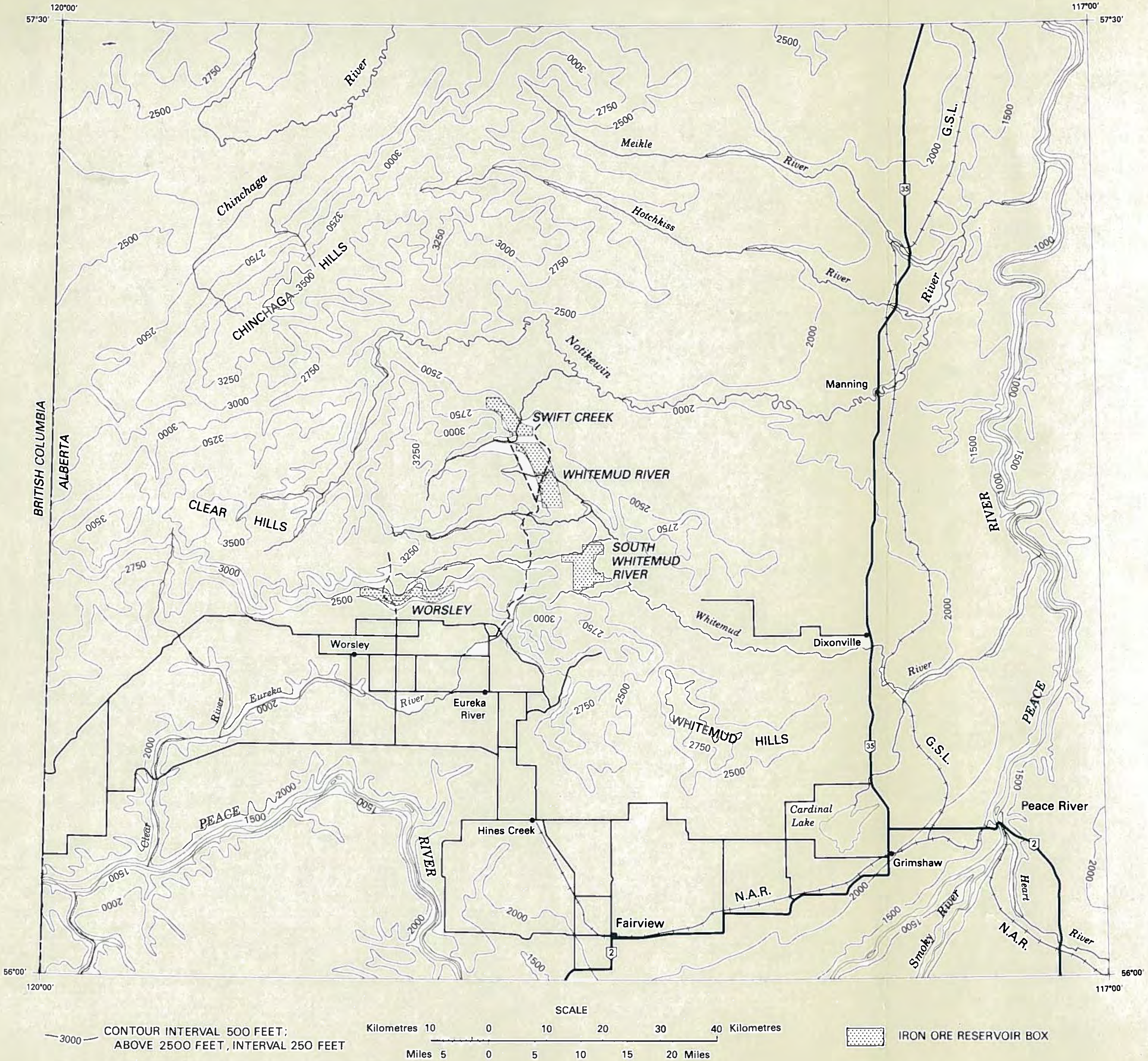

FIGURE 2. Clear Hills area: physiographic setting and main access routes.

which were estimated roughly at nearly one billion tonnes grading 34 percent iron (McDougall, 1954). A reconnaissance geological survey of the area was made as well (McColl, 1954).

Lenz (1956) made the first detailed petrographic and fossil dating studies on the iron formation, as a term paper project at the University of Alberta. The following year Colborne examined outcrops in the Swift Creek area for the Cleveland Cliffs Iron Company and submitted his results as an M.Sc. thesis, also at the University of Alberta (Colborne, 1958).

In 1956 and 1958, the Alberta Research Council mapped all the iron formation outcrops in the Clear Hills area (Kidd, 1959). In this work, Kidd made a preliminary reserves estimate of about 1.5 billion tonnes grading 29 to 35 percent iron. Also during this period, Premier Steel Mills Ltd. obtained interests in the deposit and, in cooperation with the Alberta Research Council, began metallurgical studies on the iron ore. Subsequently the company excavated bulk samples totalling several thousand tons from the Worsley segment of the deposit for laboratory and pilot plant testing (Samis and Gregory, 1962). As part of this work, mineralogical analysis of the ore was performed by the Federal Mines Branch (Nickel, *et al.*, 1960).

Between 1959 and 1962, extensive test drilling was carried out by Premier Steel Mills Ltd. and its successor, Peace River Mining and Smelting Ltd. and defined more precisely the Clear Hills iron ore reserves. The test drilling results outlined four separate ore reserve blocks in the deposit, with net recoverable reserves of 206 million tonnes proven and 814 million tonnes probable and possible combined (Edgar, 1960, 1961, 1964, 1965).

In 1962 regional geological mapping of the Clear Hills area was carried out by the Alberta Research Council (Green and Mellon, 1962). In this work, the approximate limits and stratigraphic setting of the iron formation were established. A detailed petrological study by Mellon (1962) provided insight into the geologic origin of the formation.

Results of evaluation work up to 1962 indicated that the ore deposit was not amenable to economic development because of its low grade and its resistance to conventional upgrading methods. Little further activity occurred until 1974, when proposals for an integrated steel industry in Alberta prompted a review of the deposit. A joint research program was undertaken by the Governments of Alberta and Canada to reassess the potential of Clear Hills ore in the light of advanced ore dressing technology. The program included a general assessment of the deposit by Krupp Industries Ltd. of Germany, ore dressing research by the Alberta Research Council and CANMET,[1] and mineralogy studies by CANMET.

To provide representative unweathered ore material for the program, a 135-tonne sample was excavated from beneath 15 m of overburden in the Swift Creek segment of the deposit (Hamilton, 1974). Studies carried out by Krupp (1975), while directed mainly to ore dressing, dealt also with the mineralogy and with mineability aspects of the deposit. CANMET studies included a very thorough investigation of the ore mineralogy (Petruk, *et al.*, 1974; Petruk, 1977; Petruk, *et al.*, 1977).

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[1] Canada Centre for Mineral and Energy Technology, formerly the Mines Branch.

3.0 GEOLOGY

3.1 Regional Geology and Stratigraphy

The Clear Hills region is underlain by nearly flat-lying sandstone and shale formations of Cretaceous age, covered in most places by unconsolidated glacial deposits of variable thickness (Kidd, 1959; Green and Mellon, 1962). The strata are soft and prone to slumping, and bedrock exposures thus are scarce, confined mostly to the numerous small streams that form a radial drainage pattern around the hills (Fig. 2).

The succession of strata that outcrops in the region is shown in Table 1. It comprises marine and nonmarine sandstones and shales that are divided into six formational units, the thicknesses and lithologic character of which are given in the table. The iron formation is found in the Bad Heart Sandstone, a marine sandstone unit intercalated between dark gray marine shales of the Smoky Group, which underlies the lower slopes of the hills and the surrounding lowlands. The highest parts of the hills are capped by nonmarine sandstones and shales of the Wapiti Formation (Fig. 3).

Glacial deposits are prevalent throughout the area and consist largely of pebbly clay till forming ground or hummocky disintegration moraine, or lacustrine clay with sparse pebbles (Green and Mellon, 1962). These deposits range in thickness from zero to 20 m. Outwash deposits of sand and gravel, some up to 35 m thick, are present in places along the valleys of the Notikewin and Whitemud Rivers.

Bedrock structure in the Clear Hills area is primarily that of a gently undulating homocline. Regional dips are extremely low and rarely exceed 5 m per km, generally to the southwest, although local rolls or reversals of dip result in variable dip directions (Green and Mellon, *op. cit.*). In fact, within the Clear Hills proper the shallowest beds are mainly east-dipping, as evidenced by

Table 1. Succession of Strata in the Clear Hills Area, Alberta (from Green and Mellon, 1962).

ROCK UNIT			THICKNESS (m)	LITHOLOGY
Wapiti Formation			0-120	soft, whitish sandstone; grey, blocky, carbonaceous shale; thin coal seams (continental)
Smoky Group	Puskwaskau Formation		90-180	dark grey, fissile shale (marine)
	Bad Heart Sandstone		0-9	green, ferruginous, oolitic sandstone and mudstone (marine)
	Kaskapau Formation	upper member	45-125	dark grey, fissile shale (marine)
		lower member	12-47	whitish sandstone; grey, sandy shale; oolitic siderite (marine)
Dunvegan Formation			150-235	soft, grey sandstone with calc. concretions; grey, silty, carbonaceous shale (deltaic)
Shaftesbury Formation		upper member	90-170	grey, silty shale; thin, laminated siltstone (marine)
		lower member	180-320	black, fissile shale; numerous fish scales (marine)

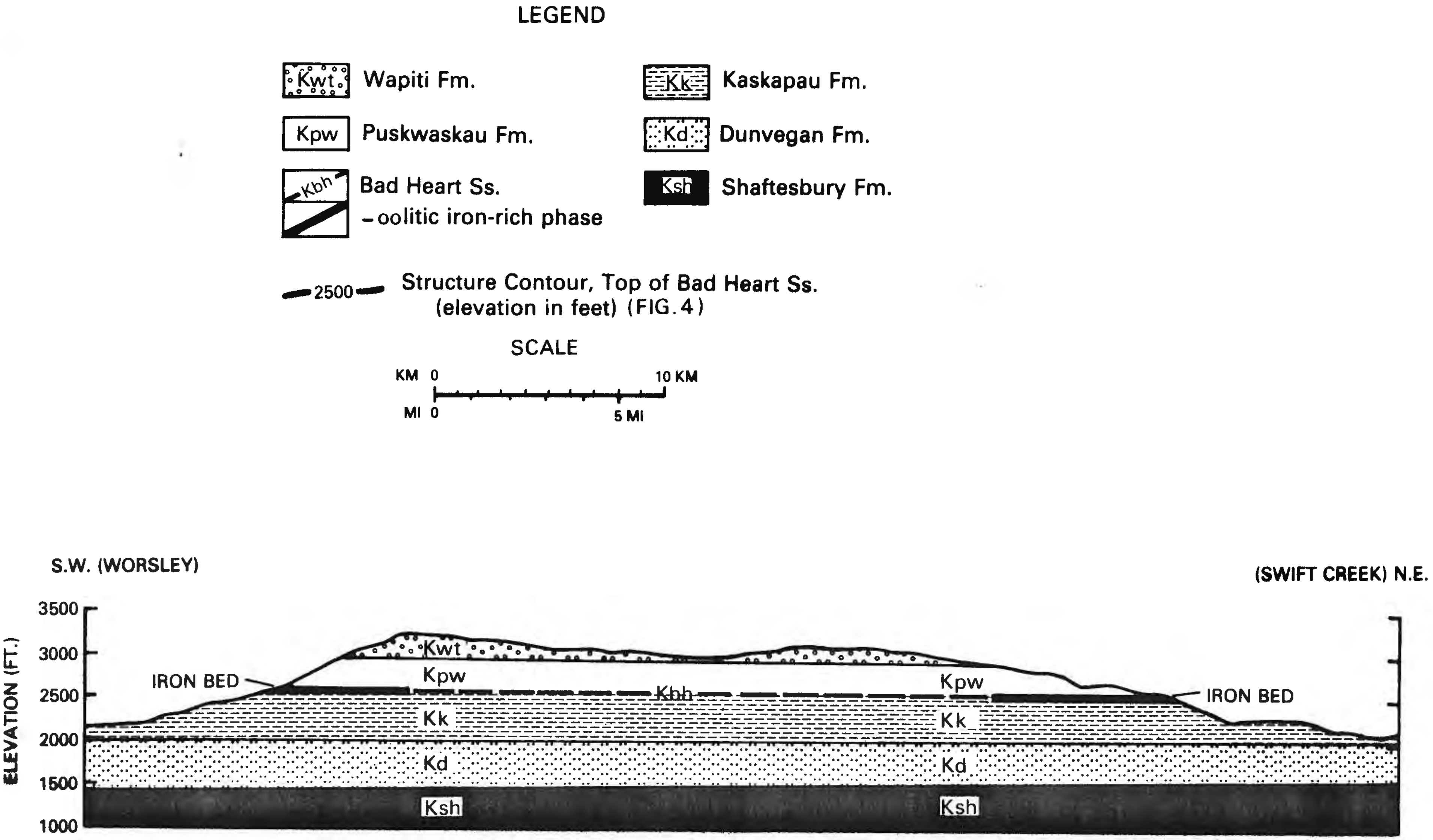
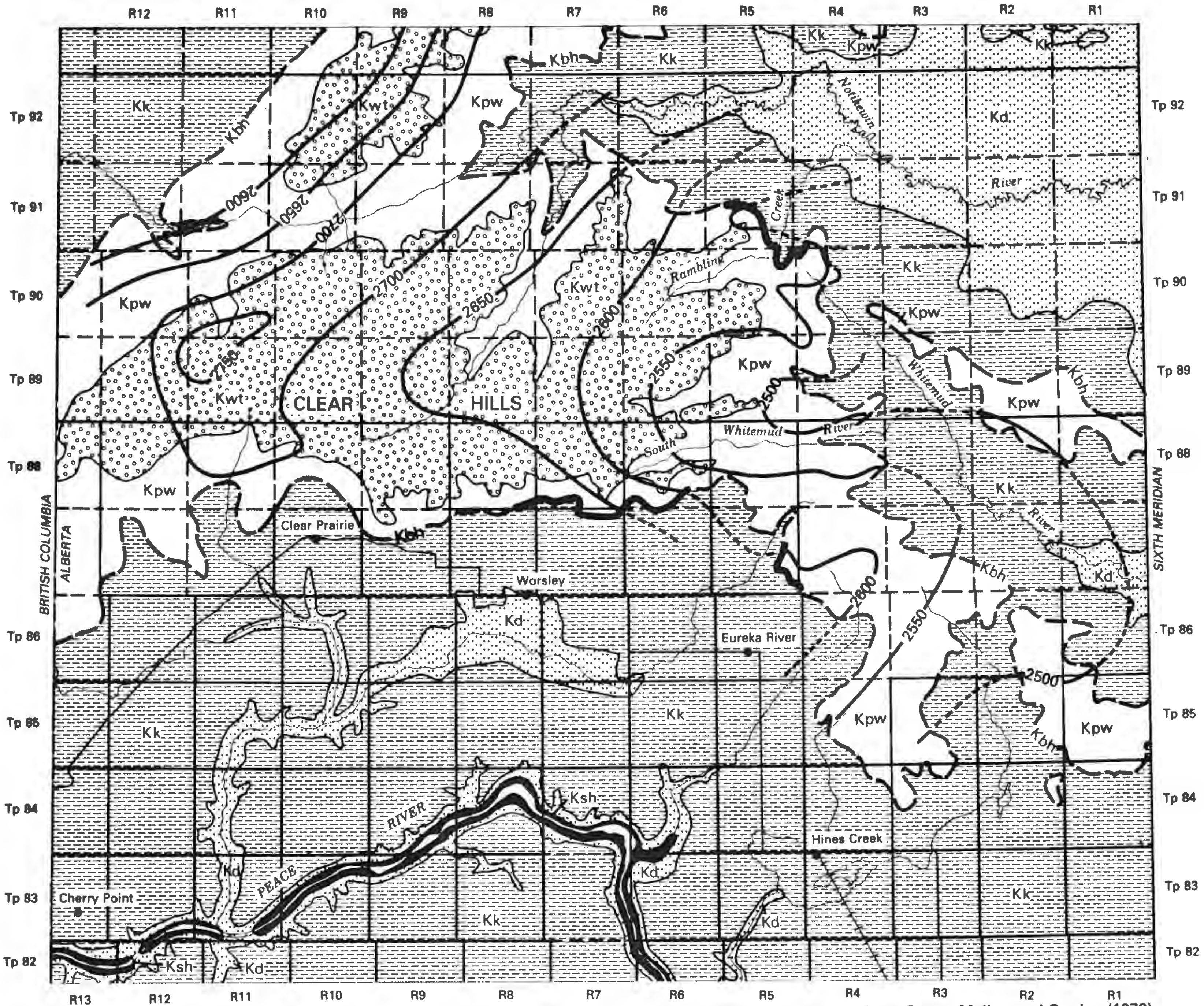


FIGURE 3. Schematic cross-section through the Clear Hills, showing stratigraphic setting of the iron formation.



Geology from Green, Mellon and Carrigy (1970).

FIGURE 4. Bedrock geology of the Clear Hills area, with structure contours on top of Bad Heart Sandstone.

structure contours drawn on the top of the Bad Heart Sandstone (Fig. 4). From a mining standpoint the beds are practically flat-lying.

3.2 Clear Hills Iron Formation

The Clear Hills iron formation is an oolitic iron-rich facies of the Bad Heart Sandstone, which separates the Kaskapau and Puskwaskau Formations of the Smoky Group (Table 1). In its type locality, 65 km south of the Clear Hills on the Smoky River, the Bad Heart is an argillaceous quartzose sandstone, 2.5 m thick, capped by a persistent ironstone layer 0.3 to 0.6 m thick. In the Clear Hills area the Bad Heart consists of a ferruginous oolite bed up to 10 m thick.

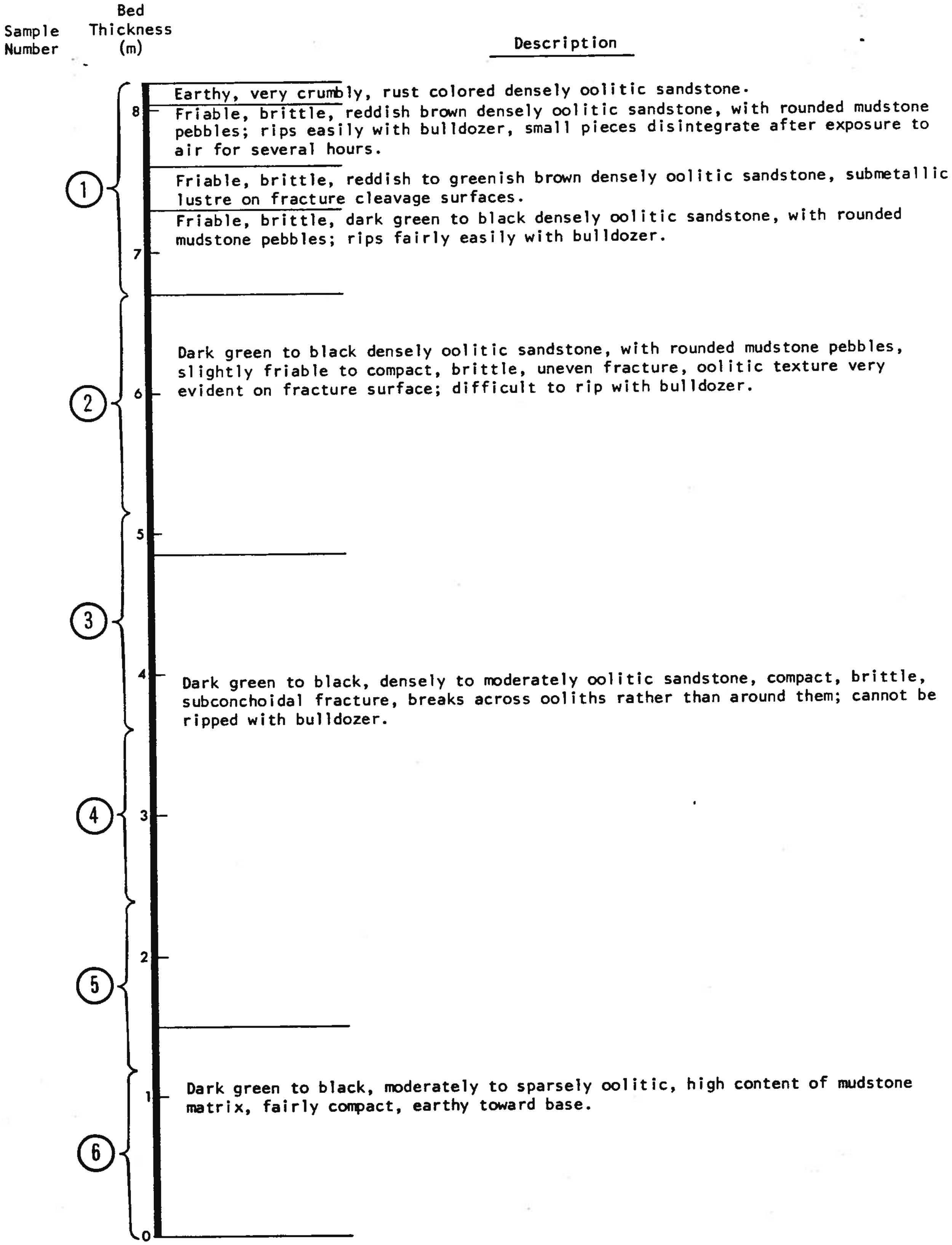
The outcrop limit of the Bad Heart Sandstone is shown in figure 4. The main outcrops are on the southern and eastern slopes of the Clear Hills, north of Worsley and on Swift Creek (Kidd, 1959). Extensive shallow test drilling has been carried out in these two areas to assess the grade and extent of the iron deposit. This and additional petroleum exploration drilling has outlined several tens of square kilometres in the Clear Hills that the deposit underlies.

The best outcrops are those along Swift Creek (now named Rambling Creek) near the eastern margin of the hills, where thicknesses up to 9 m of the oolite bed are exposed. A complete unweathered section of the unit is exposed in the sampling pit excavated in this area in 1974 (Hamilton, 1974). The succession of strata is described in Table 2.

From the eastern slopes of the Clear Hills the iron formation thins to zero a few kilometres to the west, as the Bad Heart oolitic facies passes into siltstone and argillaceous sandstone. The oolitic facies seems to form a series of elongated northwest-trending bodies, the exact limits and thicknesses of which remain to be determined.

North of Worsley, on the southern slopes of the hills, the iron formation crops out discontinuously over a distance of 16 km, with thicknesses of 3 to 5 m

Table 2. Lithology of Clear Hills Iron Formation in Swift Creek Sampling Pit (summarized from Hamilton, 1974).



Earthy, very crumbly, rust colored densely oolitic sandstone.

Friable, brittle, reddish brown densely oolitic sandstone, with rounded mudstone pebbles; rips easily with bulldozer, small pieces disintegrate after exposure to air for several hours.

Friable, brittle, reddish to greenish brown densely oolitic sandstone, submetallic lustre on fracture cleavage surfaces.

Friable, brittle, dark green to black densely oolitic sandstone, with rounded mudstone pebbles; rips fairly easily with bulldozer.

Dark green to black densely oolitic sandstone, with rounded mudstone pebbles, slightly friable to compact, brittle, uneven fracture, oolitic texture very evident on fracture surface; difficult to rip with bulldozer.

Dark green to black, densely to moderately oolitic sandstone, compact, brittle, subconchoidal fracture, breaks across ooliths rather than around them; cannot be ripped with bulldozer.

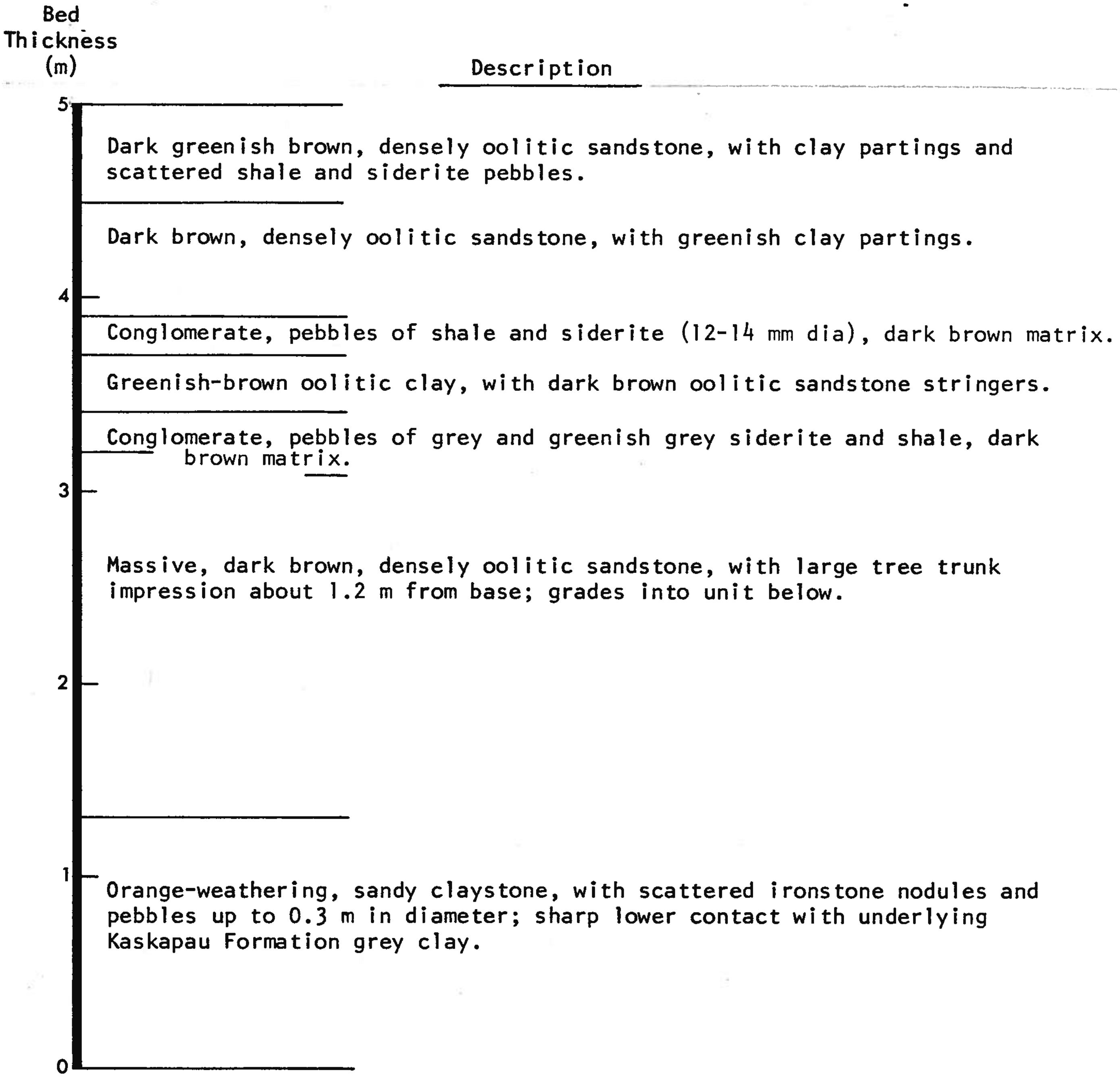
Dark green to black, moderately to sparsely oolitic, high content of mudstone matrix, fairly compact, earthy toward base.

(Kidd, 1959). The unit is well exposed in a sampling pit 10 km north of Worsley, where 4800 tonnes of material were excavated for pilot plant testing in 1960 (Samis and Gregory, 1962). A composite sequence of the Bad Heart strata exposed in this pit and in a nearby road cut is described in Table 3.

In gross lithology the iron formation consists of dark brown and green to black oolitic ironstone, with thin lenses and interbeds of hard sideritic ironstone and greenish gray mudstone. Near the outcrop margin the oolite has been oxidized to form a soft, compact, reddish brown aggregate with harder carbonate cemented lenses. The ooliths, about 0.4 mm in diameter, form 60 to 70 percent of the rock in the upper part of the bed and decrease in amount toward the base, to only 20 to 25 percent. The detrital mudstone, which forms the matrix throughout the oolite bed, thus becomes the dominant lithologic fraction at the base (Fig. 5).

The oolite appears to be a single massive bed. In unweathered exposures stratification is only vaguely defined. There are no distinct bedding plane surfaces or sedimentary structures to be seen within the unit. The upper contact with the Puskwaskau Formation is sharp; however, in most places on the flanks of the Clear Hills the Puskwaskau shale has been stripped back by glaciation and the iron formation lies in direct contact with glacial till. The lower contact generally is gradational into dark silty shales of the Kaskapau Formation, although in the Swift Creek sampling pit it was observed to be fairly sharp (Hamilton, 1974).

Table 3. Lithology of Clear Hills Iron Formation in Worsley Area, Composite Section, Sampling Pit and Road Cut (from Green and Mellon, 1962)



Dark greenish brown, densely oolitic sandstone, with clay partings and scattered shale and siderite pebbles.

Dark brown, densely oolitic sandstone, with greenish clay partings.

Conglomerate, pebbles of shale and siderite (12-14 mm dia), dark brown matrix.

Greenish-brown oolitic clay, with dark brown oolitic sandstone stringers.

Conglomerate, pebbles of grey and greenish grey siderite and shale, dark brown matrix.

Massive, dark brown, densely oolitic sandstone, with large tree trunk impression about 1.2 m from base; grades into unit below.

Orange-weathering, sandy claystone, with scattered ironstone nodules and pebbles up to 0.3 m in diameter; sharp lower contact with underlying Kaskapau Formation grey clay.

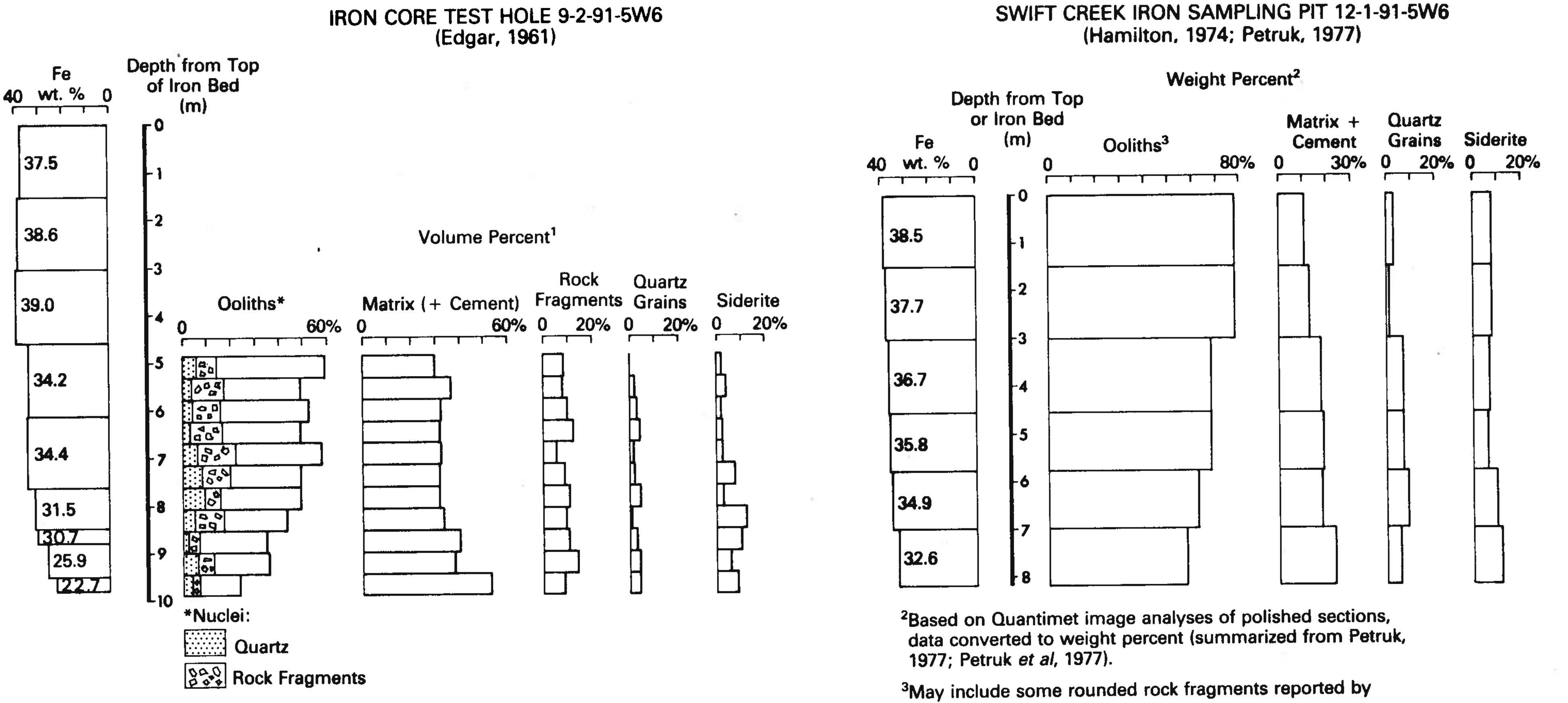
4.0 ORE QUALITY

Data presented here on the mineralogical, chemical and physical characteristics of Clear Hills iron ore are based largely on studies of the unweathered ore section in the Swift Creek segment of the deposit. The Swift Creek section, thoroughly sampled from the bulk sampling pit and from core test holes, is considered to be representative of most of the Clear Hills deposit. The only exception is a portion of the deposit along the southern flank of the hills — the Worsley segment — where deep oxidation has occurred in the iron bed, resulting in significantly different ore characteristics from the rest of the deposit. However, this affects less than 3 percent of the total ore reserves.

4.1 Mineralogy and Petrology

The Clear Hills iron deposit is a minette-type oolitic ironstone comparable in grade and nature to the sedimentary iron ores of eastern France (Gross, 1965). The ironstone consists of densely packed ooliths, rounded rock fragments, and angular grains of quartz and siderite in a soft earthy matrix (Mellon, 1962). A quantitative petrographic analysis of the ore bed is shown in Figure 5.

The oolith content is highest in the upper part of the bed (about 70 percent), decreasing progressively towards the base (Fig. 5). The ooliths range in size from 0.05 to 1.0 mm but are well sorted and are mostly about 0.4 mm in diameter. They consist of concentric layers of goethite and nontronite, normally enclosing a mineral grain nucleus (Petruk, 1977). These nuclei are principally quartz, but may also be amorphous phosphate, massive goethite, broken oolith fragments, or rock fragments. The average composition of the ooliths is about 45 percent goethite, 45 percent nontronite, 5 percent quartz and 5 percent amphorous phosphate. However, the composition varies to the extent that some ooliths are largely goethite, others almost wholly nontronite (Petruk, *op. cit.*). The goethite-rich ooliths are most abundant at the top of the iron bed, whereas the nontronite ooliths are found only at the base.



[1] Based on point-counts of thin sections, 200 points per sample (from Mellon, 1962).

[2] Based on Quantimet image analyses of polished sections, data converted to weight percent (summarized from Petruk, 1977; Petruk *et al*, 1977).

[3] May include some rounded rock fragments reported by Mellon (1962).

FIGURE 5. Petrographic analysis of iron ore bed in Swift Creek area.

The interstitial "matrix" consists of the clay minerals illite and nontronite imbedded in a ferruginous opal cement (Petruk, *op. cit.*), to form a dark green, earthy material. The matrix averages about 25 percent by volume throughout the ore bed thickness, but it varies inversely with the oolith content and toward the base it increases to a maximum of about 50 percent (Fig. 5).

Rock fragments constitute about 10 percent by volume of the ore and are fairly constant in amount throughout the ore bed (Mellon, 1962). Many of the fragments occur as well rounded, polished "pebbles" up to 1 cm in size, conspicuously larger than the more abundant ooliths. Smaller fragments are found also as cores in many of the ooliths. The fragments are composed largely of ferruginous, silty shale aggregates similar in composition to the interstitial matrix of the oolite, showing all gradation between unaltered, dark green aggregates to completely oxidized, dark brown limonitic aggregates. Presumably they originated from the breaking up of lithified iron-rich sediments in the basin, the detritus being reworked, partially oxidized and redeposited during the period of oolite deposition.

Other minor components of the oolite bed are quartz, siderite, and amorphous phosphate. The quartz is detrital, found mainly as the cores of ooliths but also as discrete, uncoated grains scattered through the matrix. Siderite is authigenic and is present mainly as intergranular crystals in the matrix, occupying portions of voids in the oolite not completely infilled by matrix material. The phosphate is confined to ooliths, as rare discrete grains in the cores and also as a diffuse impurity in the goethite and nontronite layers. The phosphate is largely amorphous but one grain gave a weak x-ray diffraction pattern of apatite (Petruk, 1977). Quartz and siderite each constitute about 5 percent of the rock, phosphate about 3 percent.

4.2 Chemical Composition

Results of chemical analyses of the ore from various segments of the Clear Hills iron deposit are presented in Table 4. These are averaged analyses of samples

Table 4. Chemical Analyses of Clear Hills Iron Deposits (from Bertram and Mellon, 1962).

Constituent	Worsley[1]	Swift Creek[2]	Swift Creek[3] Whitemud River
Fe	32.65	35.44	32.98
SiO_2	25.67	26.49	29.26
Al_2O_3	5.53	4.95	5.47
CaO	3.25	1.90	-
MgO	1.25	1.02	1.60
P	0.69	0.67	0.45
S	0.11	0.07	-
MnO	0.16	0.16	-
L.O.I.	14.36	13.78	11.91

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[1] Weighted averages of borehole samples from block A (Edgar, 1960).

[2] Weighted averages of borehole samples from block B (Edgar, 1961).

[3] Weighted averages of borehole samples from blocks B and C (given in Kidd, 1959).

from numerous boreholes and they indicate a fair degree of uniformity in average composition for the deposit. Salient features of these data are:

(1) Total iron (Fe) content averages between 32 and 36 percent, being highest in the Swift Creek segment of the deposit.

(2) Silica (SiO_2) content is relatively high, averaging between 25 and 30 percent; alumina (Al_2O_3) is constantly low at around 5 percent.

(3) Water content is high due to the abundance of opal.

(4) The higher lime (CaO) content in the Worsley segment possibly is the result of deeper oxidation, where siderite ($FeCO_3$) has reacted with groundwater solutions to form goethite ($Fe_2O_3 \cdot H_2O$) and calcite ($CaCO_3$).

Vertical variations in the iron composition within the oolite bed are shown in Figure 6. In this figure, iron percentages are plotted against stratigraphic position for representative borehole sections from the Swift Creek segment of the deposit. The upward increase in iron content (from less than 25 percent at the base of the ore bed to more than 40 percent at the top) reflects an increase in the content of ooliths, which are the main iron-bearing lithologic component.

Results of detailed chemical analyses of the ore from the Swift Creek sampling pit are given in Table 5. Two sets of results are presented for the Swift Creek ore, one obtained by the Alberta Research Council (Bertram, *et al.*, 1976), and one by CANMET (Petruk, *et al.*, 1977). In addition, analyses by the Canada Mines Branch[2] (Nickel, *et al.*, 1960) of two highly oxidized samples from the Worsley deposit are included for comparison.

The results of the two sets of Swift Creek analyses can be seen to vary. This is due to the presence of ferruginous opal, the main matrix mineral, and nontronite, a major constituent of the ooliths. Both minerals contain water: both

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[2] Now known as CANMET.

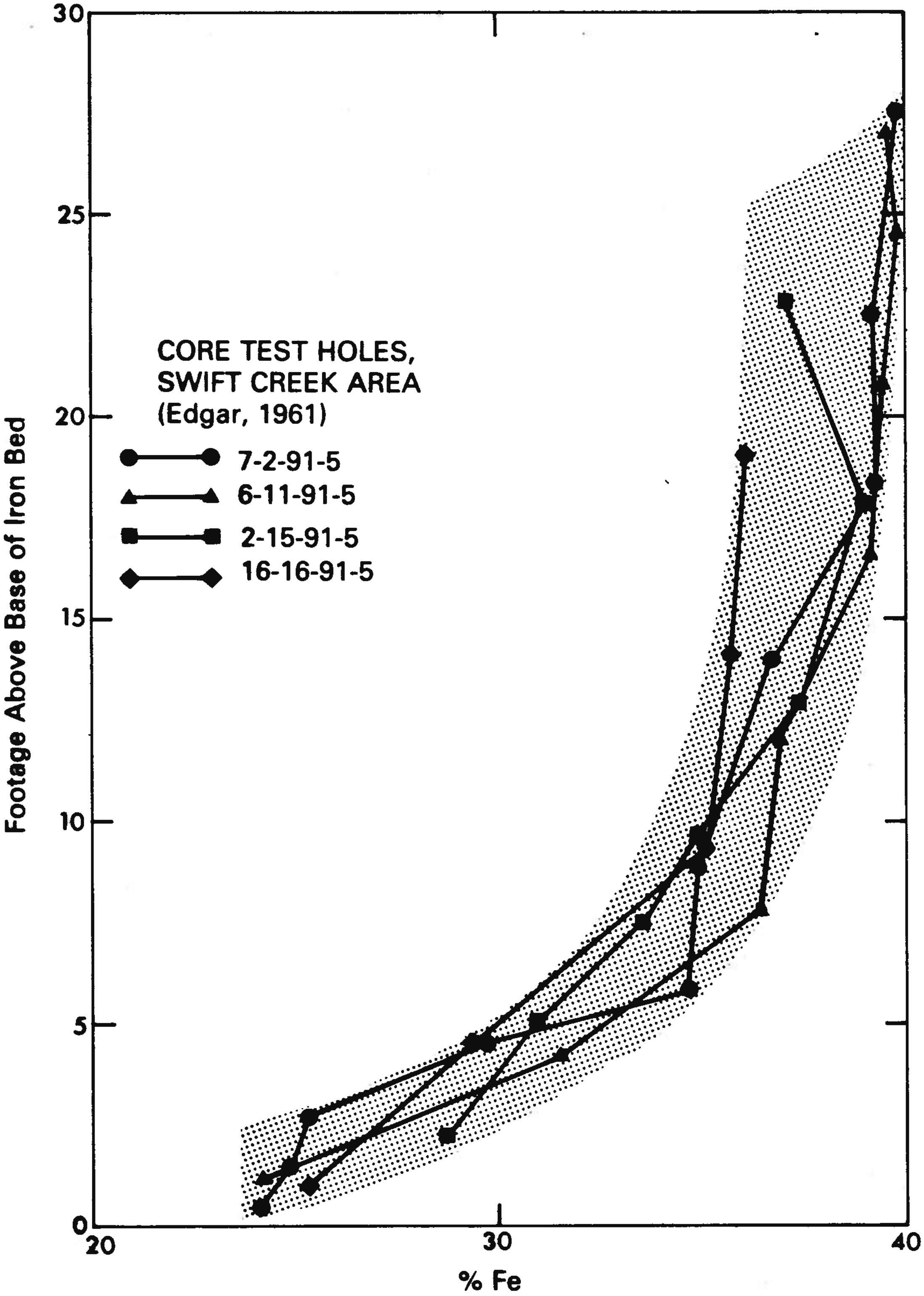

FIGURE 6. Vertical variations in iron composition within Clear Hills iron ore bed.

Table 5. Chemical Analyses of Clear Hills Iron Ore from Swift Creek and Worsley Sampling Pits

	Swift Creek[1]												Worsley[4]	
	Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6			
Constituent	ARC[2]	CANMET[3]	ARC	CANMET	ARC	CANMET	ARC	CANMET	ARC	CANMET	ARC	CANMET	A	B
Fe	33.8	38.5	32.2	37.7	33.3	36.7	32.7	35.8	30.15	34.9	28.0	32.6	34.6	32.7
Fe_2O_3	39.2	50.4*	29.6	48.2*	28.2	47.7*	26.3	43.8*	33.1	-	28.8	-	48.0	47.0
FeO	9.6	4.5*	17.6	5.3*	20.6	5.1*	21.9	6.7*	10.8	-	13.8	-	1.3	0.7
SiO_2	16.6	21.9	17.4	23.4	17.8	25.2	17.3	26.4	17.9	26.8	19.3	28.6	16.6	22.0
Al_2O_3	5.7	5.4	5.3	5.2	5.3	5.1	4.9	5.1	4.7	5.2	4.7	5.4	8.3	8.4
CaO	2.0	2.1	1.6	1.8	1.4	1.7	1.6	1.9	1.9	2.0	2.0	2.2	4.3	4.7
MgO	1.0	1.0	0.9	1.0	0.9	1.0	1.0	1.0	1.1	1.2	1.3	1.5	2.7	1.8
P_2O_5	1.6	1.9*	1.8	1.8*	1.3	1.7*	1.4	1.5*	1.4	1.6*	1.4	-	0.8	0.8
S	0.03	0.04*	0.02	0.03*	0.02	0.03*	0.03	0.03*	0.03	0.14*	0.07	-	0.11	0.11
Na_2O	-	0.2*	-	0.2*	-	0.2*	-	0.2*	-	0.2*	-	-	0.1	0.1
K_2O	-	0.5*	-	0.4*	-	0.5*	-	0.5*	-	0.6*	-	-	0.6	0.7
MnO	0.7	-	0.6	-	0.7	-	1.1	-	0.9	-	0.8	-	0.1	0.1
TiO_2	-	-	-	-	-	-	-	-	-	-	-	-	0.3	0.4
V	0.2	-	0.2	-	0.2	-	0.2	-	0.2	-	0.2	-	-	-
CO_2	-	-	-	-	-	-	-	-	-	-	-	-	3.3	2.9
H_2O	-	-	-	-	-	-	-	-	-	-	-	-	13.7	10.4
L.O.I.	24.3	10.6	24.3	10.3	24.1	10.0	24.0	10.0	25.1	10.2	28.9	10.3	-	-

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[1] See Table 2 for sample number intervals.

[2] ARC analyses are for samples *as received*, analyzed by Alberta Research Council (Bertram, *et al.*, 1976).

[3] CANMET analyses are for *dried* samples, analyzed by Canada Centre for Mineral and Energy Technology (Petruk, *et al.*, 1977): asterisk (*) denotes analyses by Krupp Industries Limited.

[4] Samples A and B are both for the whole ore bed thickness of 3 m, analyzed by Canada Mines Branch (Nickel, *et al.*, 1960).

absorb it under humid conditions and expel it upon drying (Petruk, *et al.*, 1977). The ARC analyses are representative of the unweathered ore material *in situ*, which has up to 25 percent water. The CANMET analyses were made after drying the ore for several hours at 105°C, with a weight loss of about 15 percent (absorbed water) and proportionate increases in the chemical constituents. Accordingly, the average iron content jumps from 32 to 37 percent.

The oxidized Worsley samples show a water content similar to that of the dried Swift Creek samples. Seemingly, water loss has occurred in this weathered ore as a result of exposure to dry atmospheric conditions. Petruk (1977) suggests that water loss may be related also to the mechanism of oxidation of ferrous iron in the nontronite, involving a release of combined water.

4.3 Mineral-Chemical Relationships

The mineral composition of the Clear Hills iron ore is summarized in Table 6. Mineral contents were determined by Quantimet image analyses of polished sections and the data converted to weight percent (Petruk, 1977). The average chemical compositions of the minerals are given in Table 7, determined by microprobe analyses (Petruk, *et al.*, 1977).

The main iron-bearing minerals in the ore are *goethite* ($Fe_2O_3 \cdot H_2O$), *nontronite* ($[Fe, Al]_2O_3 \cdot 3SiO_2 \cdot nH_2O$), *ferruginous opal* ($[SiO_2+Fe_2O_3] \cdot nH_2O$) and *siderite* ($FeCO_3$). The proportion of iron content ascribed to each is indicated in Table 6 (back-calculated from the data in Table 7), and these calculated iron values are compared with the analytically determined values from Table 5.

4.4 Physical Characteristics

Properties of the Clear Hills iron ore are dependent on the degree of oxidation of the ore. Unweathered, completely unoxidized ore is dark green to black in color, moderately hard, compact and brittle. The rock is uniformly hard within

Table 6. Mineral Composition of Clear Hills Iron Ore from Swift Creek Sampling Pit (from Petruk, 1977; Petruk *et al.*, 1977)

	Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6	
Mineral	Wt % in ore	% Fe	Wt % in ore	% Fe	Wt % in ore	% Fe	Wt % in ore	% Fe	Wt % in ore	% Fe	Wt % in ore	% Fe
Goethite	30	15.0	33	16.2	32	16.0	27	13.5	27	13.5	13	6.4
Nontronite	42	16.4	38	14.8	32	12.6	37	14.4	29	11.3	38	14.8
Ferruginous Opal	8	1.9	10	2.4	15	3.6	16	3.8	15	3.6	21	5.0
Siderite	8	3.7	8	3.7	7	3.2	6	2.8	10	4.6	12	5.6
Quartz	6	-	5	-	8	-	8	-	13	-	10	-
Phosphate (est.)	3	0.2	3	0.2	3	0.2	3	0.2	3	0.2	3	0.2
Illite (est.)	3	0.9	3	0.9	3	0.9	3	0.9	3	0.9	3	0.9
Total Fe (Analytical Fe)*		38.1 (38.5)		38.2 (37.7)		36.5 (36.7)		35.6 (35.8)		34.1 (34.9)		32.9 (32.6)
Ooliths	78		78		68		68		63		58	

*From Table 5

Table-7. Partial Chemical Compositions of Minerals in Clear Hills Iron Ore, from Microprobe Analyses (from Petruk, *et al.*, 1977).

Constituent	Goethite	Nontronite	Ferruginous Opal	Siderite	Phosphate	Illite
Fe	49.9	39.0	23.9	46.3	7.8	25.5
SiO_2	6.0	20.0	35.3	0.0	8.1	34.8
Al_2O_3	4.6	5.4	5.3	0.0	3.0	10.1
CaO	0.4	0.2	2.1	0.9	42.9	1.9
P_2O_5	1.6	0.9	0.0	0.0	29.2	0.0
K_2O	0.3	-	-	0.0	1.0	0.5
H_2O^+	14.1*	3.5*	6.9*	-	-	-
H_2O^-	-	15.8*	10.0*	-	-	-

*From chemical analysis

its textural framework and tends to break across the ooliths rather than around them, giving a subconchoidal aspect to the fracture surfaces. Ore of this nature could NOT be ripped with a bulldozer (Caterpillar D-8) ripping blade, although it was easily drilled with compressed air hammer rock drills at penetration rates of 30 to 45 seconds per metre. Blasting of the rock produced good uniform fragmentation with essentially no oversize.

Where the ore bed has been exposed to prolonged weathering, the material on the surface is oxidized to a reddish colored, soft and friable earthy material. The highly oxidized zone normally extends less than 1 m into the bed, below which the effects of less intense oxidation may be evident for a further 2 or 3 m. In this sub-weathering zone the rock resembles unoxidized ore, is dark green to black in color, but is less hard and dense. The rock tends to break around the ooliths, showing up the oolitic texture very clearly on broken surfaces. This seems to reflect a weakening of the matrix material, caused by the loss of absorbed water from ferruginous opal on exposure to atmospheric conditions (Petruk, 1977). The material can be ripped with bulldozer ripper, although the ripping becomes increasingly difficult downward toward the unoxidized zone (Hamilton, 1974).

The depth and intensity of oxidation is variable from place to place in the deposit. In the Worsley area the ore bed has been exposed to surficial weathering from preglacial time to the present and intense oxidation extends throughout the bed. In the Swift Creek area, where the ore bed was exposed only for a time following preglacial erosion, the ore is unoxidized except for the upper 2 or 3 m of the bed. It is now covered by thick till. Where the ore bed is overlain by bedrock (i.e., where it was not preglacially exposed) it is entirely unoxidized.

The lower part of the ore bed (lower 2 m or so) is somewhat softer than the main part, due to the higher mudstone content and the decline in the oolitic framework component. However, the effect on the rock characteristics is not noticeable.

The ore bed as a whole is massive. It lacks any well developed bedding separation planes or horizontal cleavage that would facilitate ripping. However, it is intensely fractured by a vertical joint system, which is an asset in blasting and fragmentation of the rock. Two distinct sets of joint planes are developed, one set striking at an average of 060 degrees, the other 130 degrees.

Specific gravity determinations of the unweathered ore vary from 2.5 (Edgar, 1961) to 2.82 (Krupp, 1975). Petruk, *et al.* (1977) measured specific gravities for the mineral end-members of the ore as follows: for goethite 3.8, for siderite 3.8, for nontronite 2.6 and for ferruginous opal 2.0. For an average goethite it was calculated as 3.1 and for an average oolith as 2.8.

No determinations have been made of compressive and shear strengths, or seismic velocity of the ore material.

5.0 ORE RESERVES

Assessment of reserves in the Clear Hills iron deposit has been made in four main areas or "blocks", which are outlined in Figure 2. Reserves estimates for each block are summarized in Table 8, based on results of test drilling programs carried out between 1959 and 1965 by Peace River Mining and Smelting Limited (Edgar, 1960, 1961, 1964, 1965). The four areas, corresponding to iron prospecting permit areas previously held by the company, are defined as Worsley (block A), Swift Creek (block B), Whitemud River (block C) and South Whitemud River (block D).

In blocks A and B the reserves are essentially *proven,* by 120 and 115 drill holes respectively. The reserves in blocks C and D are only roughly outlined, by 8 and 2 drill holes respectively, and are categorized therefore as *probable* and *possible.* The average grade and maximum overburden thickness for the reserves of each block are given in Table 8.

The most accessible of the four areas is block A, extending along the southern slope of the Clear Hills just 10 km north of Worsley townsite (Fig. 2). However, the block A reserves are small. Although shown as a continuous band in Figure 2, block A is actually a series of discontinuous sub-blocks, separated by erosional depressions filled with glacial deposits. Moreover, the ore bed is relatively thin here, only 3 m thick compared to about 7 m average for block B.

Block B, which partly straddles Swift (Rambling) Creek along the northeast slope of the Clear Hills (Fig. 2), is less accessible than block A and has greater overburden, but the ore bed is much thicker and areally more continuous. With proven reserves in the order of 180 million tonnes, block B is the most likely site for future mine development.

Prospects for additional large reserves exist in blocks C and D. More drilling is necessary to confirm the extent and grade of the iron-bearing bed in these areas. The need for this confirmation at the present time is questionable, however, for the proven reserves in block B are ample to sustain a major steel plant in Alberta.

Table 8. Reserves and Grades of Iron Ore, Clear Hills Iron Deposit.

Block	Reserves (Tonnes) Proven	Probable	Possible	Average Grade (% Fe)	Average Thickness (m)	Maximum Overburden Thickness (m)
Worsley (block A)	23,360,000	7,460,000	-	32.6	2.4	20
Swift Creek (block B)	182,340,000 or 144,240,000	- - -	- - -	33.9 or 35.4	6.7 or 5.3	40
Whitemud River (block C)	-	620,300,000	-	34	5.2	60
South Whitemud R. (block D)	-	-	186,000,000	34	3.4	60

Figures 7 and 8 are maps of the ore deposit in block B, giving isopachs of the ore bed and overburden respectively. The erosional edge of the ore bed and the proposed limit of stripping are indicated on both maps. Within the limits of block B the ore bed is practically flat-lying; its upper surface is at an average elevation of 780 m (2550 feet) and does not vary in elevation by more than 3 or 4 m. Thus the overburden isopachs are a direct reflection of topography.

The assessment work in block B has limited the economic ore reserves somewhat arbitrarily to that area with maximum overburden cover of 40 m (Edgar, 1961). This provides for a stripping ratio of approximately 3/1 for an average ore bed thickness of 6.7 m. However, the ore bed is continuous under overburden that thickens in the westerly direction to as much as 150 m. In very large scale mining operations, stripping costs may be reduced to allow a greater stripping ratio, thus providing a substantial increase in reserves. On the other hand, a smaller scale mining operation may be constrained to a lower stripping ratio, with corresponding decrease in reserves.

Variations in grade within the ore bed also may affect reserves. As indicated in a previous section (see Fig. 6), the iron (Fe) content in the Swift Creek ore bed increases upward, from less than 25 percent at the base to 40 percent at the top. Should an ore grade cut-off be established to reject lower grade material near the base, a substantial reduction in tonnage would result. In Table 8 it will be noted that two estimates are given for both tonnage and grade in block B. The smaller tonnage figure results from the elimination of material grading less than 30 percent Fe.

Another factor that can affect reserve estimates is the mining method to be used. In the studies carried out by Krupp (1975) it was proposed that overburden stripping be done by bucket wheel excavators. Accordingly, the shape of the area delineated for mining in block B was selected to facilitate a bucket wheel operation (see Fig. 7), but the selection of this area excludes a large portion of the ore reserves. Thus the reserves are decreased from 144 million tonnes

(Table 8) to 95 million tonnes of "economically mineable" ore. Both tonnages are for ore with average grade of 35.4 percent Fe (i.e., with the lower grade basal material rejected).

6.0 AVAILABILITY OF OTHER RAW MATERIALS

In the iron making process proposed for use on Clear Hills iron ore, the raw materials required include coal, calcium chloride, limestone, and natural gas. These materials are found in good supply in northwestern Alberta (Fig. 1), generally within economic reach of the Clear Hills region and the town of Peace River, which is the most likely location for an iron ore processing plant. Some deposits in northeastern British Columbia may in fact be better situated with respect to Peace River.

6.1 Coal

Coal is required in the iron making process as a source of carbon nuclei. It may also be required as fuel for the reactor, if natural gas is unavailable or economically less favorable as a fuel alternative. For the processing, approximately 1 tonne of coal is required for every 5 tonnes of iron ore. High grade coal is not specified; subbituminous B or C rank is indicated to be adequate.

Coal is extensive along the Foothills belt in Alberta and British Columbia (Fig. 1) and is mined at several localities. The Foothills coal is low-volatile bituminous grade, of both coking and non-coking varieties. The nearest deposits to Peace River are in the Smoky River coal field near Grande Cache, approximately 270 km southwest. McIntyre Mines Limited currently mines 1 to 2 million tonnes of coking coal annually from these deposits. The reserves in the Smoky River coal field total 360 million tonnes, 154 million of which are recoverable by open pit mining (ERCB, 1979b).

In British Columbia, the Sukunka - Quintette coal field, lying about 90 km southwest of Dawson Creek, has coal reserves of 325 million tonnes. Eighty-five percent of these reserves is high grade metallurgical coal and 15 percent is highly oxidized (B.C. Ministry of Mines and Petroleum, 1979). Development work is underway by British Petroleum Limited and others to bring these deposits on production in the early 1980's. Huge deposits in the Peace River coal field northwest of Sukunka-Quintette are currently being explored as well.

On the Plains of northwestern Alberta, several deposits of subbituminous grade coal are known. The largest deposits are in the Fox Creek coal field near the town of Fox Creek, about 185 km south of Peace River. In this coal field an estimated 620 million tonnes of high-ash subbituminous coal are recoverable by strip mining methods (ERCB, 1979b). The South Swan Hills coal field, lying 80 km east of Fox Creek, contains an estimated 290 million tonnes of strippable coal reserves. Neither of these coal fields has been developed to date.

Locally in the Clear Hills area, some thin coal seams have been observed in the Wapiti Formation which caps the upper part of the hills (Fig. 3). The coal is lignitic or subbituminous in grade, but the extent and mineability of the seams are undetermined.

6.2 Calcium Chloride

Chloride is used as a catalyst in the iron making process and is preferred in the form of calcium chloride. The requirement is about 35 kg chloride per tonne of iron ore, but the chloride is not consumed in the process and the makeup requirement is only about 2 kg per tonne.

Calcium chloride occurs in northwestern Alberta as calcium-enriched formation brines in several of the subsurface Devonian reservoirs (Hitchon and Holter, 1971). In the Peace River region the enriched brine zones in most reservoirs have calcium concentrations of about 20,000 mg/l, which is probably too low for commercial extraction of calcium chloride. Even the highest concentrations found in this region, 30,000 to 40,000 mg/l (in the Granite Wash formation waters), may be too low. However, bordering on the eastern fringe of the region, east of Lesser Slave Lake, is a major brine field in the Keg River Formation which has calcium concentrations of more than 60,000 mg/l. This concentration is similar to that of brines commercially exploited for calcium chloride elsewhere, and it gives the brine field east of Lesser Slave Lake the best potential for calcium chloride extraction in northern Alberta.

Even so, with a calcium chloride market in iron making of less than 3,000 tonnes annually, its development is doubtful. Unless other markets open up, it would be more economical to purchase calcium chloride from outside the region.

6.3 Limestone

The limestone requirements in iron ore processing are low, only 10 to 20 tonnes per day. The nearest source of limestone to the Peace River region is in the Rocky Mountains southwest of Grande Cache, about 300 km in distance (Macdonald and Hamilton, 1979). However, these deposits are undeveloped and would require markets for large-scale production (i.e., 100,000 tonnes or more per year) to warrant quarry development.

High quality limestone is presently mined at several localities farther southeast: at Cadomin 260 km southwest of Edmonton, at Exshaw west of Calgary, and near Crowsnest Lake in southwestern Alberta. It may be most economical to haul the limestone from one of these sources, or from deposits in British Columbia. One deposit near McLeod Lake, 270 km southwest of Dawson Creek, is presently being explored for development.

6.4 Natural Gas

Natural gas is used in the iron making process essentially as fuel. Although coal is a possible alternative, the fuel requirements are large and would seem to be most easily and economically met by natural gas, which is the most widely developed energy resource to date in northwestern Alberta. Fuel requirements are expressed as approximately 4.3×10^6 Btu per tonne of iron ore, or about 120 m^3 of natural gas per tonne.

A large number of gas fields are developed in the Peace River region. Those of moderate to large size in the vicinity of Peace River are outlined on Figure 1, with the established reserves given for each. Total reserves for the region (including many fields not shown on Fig. 1) exceed 150,000 million m^3.

The recently discovered Elmworth gas field 185 km southwest of Peace River is the largest in the region, with established reserves of 33,000 million m^3 (ERCB, 1979a).

7.0 RECOMMENDATIONS

Further work pertaining to geology and ore reserves of the Clear Hills iron formation is recommended in two phases. If the present study is considered Phase I, an extension of the present study is recommended as Phase II, based also on existing data. Phase III entails acquisition of new data, by test drilling and coring.

In addition to the iron studies, it is recommended that evaluation of coal deposits in the Clear Hills area be undertaken.

7.1 Phase II

As stated in the Introduction, no comprehensive geological study of the Clear Hills iron formation has been made, even though a considerable mass of data has been generated from exploration of the deposit. The present study is essentially a bibliographic review, summarizing the state of geological knowledge accrued from numerous works of limited scope and extent. The proposed Phase II study involves a complete reworking of the raw data, utilizing the full data base in a regional geological synthesis.

The study, taking 5 to 6 months to complete, would provide a better indication of ore reserves, grade variations, and mineability. It would be carried out as follows:

1. Assemble all data from iron assessment work, other published and unpublished geological reports, wildcat oil well drilling, coal test drilling and water well drilling in the Clear Hills region.
2. Synthesize these data for an interpretation of regional ore body geometry and depositional controls, and for detailed (1:50,000 scale) mapping of the distribution, thickness, ore grade and overburden conditions of the deposit throughout its mineable limits.

3. Refine estimates of probable and possible reserves in blocks C and D.
4. Locate optimum test drilling sites to permit more precise ore body definition and also to provide representative cores for future petrologic and facies studies.

7.2 Phase III

Advanced studies are recommended on ore petrology and facies distribution, toward a thorough understanding of the depositional and diagenetic history of the iron formation. These studies would be based essentially on core data and would entail a fairly extensive test drilling and coring program. Accordingly, they are scheduled for the "Pilot Plant Phase", at the stage where predevelopment drilling would be required in any case for precise ore body definition.

The studies would involve the following elements:

1. Execute a test drilling and coring program designed on the basis of Phase II study results, and incorporate the test hole data into ore body definitions for development of a mine plan.
2. Undertake detailed petrographic study of the core material based on thin-section and SEM analysis. This study should be addressed to precise mineralogical determinations, diagenetic alterations, oxidation effects, and quantitative variations in the ooliths, "pebbles" and iron minerals laterally and vertically in the ore body.
3. Make a complete facies analysis of the iron formation, utilizing petrographic data derived from cores, outcrop and ore sample excavation material, plus lithologic descriptions from previous test drilling.

The petrographic study outlined above is essential for better mineralogical characterization of the ore, as an aid in understanding the grain enlargment process, why it works, and how it may be made to work better. In conjunction with the facies study, it could also yield significant scientific data on the origin and diagenesis of oolitic iron formations. The facies analysis study will provide a depositional model which can be used to predict ore grade and thickness away from the control points and in different segments of the ore body.

7.3 Coal Evaluation

Coal of undetermined extent is known to be present in the Clear Hills, generally within 15 km of the Swift Creek (block B) iron deposit. Inasmuch as coal is a major raw material of the iron making process, an evaluation of the development potential of Clear Hills coal is important to further iron ore studies.

Some coal drilling data already exists for the area. It is recommended that these data be reviewed and a preliminary assessment of reserves and mineability be made in conjunction with the Phase II iron study. If further exploration appears warranted, a drilling program should be set up to fully evaluate the coal potential. This program should be planned and carried out in conjunction with the iron test drilling in Phase III.

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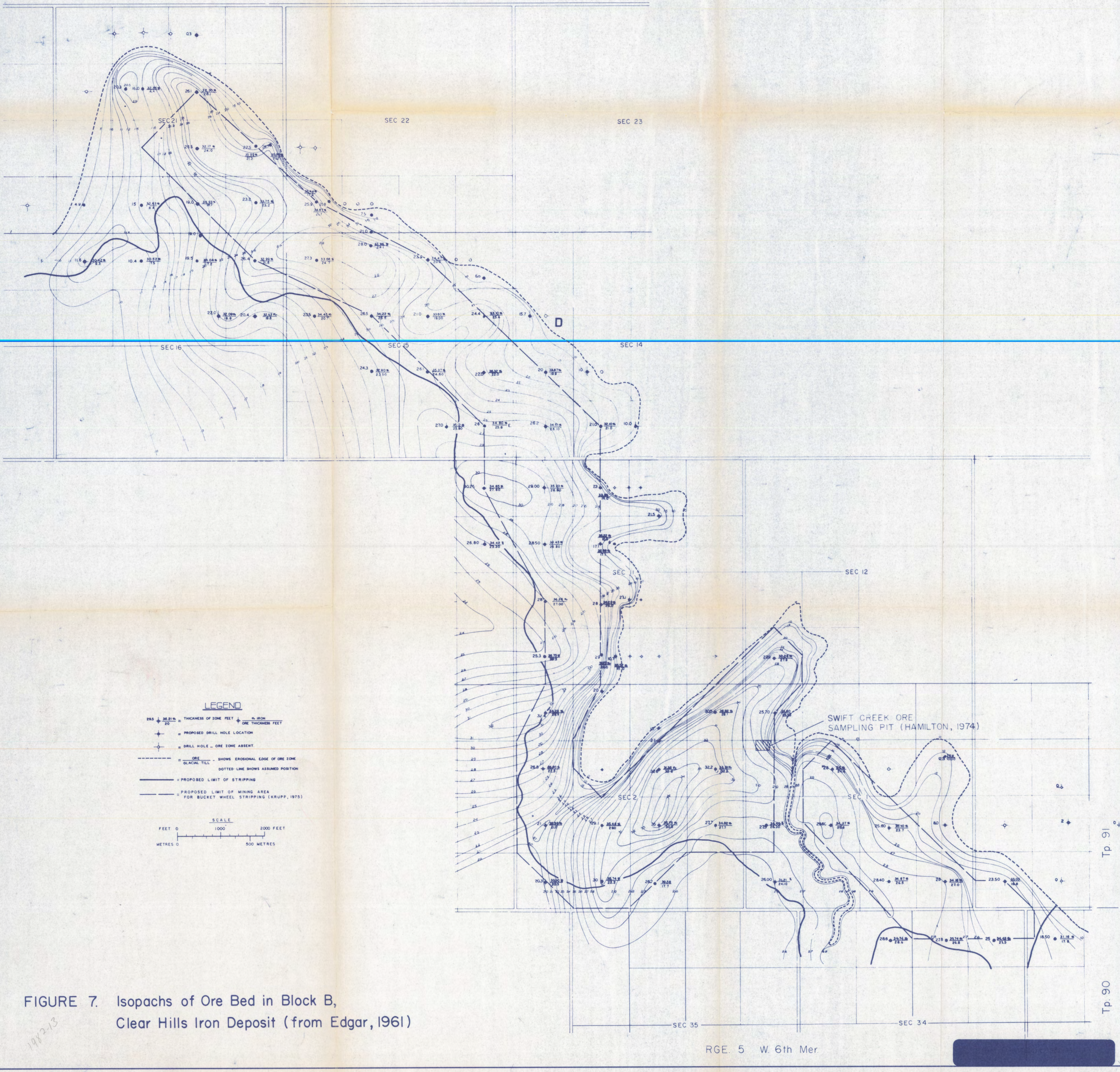

FIGURE 7. Isopachs of Ore Bed in Block B, Clear Hills Iron Deposit (from Edgar, 1961)

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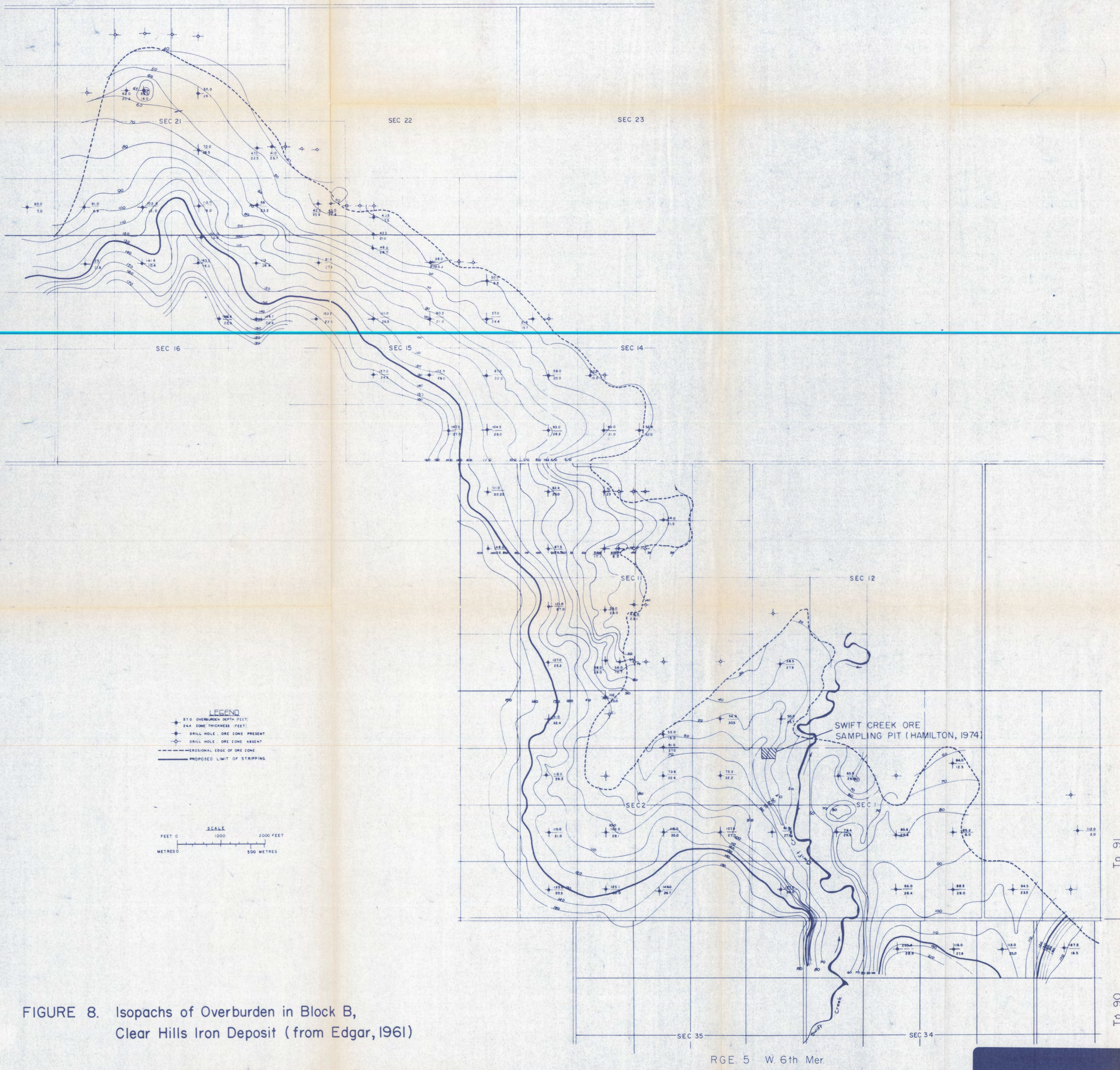

FIGURE 8. Isopachs of Overburden in Block B,
Clear Hills Iron Deposit (from Edgar, 1961)

[redacted]