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REGIONAL ANALYSIS OF THE ARDLEY COAL ZONE, ALBERTA, CANADA, FOR COALBED METHANE PRODUCTION AND CO_2 SEQUESTRATION

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Abstract

This study evaluated the geological characteristics of the late Cretaceous to early Tertiary Ardley Coal Zone, over a 300 by 300 kilometre area underlying the Alberta Plains, for its potential for coalbed methane production and as a reservoir for CO_2 sequestration. Penetrations of the Ardley Coal Zone in a total of 1,362 wells spaced at seven to fifteen kilometres formed the basis of this study. Parameters including zone depth, elevation, aggregate coal thickness, total zone thickness, in situ methane gas content, CO_2 storage capacity and distance from point sources of CO_2 were used to quantify in situ coalbed methane resources and CO_2 storage capacity, and to delineate areas of high potential for more detailed assessment to site exploration drill holes.

This study indicates that the Ardley Coal Zone offers considerable potential as an exploration target for coalbed methane production and as a potential reservoir for CO_2 sequestration. It is the shallowest and thickest of the eight major coal zones underlying the Alberta Plains and, by analogy to coals of similar maturity in the Powder River Basin of Wyoming, should contain substantial amounts of biogenic and lesser amounts of thermogenic methane gas. Total in situ methane resources determined in this study are 74 trillion cubic feet, of which perhaps twenty per cent may ultimately be recoverable, and total in situ CO_2 storage capacity is greater than 16,000 megatonnes. Areas with the highest potential are relatively restricted geographically, however, and considerable additional geological evaluation will be required to map reservoir characteristics including coalbed geometry and permeability needed to select optimal completion intervals and drilling locations. The best portions of the Ardley Coal Zone offer aggregate reservoir thicknesses of greater than 20 metres, in situ methane gas concentrations of greater than nine billion cubic feet per section, and CO_2 storage capacities of greater than 500 million cubic metres per square kilometre or one megatonne per square kilometre. The Ardley Coal Zone lies adjacent to many potential point sources of CO_2 and can be accessed at relatively low cost because of its shallow depth. Two high potential areas have been identified by this study for more detailed geological evaluation.

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Introduction

The late Cretaceous to early Tertiary strata of the Scollard Formation of central and western Alberta contain thick coal seams, collectively termed the Ardley Coal Zone, which are reservoirs of methane gas and may be suitable for the sequestration of CO_2. An industry consortium led by the Alberta Research Council is investigating the feasibility of utilizing these coal seams for disposal of CO_2 and enhancing the production of methane gas (Gunter et al, 1997). This study comprises a regional geological evaluation of the stratigraphy, thickness, geometry, maturity, potential methane gas distribution, potential CO_2 storage capacity, drilling costs and the location of point sources of CO_2 in order to identify the coalbed methane production and CO_2 disposal potential and then the most favourable areas for more detailed geological study of the Ardley Coal Zone which are required to optimize the selection of potential drilling targets for CO_2 injection and methane production.

The study area lies within a 30 by 30 Township area (300 by 300 km) bounded on the west by the eastern edge of the Rocky Mountain Foothills and on the east by the subcrop of the Ardley Coal Zone. The study area is bounded on the north and south by Townships 60 and 30 respectively (Figure 1), which define the north and south depostional limits, respectively, of the Ardley Coal Zone. Two areas of high potential were delineated from this regional evaluation which will require more detailed assessment of reservoir geometry, CO_2 storage capacity and permeability indicators in order to select optimal drill sites for CO_2 sequestration and methane gas production.

Funding for this study was provided by the Federal Panel on Energy Research and Development (PERD) via Environment Canada, as well as directly by the Alberta Geological Survey and the Geological Survey of Canada - Calgary.

Data Sources, Interpretation and Computer Modeling

Drilling information used in the study came from two principal sources. These comprised existing information from previously interpreted wells penetrating the Ardley Coal Zone in the zero to 400 metres depth range contained in the Geological Survey of Canada's National Coal Inventory (818 wells), and new information collected specifically for this study in the deeper parts of the area (544 wells total). New wells were selected from the more than 50,000 wells available based on available log suites (density, natural gamma and induction logs were mandatory), casing depth (wells with the shallowest casing were selected) and a minimum separation of seven kilometres. Although more than 700 new wells were initially selected many had to be discarded on subsequent examination as these wells were cased over all or a portion of the Ardley Coal Zone. Information on the maturity of the coals as determined by vitrinite reflectance measurements on coal cuttings was obtained from the Alberta Geological Survey archives (31 samples), from the data files of the Canadian Coalbed Methane Forum (12 samples) and from cuttings collected from eleven new locations (54 locations total). Gas content data were obtained from the Canadian Coalbed Methane Forum and CO_2 storage

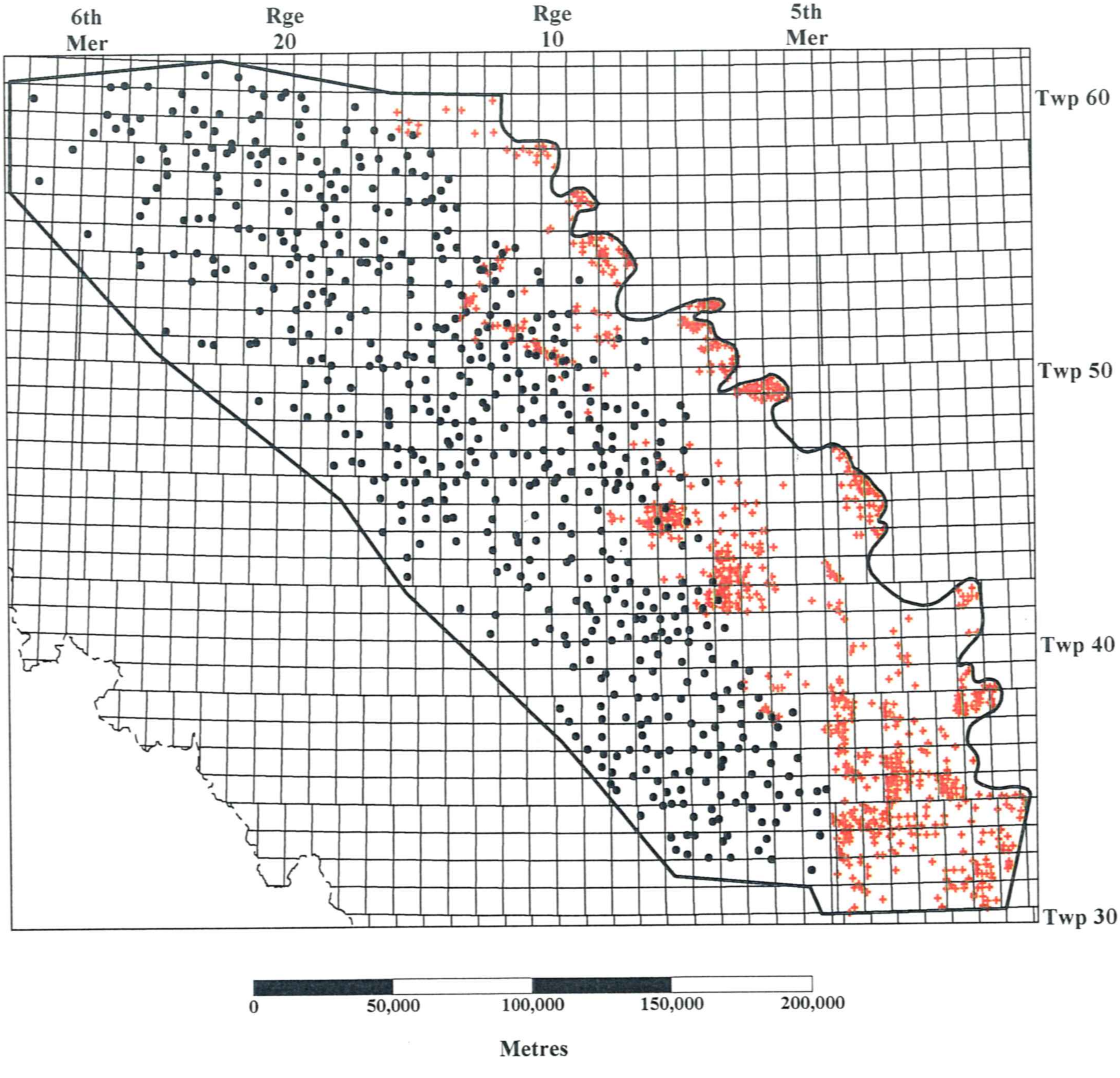

Figure 1 - Borehole data used for the study of the Ardley Coal Zone. Black dots indicate oil wells interpreted specifically for this study (544 wells total) whereas red crosses indicate oil and conventional coal exploration wells contributed by the Geological Survey of Canada from its National Coal Inventory (818 wells total). A total of 1362 wells were used for this study. The study area as outlined above is limited on the west by the edge of the disturbed belt and on the east by the subcrop of the Ardley Coal Zone.

capacity isotherms were obtained from analyses of Ardley coals performed at the University of British Columbia (Bustin, 1998).

Log interpretation protocols utilized techniques documented in Hughes (1984). Coal seam boundaries and thicknesses were primarily interpreted utilized the density log with corroboration from the natural gamma and induction logs and reference to the caliper log to ensure absence of caving. A primary database of the depths of individual coal seam tops and bottoms, well ids and kelly bushing elevations was developed and preliminary validation was conducted utilizing double data entry and computer checks. Software developed by Hughes (1996) was then utilized to compute a variety of other statistics from this primary database for each well. These statistics include zone top and bottom depth, zone top and bottom elevation, overall zone thickness, aggregate coal thickness, per cent of coal in overall interval and number of individual coal beds. Similar statistics were computed for data from the National Coal Inventory and the two datasets were integrated for mapping. The final level of data validation was conducted by mapping all statistical parameters and examining and correcting apparent anomalies identified from this process. This resulted in the elimination of more than 100 wells primarily due to the presence of casing over part of the coal-bearing interval. The final database incorporated 1362 wells from both sources.

Distribution, thickness, geometry and maturity of the Ardley Coal Zone

The Ardley Coal Zone typically comprises many individual coal beds distributed over a stratigraphic interval of up to 260 metres thick. In the western and northwestern part of the study area the coal zone contains up to 38 individual coal beds (Figure 2) distributed over a 150 to 260 metre interval (Figure 3), whereas in the southeastern part of the study area the coal zone consists of less than five coal beds over an interval of less than 20 metres thick. The coal zone contains more than 20 metres of aggregate coal thickness where it is best developed in the west-central and northwestern part of the study area (Figure 4). Figure 5 indicates the percentage of coal within the overall coal zone interval.

The Ardley Coal Zone dips southwest from its subcrop, where four major coal mines produce feedstock for much of Alberta's electrical power generation capacity, to depths of more than a kilometre along the western edge of the study area. Figures 6 and 7 indicate the depths to the top and base of the coal zone, respectively, and figures 8 and 9 indicate the top and bottom elevations of the coal zone, respectively, relative to sea level.

The maturity level of the coal is a function of the temperatures to which the coal has been exposed during burial as well as the duration of exposure to those temperatures, and determines the chemical processes, including methane gas generation, that have occurred. Maturity information for this study has been determined by vitrinite reflectance measurement ($R_o$max%) on cuttings obtained from 54 boreholes. Reflectance ranges from 0.45% in the shallowest to 0.8% in the deepest parts of the study area (Figure 10), corresponding to an ASTM rank classification ranging from subbituminous B to high volatile bituminous A. Above a reflectance level of 0.65%, the gas content of saturated coals increases with increasing reflectance according to an empirical relationship described by Ryan (1992), indicating gas has

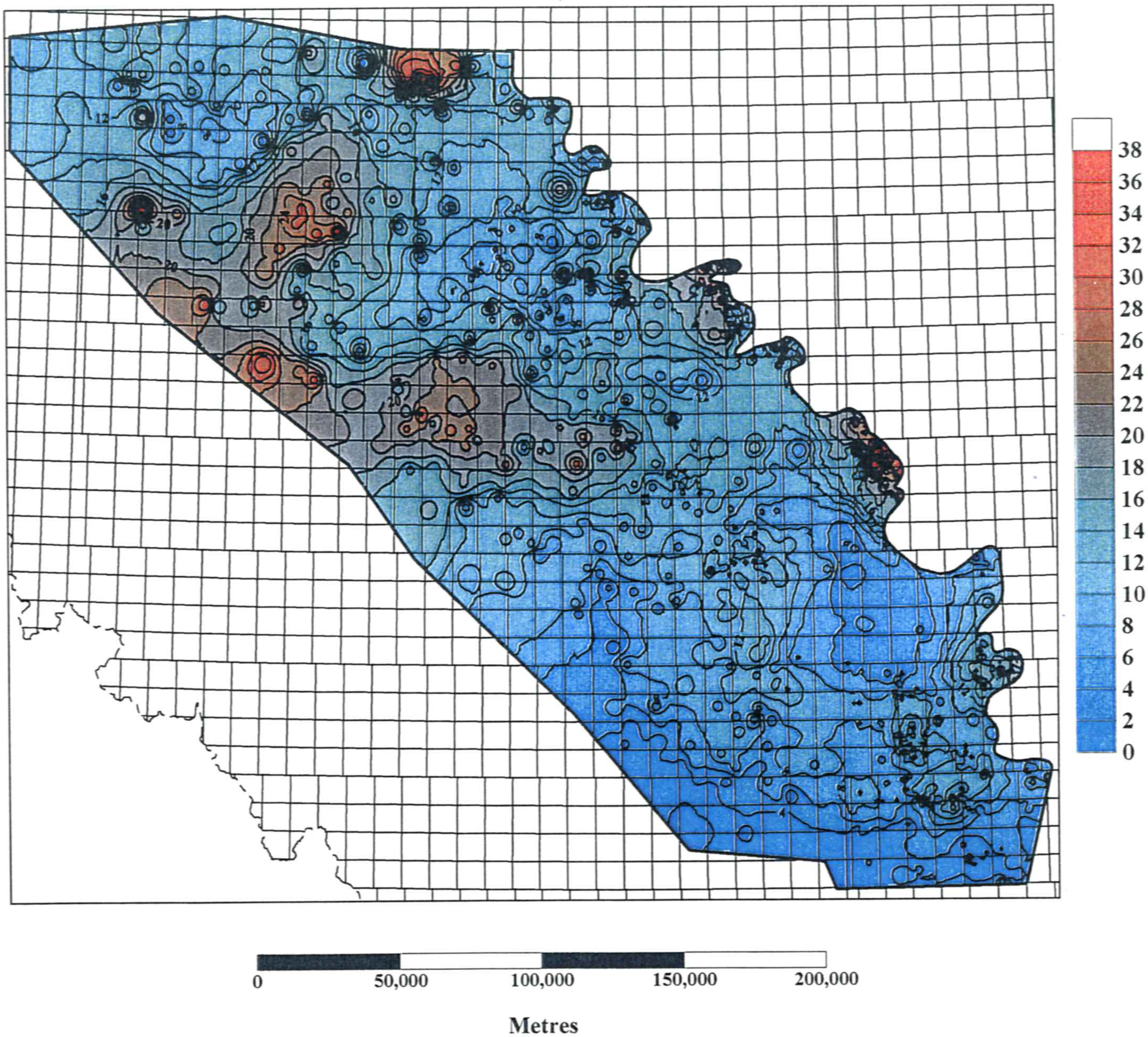

Figure 2 - Number of individual coal beds within the Ardley Coal Zone.

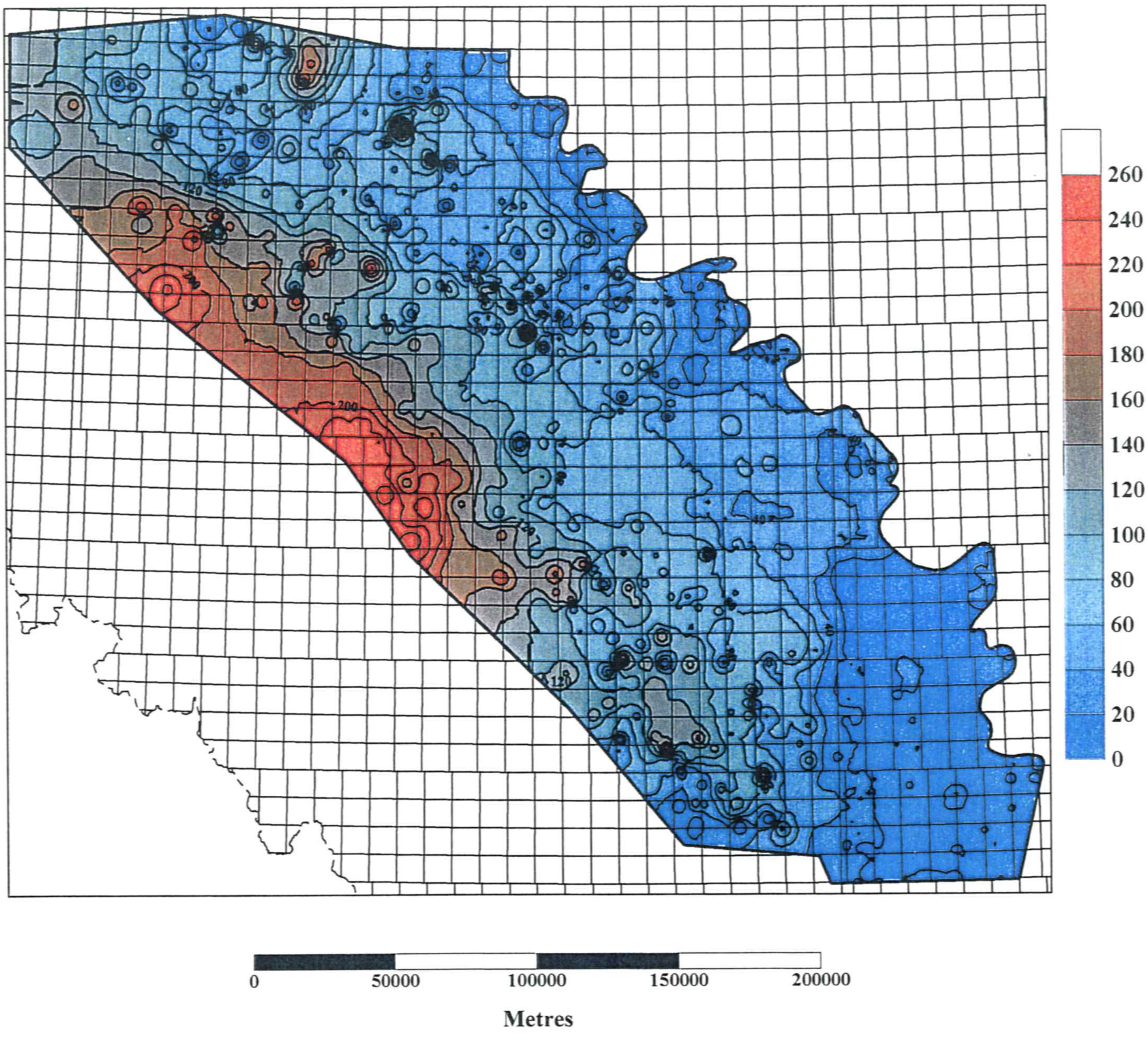

Figure 3 - Overall thickness of the Ardley Coal Zone from the top of the uppermost coal bed to the base of the lowermost coal bed (in metres).

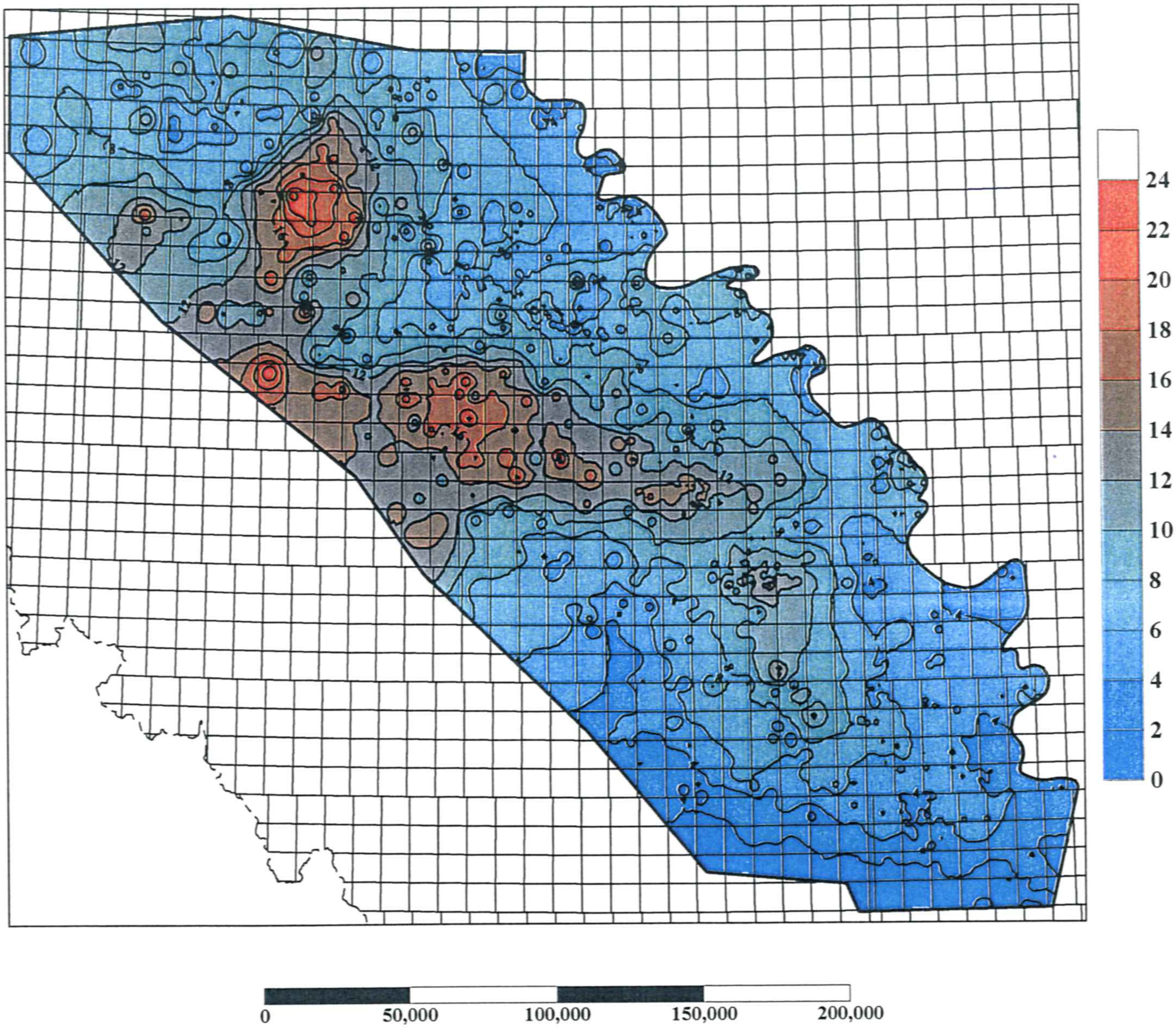

Figure 4 - Aggregate coal thickness in the Ardley Coal Zone (in metres).

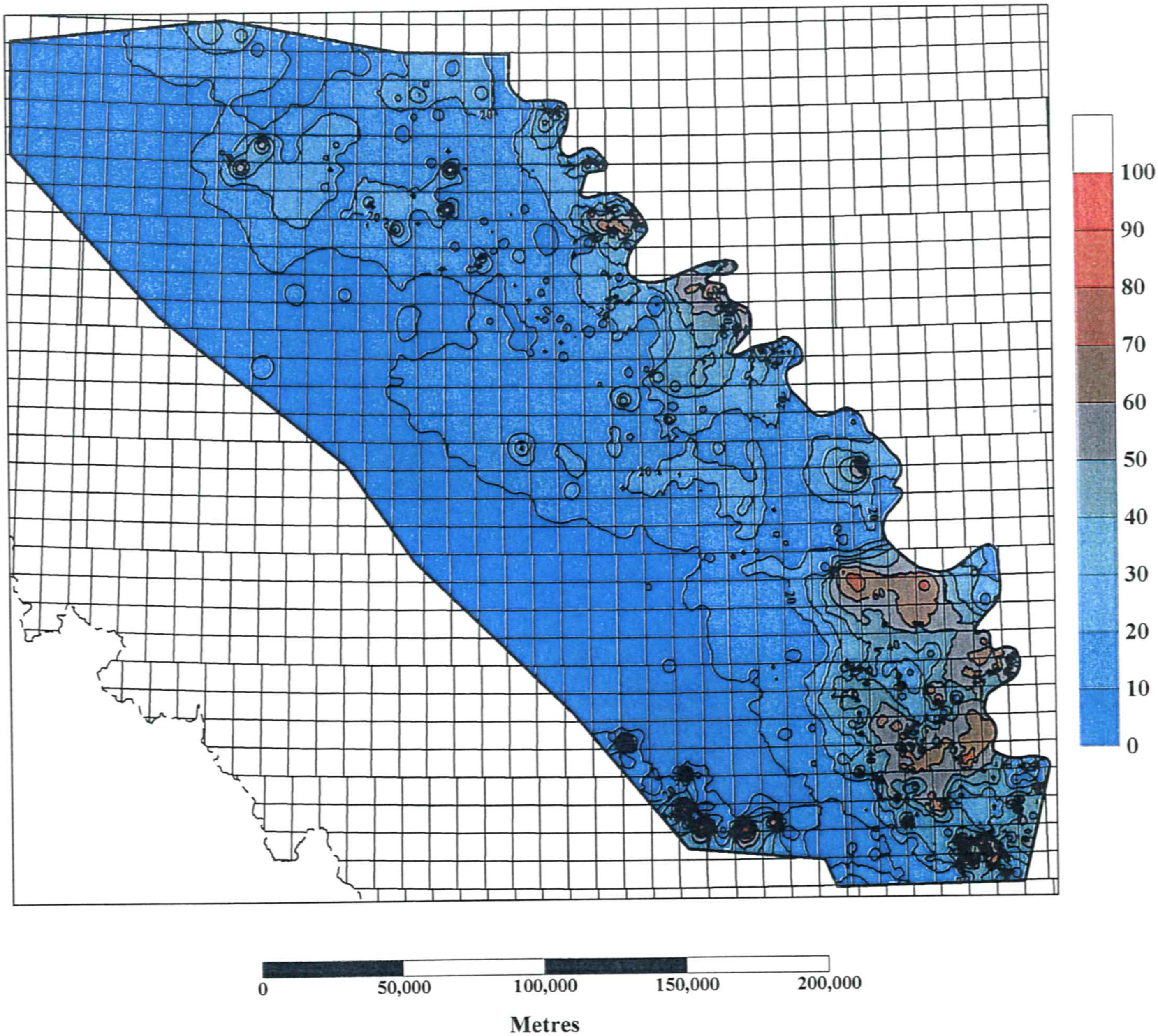

Figure 5 - Percentage of coal within the overall thickness of the Ardley Coal Zone.

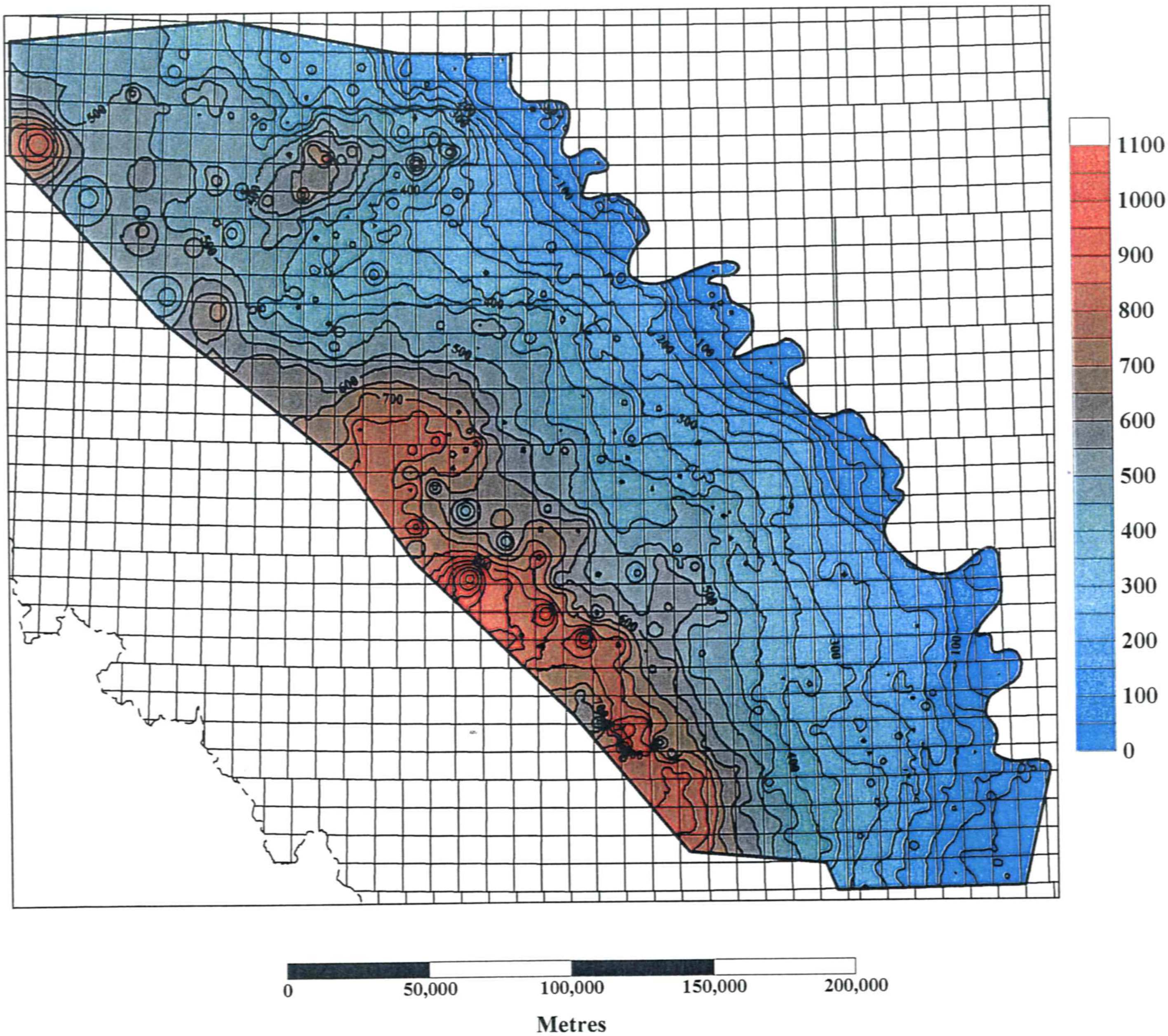

Figure 6 - Depth to the top of the uppermost coal bed in the Ardley Coal Zone (in metres).

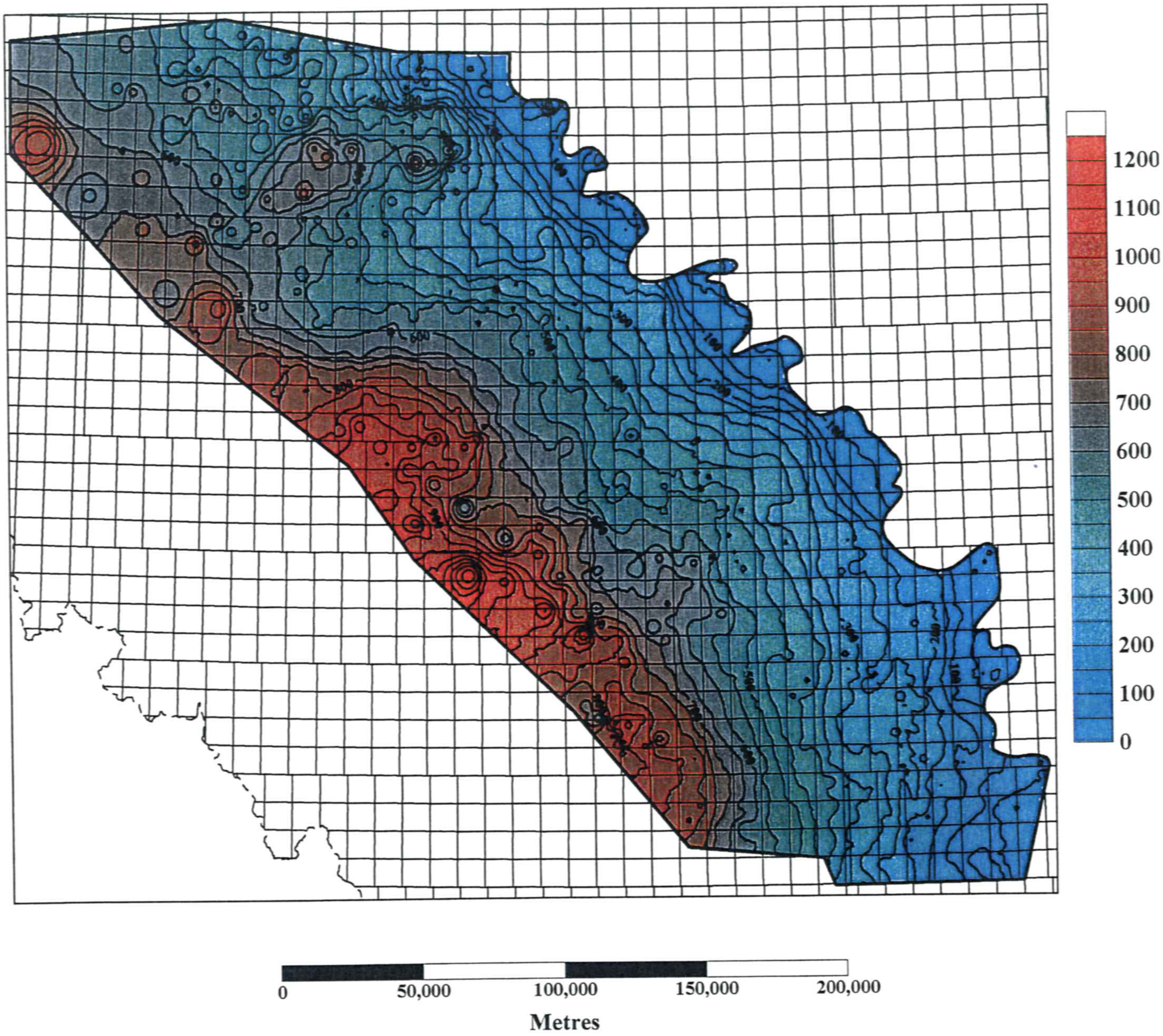

Figure 7 - Depth to the base of the lowermost coal bed in the Ardley Coal Zone (in metres).

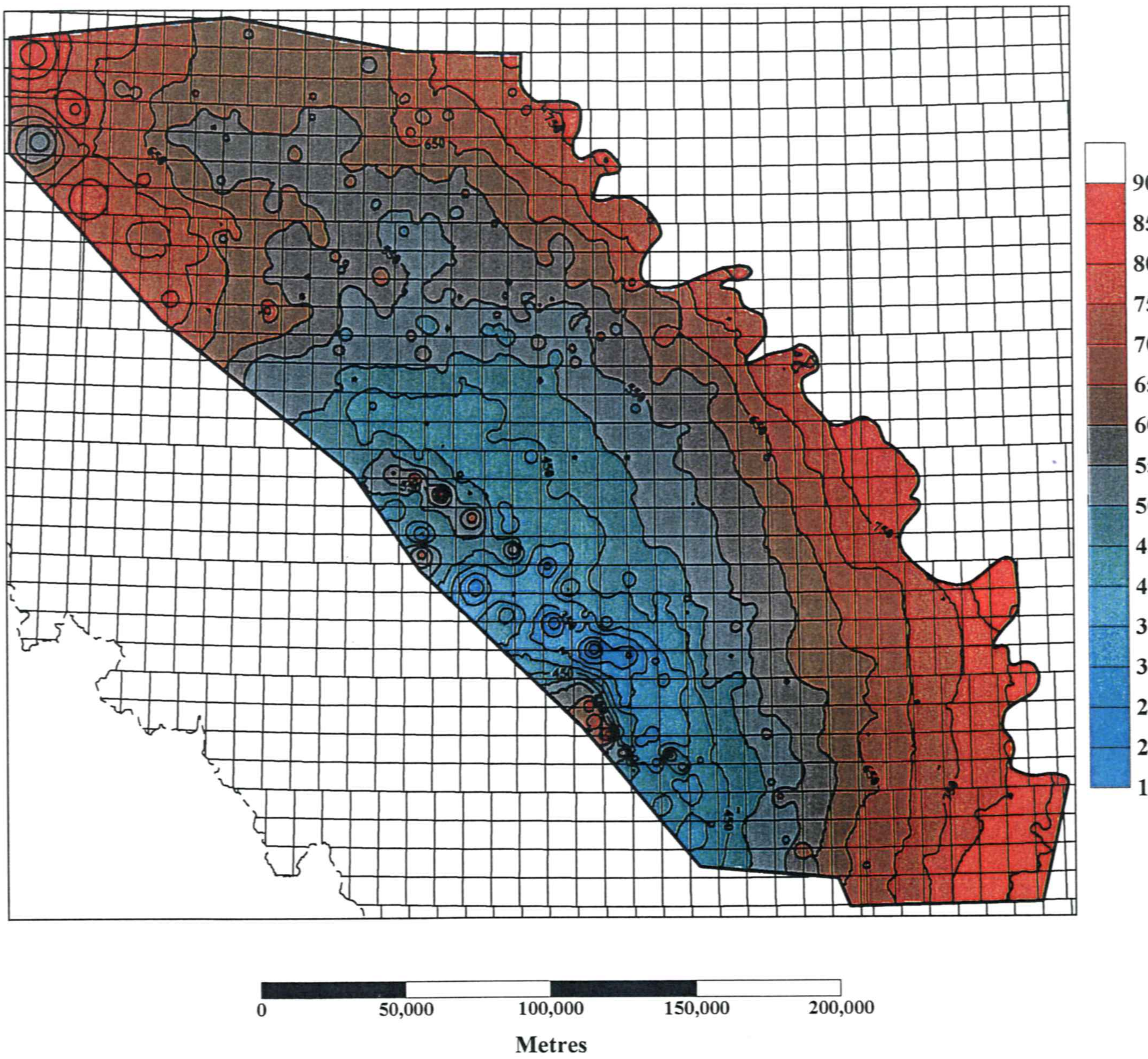

Figure 8 - Elevation of the top of the uppermost coal bed in the Ardley Coal Zone relative to sea level (in metres).

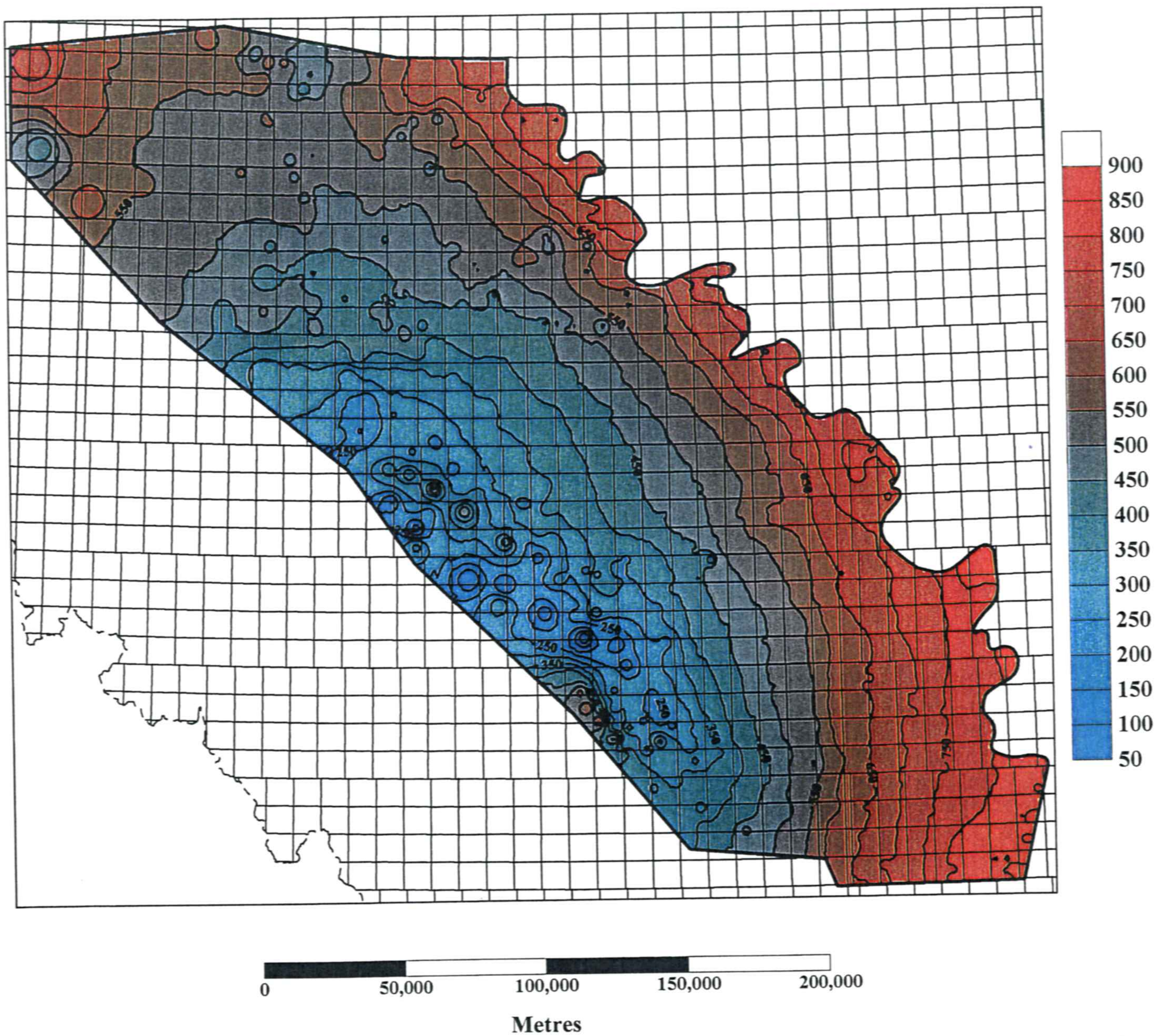

Figure 9 - Elevation of the base of the lowermost coal bed in the Ardley Coal Zone relative to sea level (in metres).

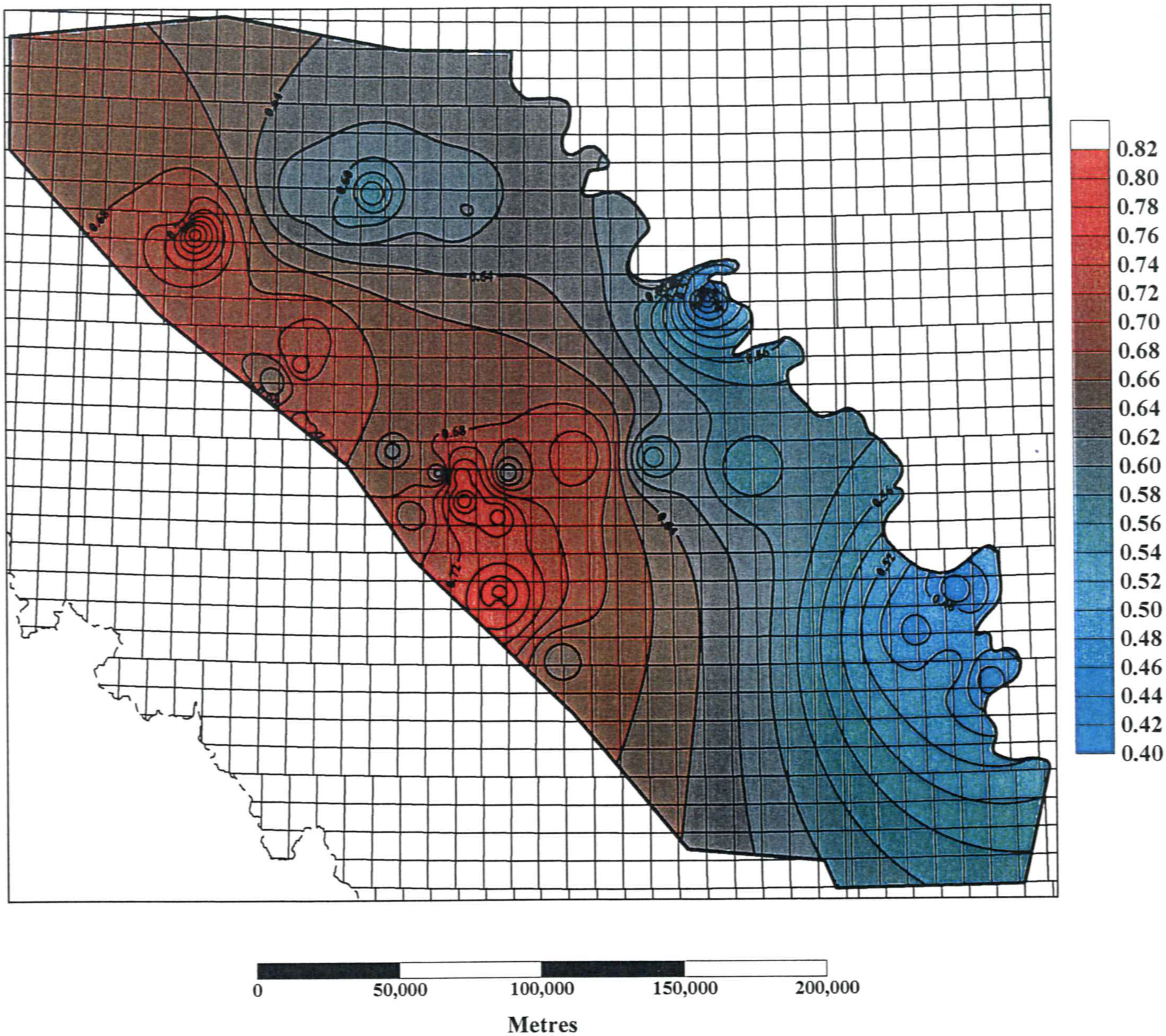

Figure 10 - Maturation level of the Ardley Coal Zone as determined by vitrinite reflectance (R_oMax%).

been generated by thermogenic processes. Below 0.65% the relationship of gas content to reflectance is less certain as much of the gas in saturated reservoirs is of biogenic origin (Figure 11). The map of theoretical in situ gas content in Figure 12 was created using the following assumptions:

- the reservoir is completely saturated with methane.

- in situ gas content in areas with a maturity of greater than 0.65% was determined using the Ryan (1992) equation assuming an ash content of 10% and moisture content of 18%, and utilized the mean reservoir depth and vitrinite reflectance.

- in situ gas content in areas with a maturity of less than 0.65% were assumed to be the mean gas content of available sample data shown in Figure 11, which is 3.4 cc/gm.

Distribution of Coalbed Methane Resources

The distribution of coalbed methane resources can be expressed as methane resource concentration, which is the product of in situ gas content, assuming 100% reservoir saturation, and reservoir thickness. Software developed by Hughes (1996) was utilized to convert coal reservoir volume to weight, to determine the in situ methane resource concentration in terms of methane volume per unit area, and to quantify resources according to reservoir depth, reservoir methane concentration and other parameters. Figure 13 illustrates the distribution of the in situ methane resource expressed as millions of cubic metres per square kilometre whereas Figure 14 illustrates the resource distribution expressed as billions of cubic feet per square mile (units conventionally used in the petroleum industry).

In situ coalbed methane resources for the entire study area quantified by depth from surface are given in Table 1 and illustrated graphically in Figure 15 (incrementally by depth) and Figure 16 (cumulatively by depth). In situ coalbed methane resources for the entire study area quantified by resource concentration are given in Table 2 and illustrated graphically in Figure 17 (incrementally by resource concentration) and Figure 18 (cumulatively by resource concentration). The total resource base is 2.1 trillion cubic metres or 74.3 trillion cubic feet, of which perhaps twenty per cent, or fifteen trillion cubic feet, may ultimately be recoverable, by analogy to coalbed methane production from coals of equivalent rank in the U.S.

Distribution of CO_2 Storage Capacity

The amount of CO_2 that coal can adsorb is a function of coal maturity, coal composition and reservoir pressure, and can be measured using CO_2 adsorption isotherms. Bustin (1998) performed several CO_2 adsorption isotherm experiments on fresh coal samples from the Ardley Coal Zone where it is exposed in the Highvale Mine west of Edmonton. Figure 19 illustrates the CO_2 adsorption isotherm from one of these samples. The average CO_2 adsorption isotherm for all measured samples was utilized to produce a map of CO_2 storage capacity utilizing the

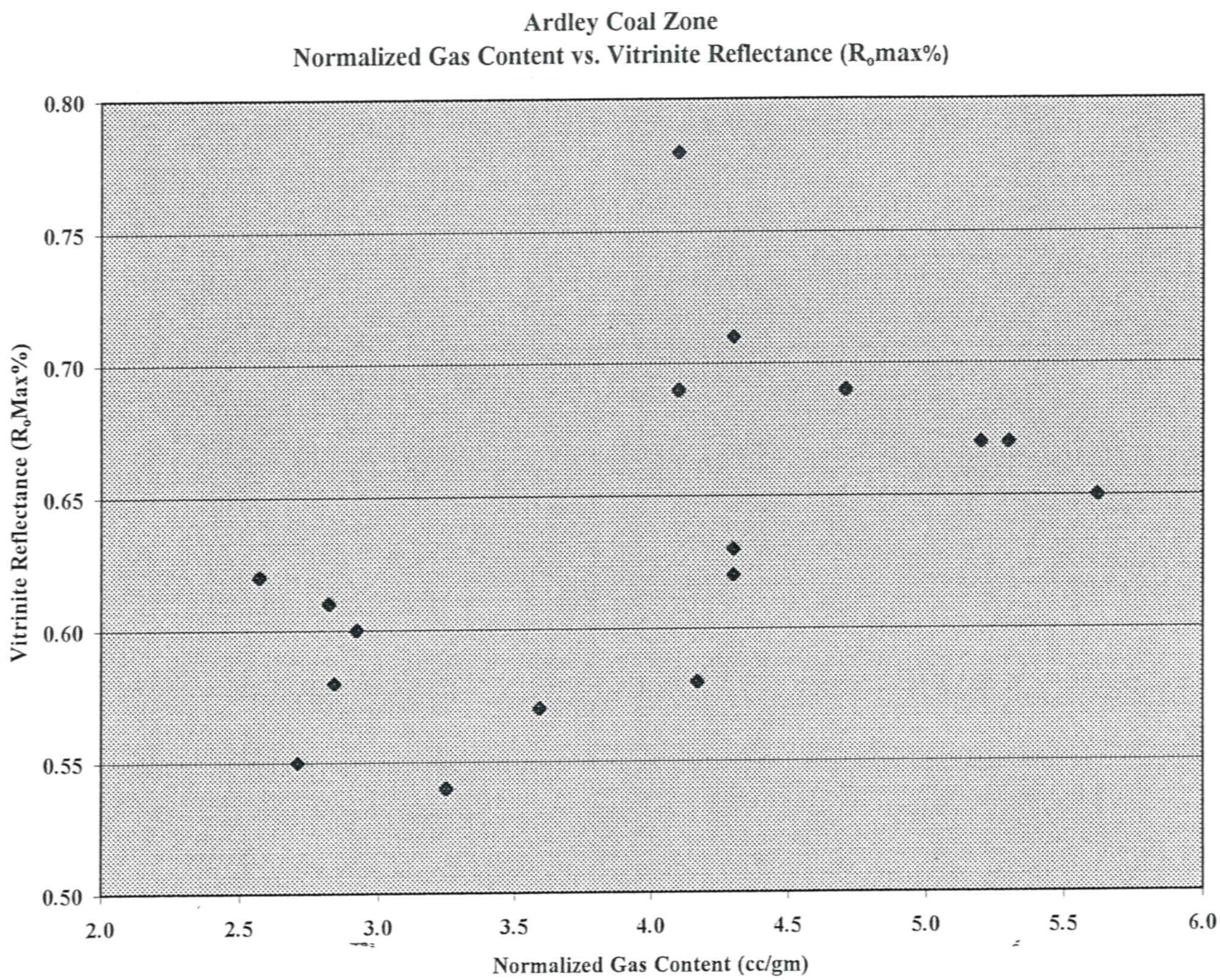

Figure 11 - Relationship between the normalized gas content (cc/gm) and vitrinite reflectance (R_oMax%) for available information from the Ardley Coal Zone.

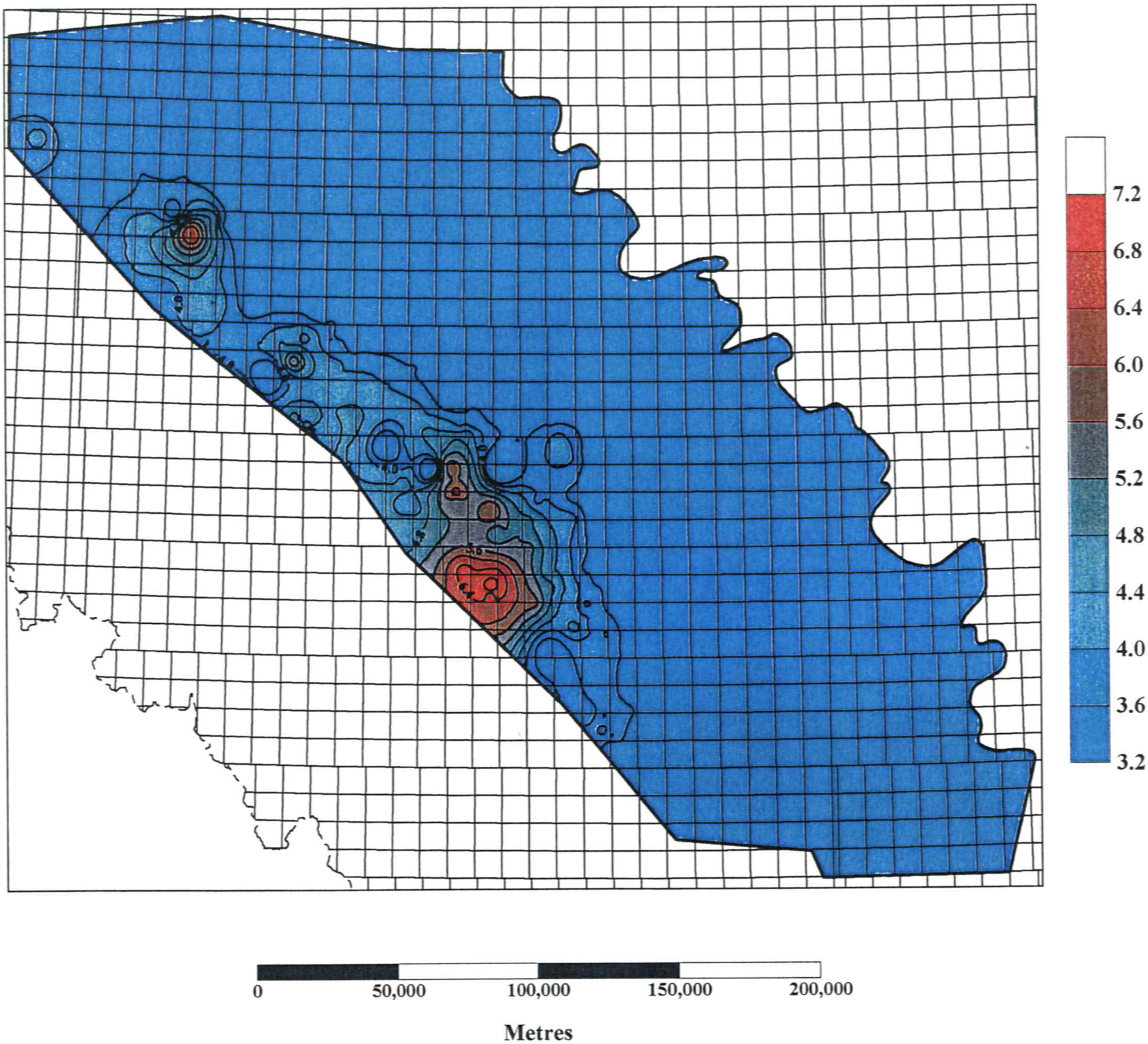

Figure 12 - Theoretical in situ gas content (cc/gm) in the Ardley Coal Zone computed from mean reservoir depth and vitrinite reflectance using the empirical relationship of Ryan (1992).

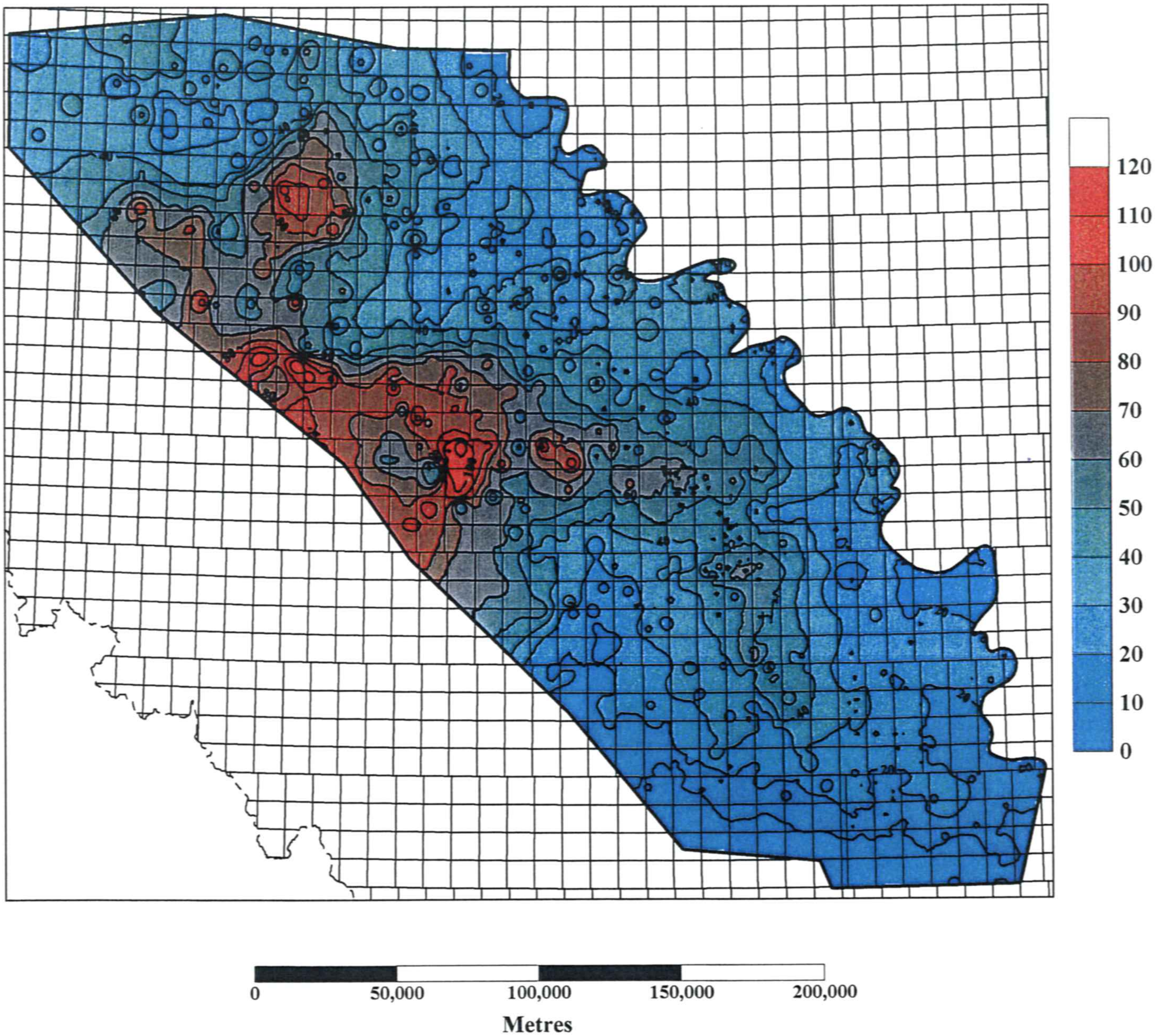

Figure 13 - In situ methane gas concentration expressed as millions of cubic metres per square kilometre. Methane gas concentration is the product of in situ gas content and aggregate reservoir thickness.

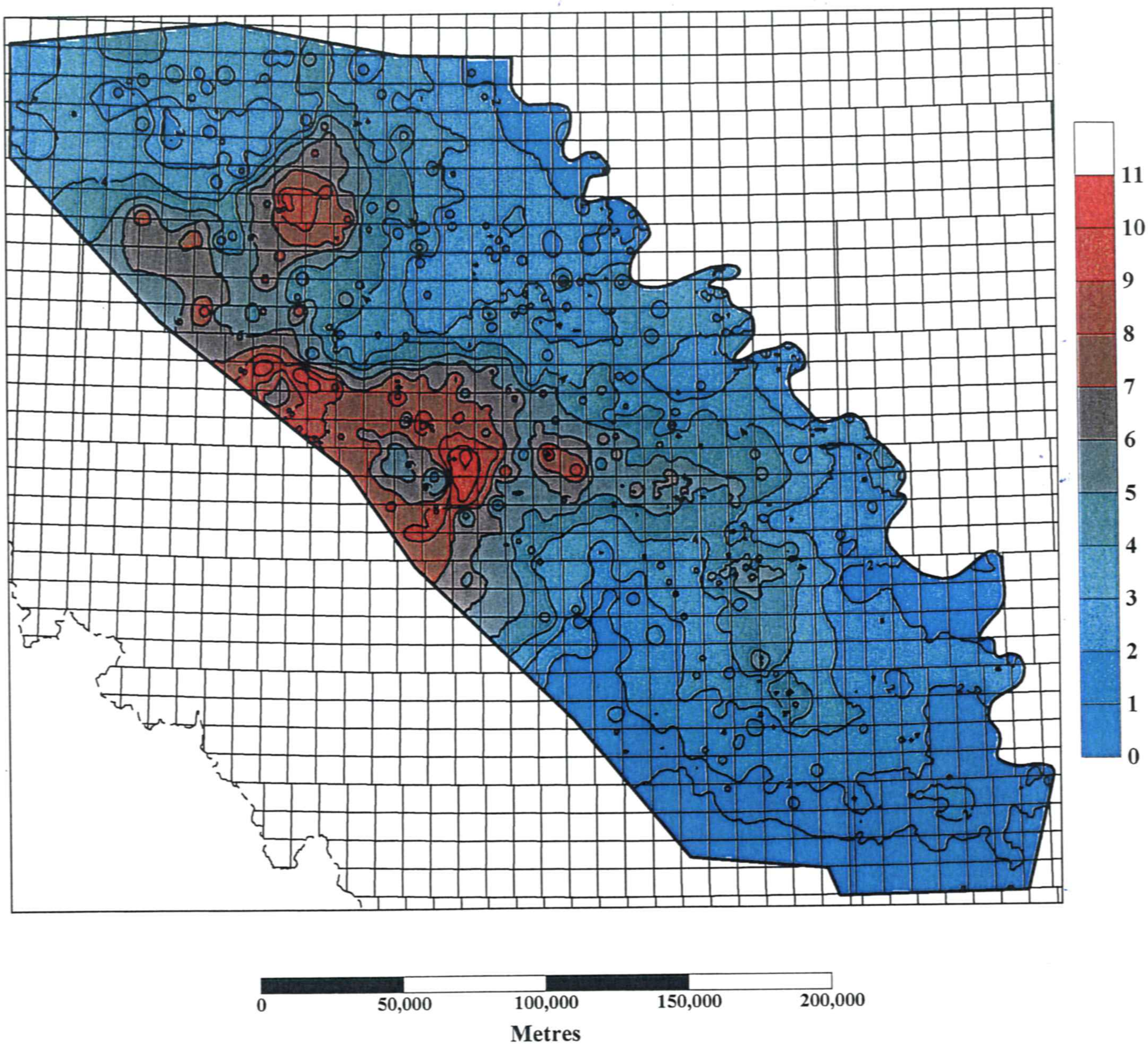

Figure 14 - In situ methane gas concentration expressed as billions of cubic feet per square mile. Methane gas concentration is the product of in situ gas content and aggregate reservoir thickness.

Mean Depth from Surface (metres)	Incremental In Situ Resources (millions of cubic metres)	Cumulative In Situ Resources (millions of cubic metres)
25	28069	28069
75	56812	84881
125	46888	131770
175	51067	182837
225	74294	257130
275	93950	351080
325	98827	449908
375	131033	580941
425	159229	740170
475	185753	925923
525	239933	1165856
575	224227	1390083
625	173983	1564067
675	129216	1693283
725	123548	1816831
775	85766	1902597
825	81655	1984252
875	73760	2058012
925	27300	2085311
975	9004	2094315
1025	4612	2098927
1075	2331	2101259
1125	1648	2102907

Table 1 - In situ methane resources versus mean reservoir depth from surface (in metres) in the Ardley Coal Zone in the study area.

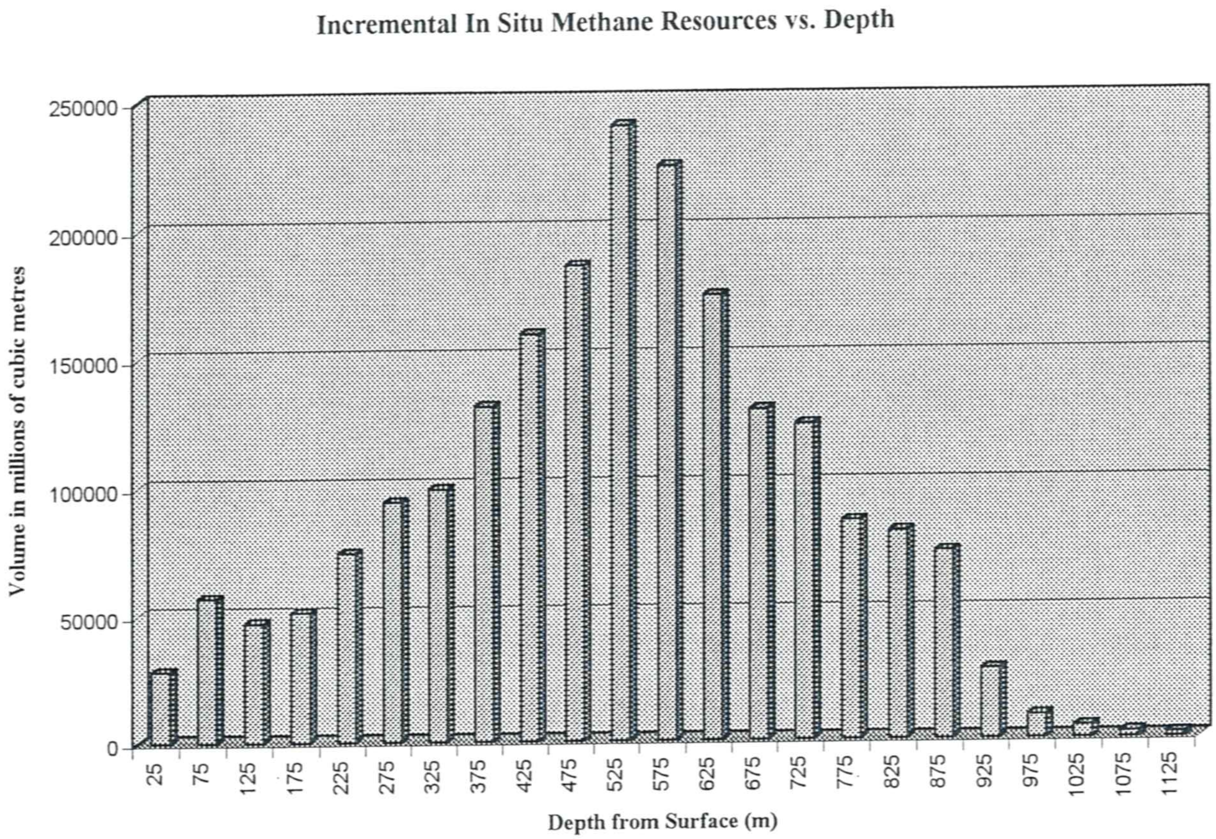

Figure 15 - In situ methane resources versus mean incremental reservoir depth from surface in the Ardley Coal Zone in the study area (in millions of cubic metres - multiply by 35.3147 to convert to trillion cubic feet).

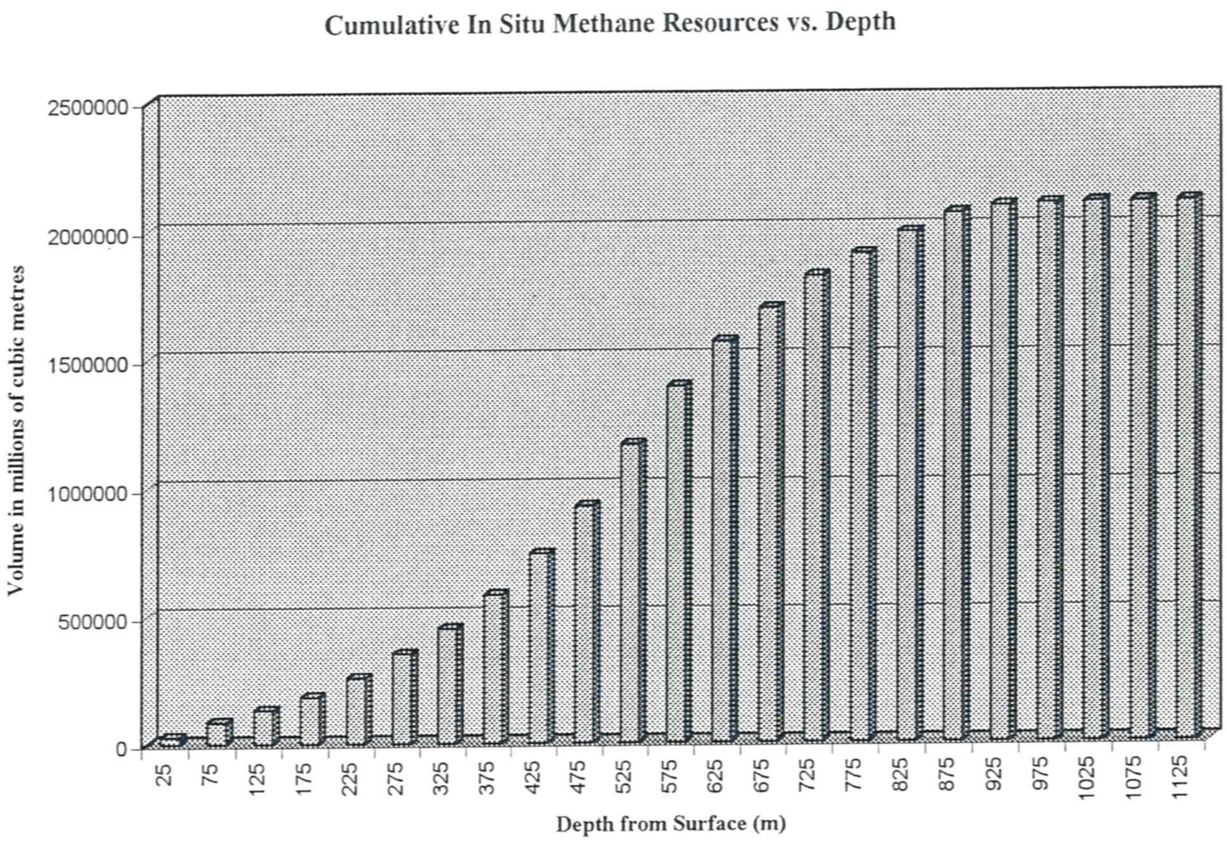

Figure 16 - In situ methane resources versus mean cumulative reservoir depth from surface in the Ardley Coal Zone in the study area (in millions of cubic metres - multiply by 35.3147 to convert to trillion cubic feet).

In Situ Methane Concentration (millions of cubic metres per square kilometre)	Incremental In Situ Resources (millions of cubic metres)	Cumulative In Situ Resources (millions of cubic metres)
2.5	58	58
7.5	17403	17461
12.5	22604	40065
17.5	56784	96848
22.5	111892	208741
27.5	157685	366426
32.5	217679	584105
37.5	215701	799806
42.5	176002	975808
47.5	154776	1130584
52.5	134516	1265101
57.5	113114	1378215
62.5	132963	1511178
67.5	124836	1636014
72.5	113579	1749593
77.5	88854	1838448
82.5	110545	1948993
87.5	73401	2022394
92.5	39403	2061797
97.5	19840	2081637
102.5	11359	2092995
107.5	8047	2101042
112.5	1340	2102382
117.5	590	2102971

Table 2 - In situ methane resources versus methane gas concentration in the Ardley Coal Zone in the study area (in millions of cubic metres per square kilometre).

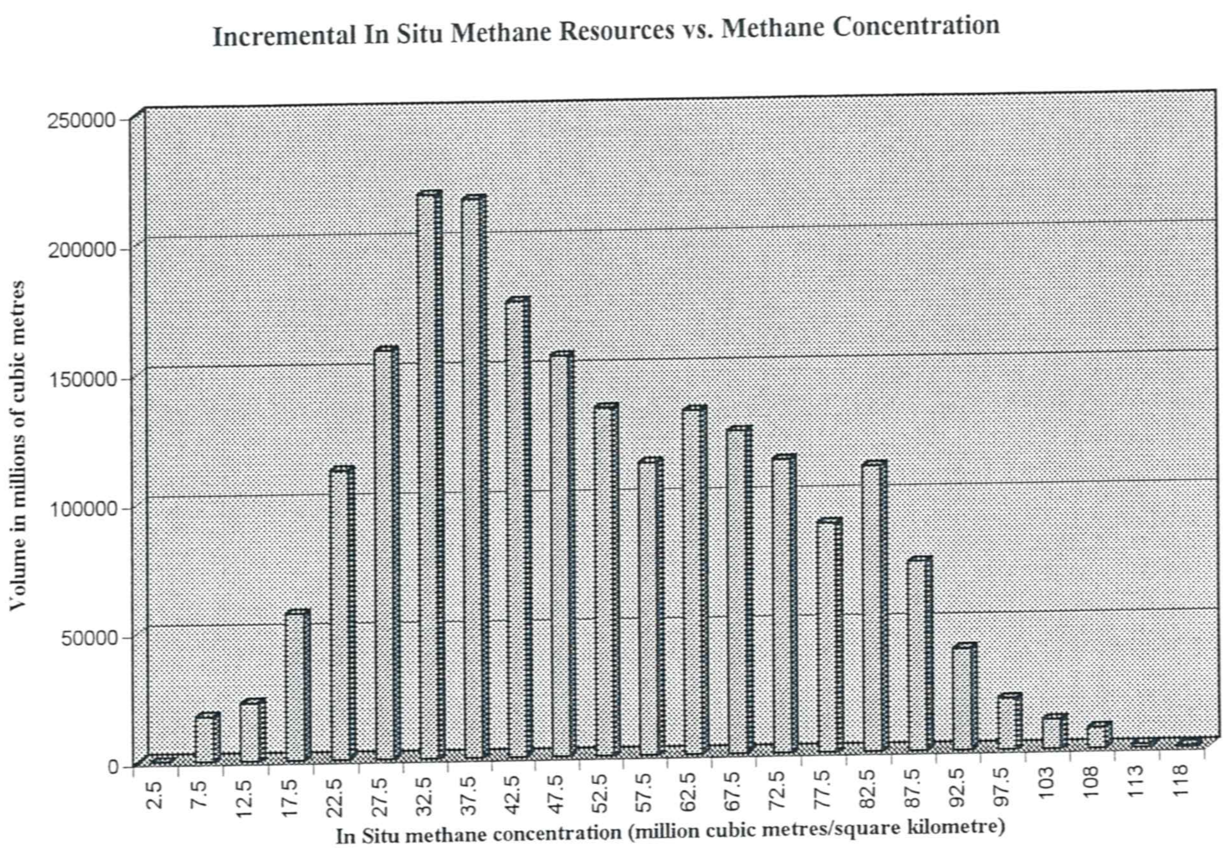

Figure 17 - Incremental in situ methane resources versus methane gas concentration in the Ardley Coal Zone in the study area (in millions of cubic metres - multiply by 35.3147 to convert to trillion cubic feet).

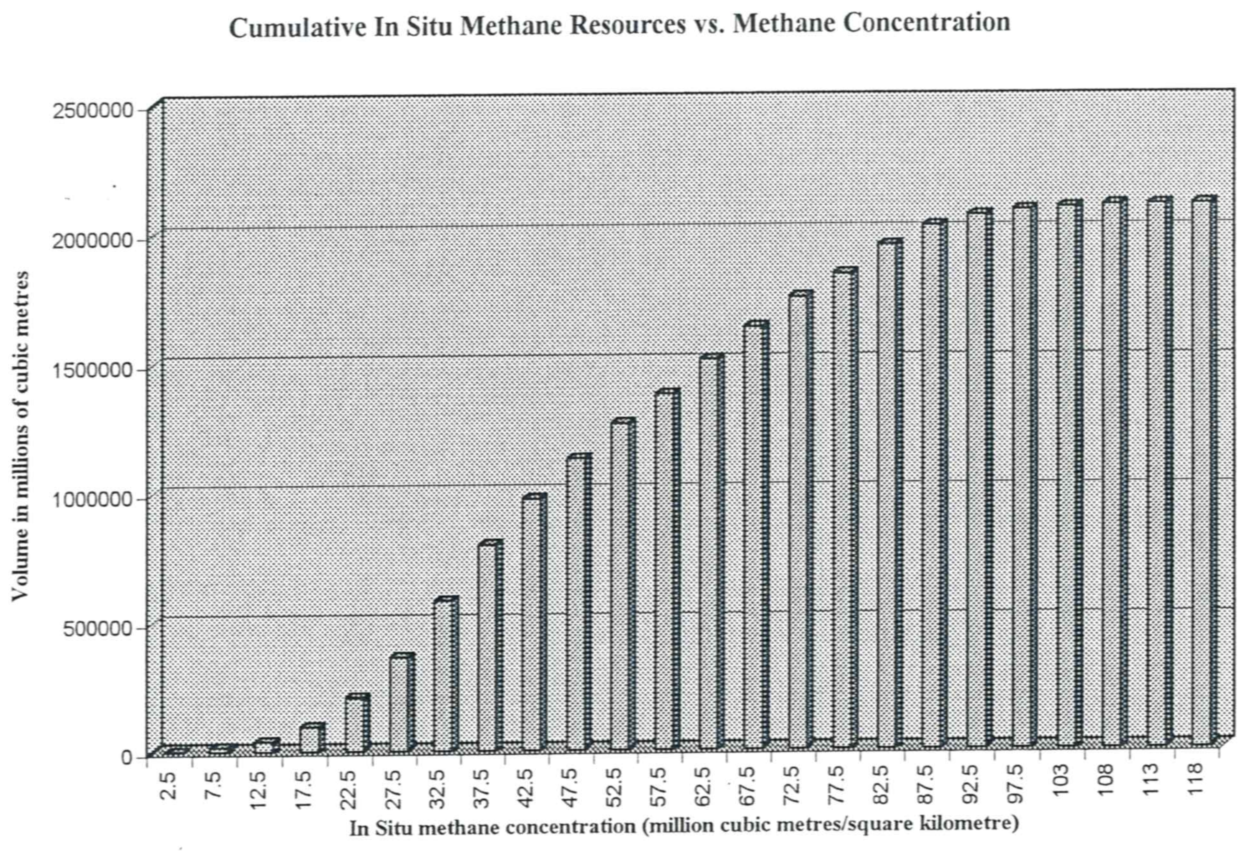

Figure 18 - Cumulative in situ methane resources versus methane gas concentration in the Ardley Coal Zone in the study area (in millions of cubic metres - multiply by 35.3147 to convert to trillion cubic feet).

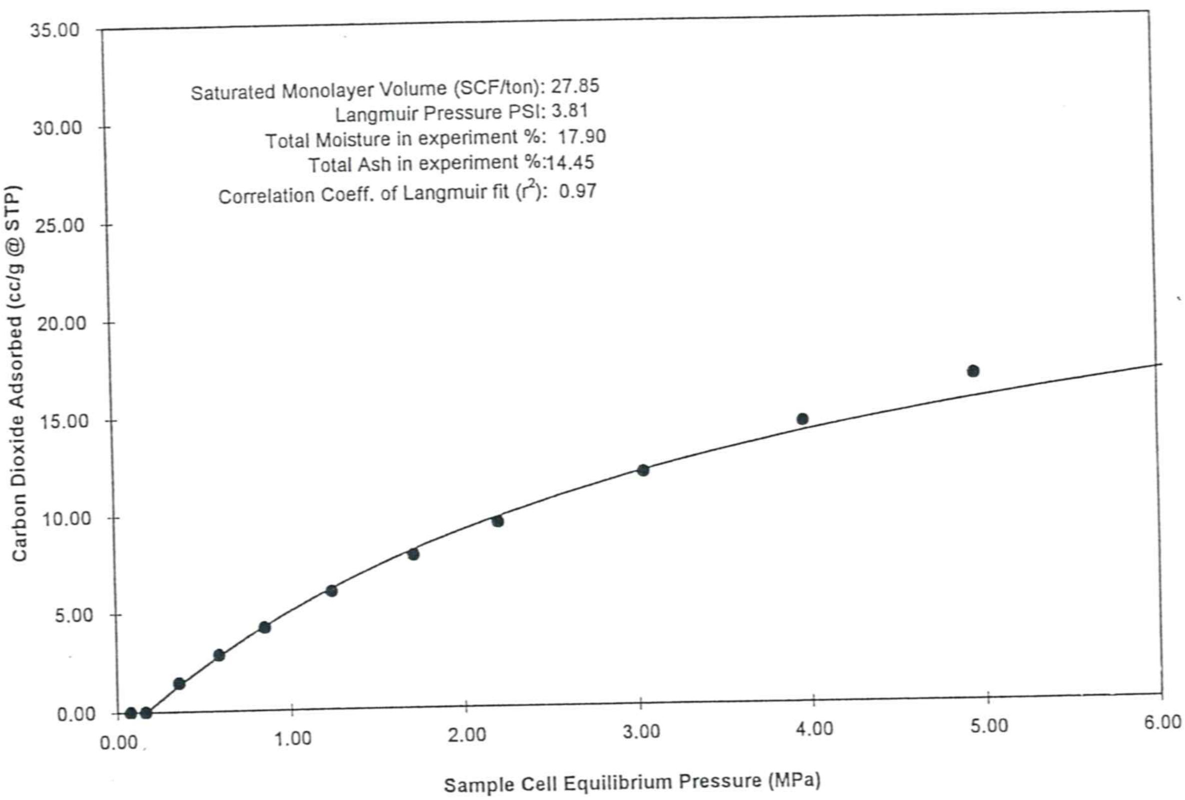

Figure 19 - CO_2 adsorption isotherm from one of several samples collected from the Ardley Coal Zone in the Highvale Mine area west of Edmonton (from Bustin, 1998).

following relationship:

CO_2 storage volume = 28.23 cc/gm x (pressure (Mpa)/(3.965 Mpa + pressure (Mpa)))

Existing information on depth versus pressure relationships in the Ardley Coal Zone comes from three localities in the northwest-central part of the study area (see Figure 20 for location), and suggests the reservoir is slightly under pressured with a pressure gradient of .009787 megapascals per metre. If this gradient is applied to the entire study area, a map of pressure at mean reservoir depth can be created as illustrated in Figure 20. From this map and the above relationship, a map illustrating the CO_2 storage capacity within the study area can be generated (Figure 21). The determination of CO_2 storage capacity assumed an ash content within the coal reservoir of ten per cent and a moisture content of eighteen per cent.

The distribution of the CO_2 storage capacity within the Ardley Coal Zone can be expressed as CO_2 storage capacity concentration, which is the product of CO_2 storage capacity and reservoir thickness. Software developed by Hughes (1996) was utilized to determine the in situ CO_2 storage capacity concentration per unit area, and to quantify CO_2 storage capacity according to reservoir depth, reservoir CO_2 storage capacity concentration and other parameters. Figure 22 illustrates the distribution of CO_2 storage capacity expressed as millions of cubic metres of CO_2 storage capacity per square kilometre, whereas Figure 23 illustrates CO_2 storage capacity expressed as megatonnes per square kilometre, assuming a volume to weight conversion factor of 1.903 kilogram/cubic metres.

CO_2 storage capacity for the entire study area quantified by depth from surface is given in Table 3 and illustrated graphically in Figure 24 (incrementally by depth) and Figure 25 (cumulatively by depth). CO_2 storage capacity for the entire study area quantified by CO_2 storage capacity concentration is given in Table 4 and illustrated graphically in Figure 26 (incrementally by CO_2 storage capacity concentration) and Figure 27 (cumulatively by CO_2 storage capacity concentration). The total in situ CO_2 storage capacity is 8.5 trillion cubic metres or 16,226 megatonnes.

Selection of Optimal Exploration Targets

One of the major objectives of this study was the selection of the most promising areas for more detailed geological evaluation as a precursor to siting exploration test holes. Such detailed evaluations, which are too costly to be undertaken for large areas, would include correlations of individual coal beds based on boreholes spaced at a kilometre or less (versus the minimum spacing of eight kilometres used in this study), in order to permit mapping of permeability indicators and other reservoir properties including seals, thickness, methane content and CO_2 storage capacity within the best intervals defined for completion.

Factors affecting the favourability of a reservoir for coalbed methane production and/or CO_2 sequestration include the amount of in situ methane gas or CO_2 storage capacity available,

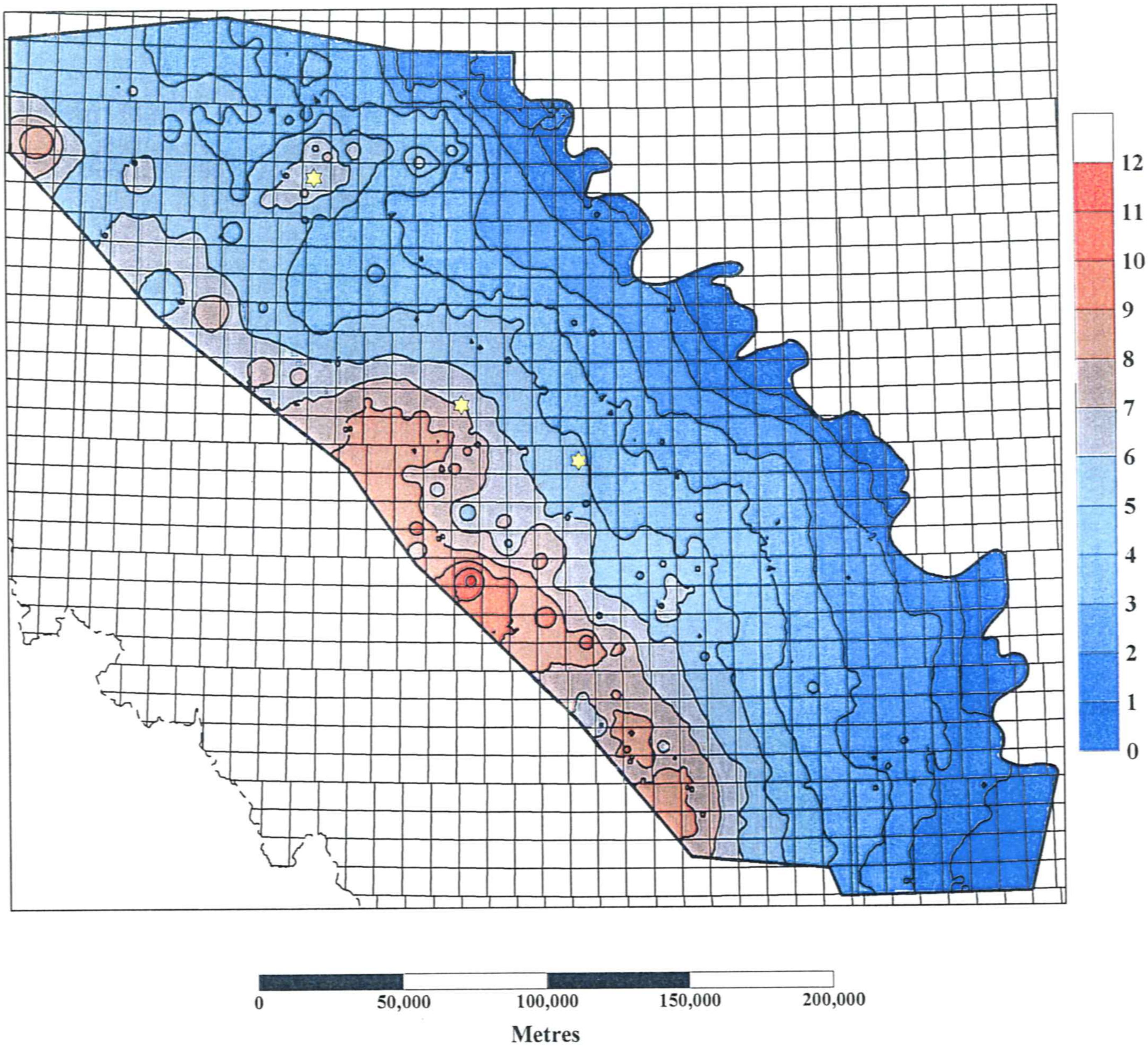

Figure 20 - Estimated reservoir pressure at mean reservoir depth in the Ardley Coal Zone in the study area (in megapascals). A pressure gradient of .009787 megapascals/metre was assumed based on existing measurements from three localities in the northwest-central part of the study area (shown in yellow).

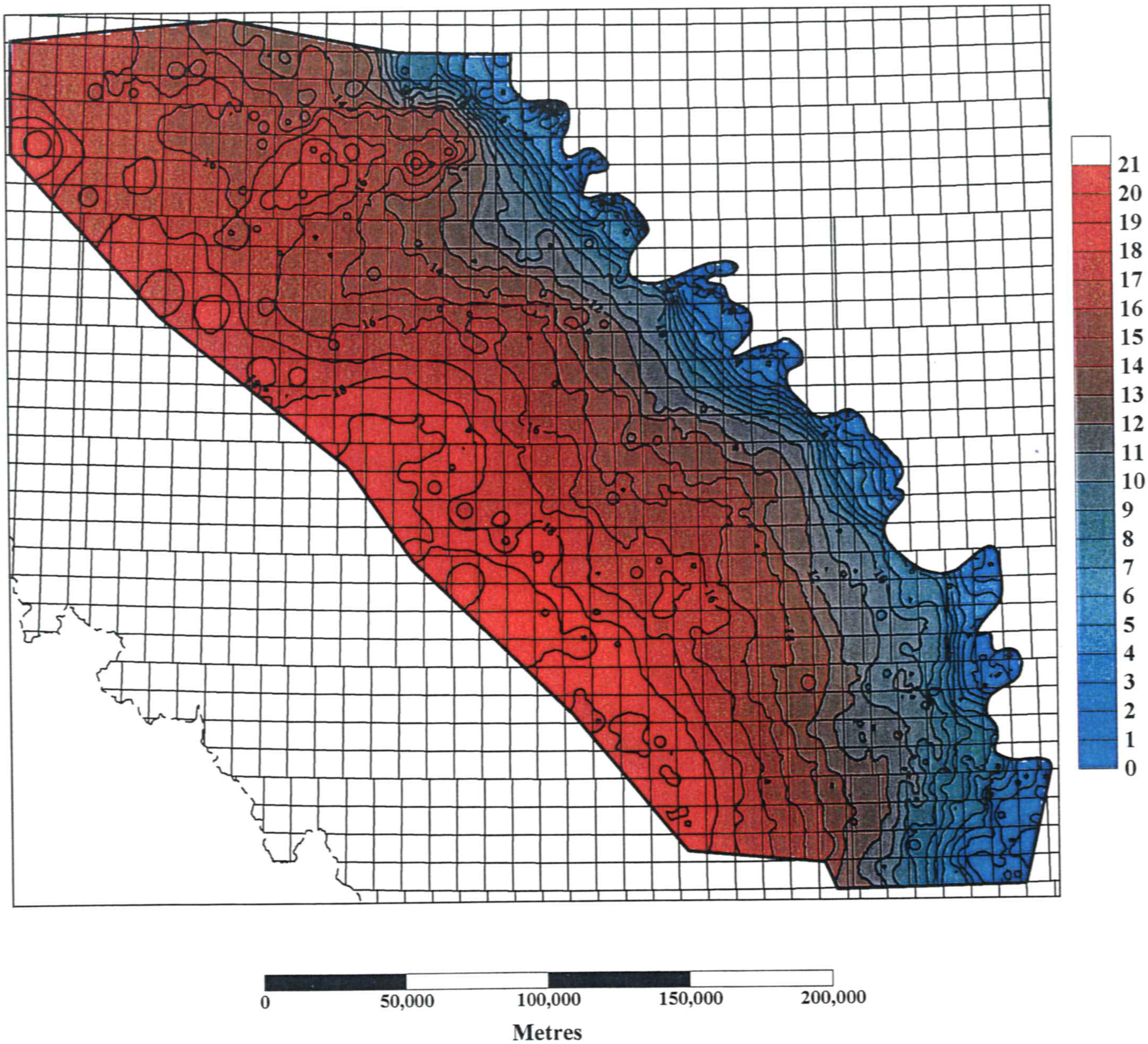

Figure 21 - CO_2 storage capacity (cc/gm) in the Ardley Coal Zone computed using relationships established by Bustin (1998) based on CO_2 adsorption isotherms from Ardley coals collected from the Highvale Mine on the eastern edge of the study area.

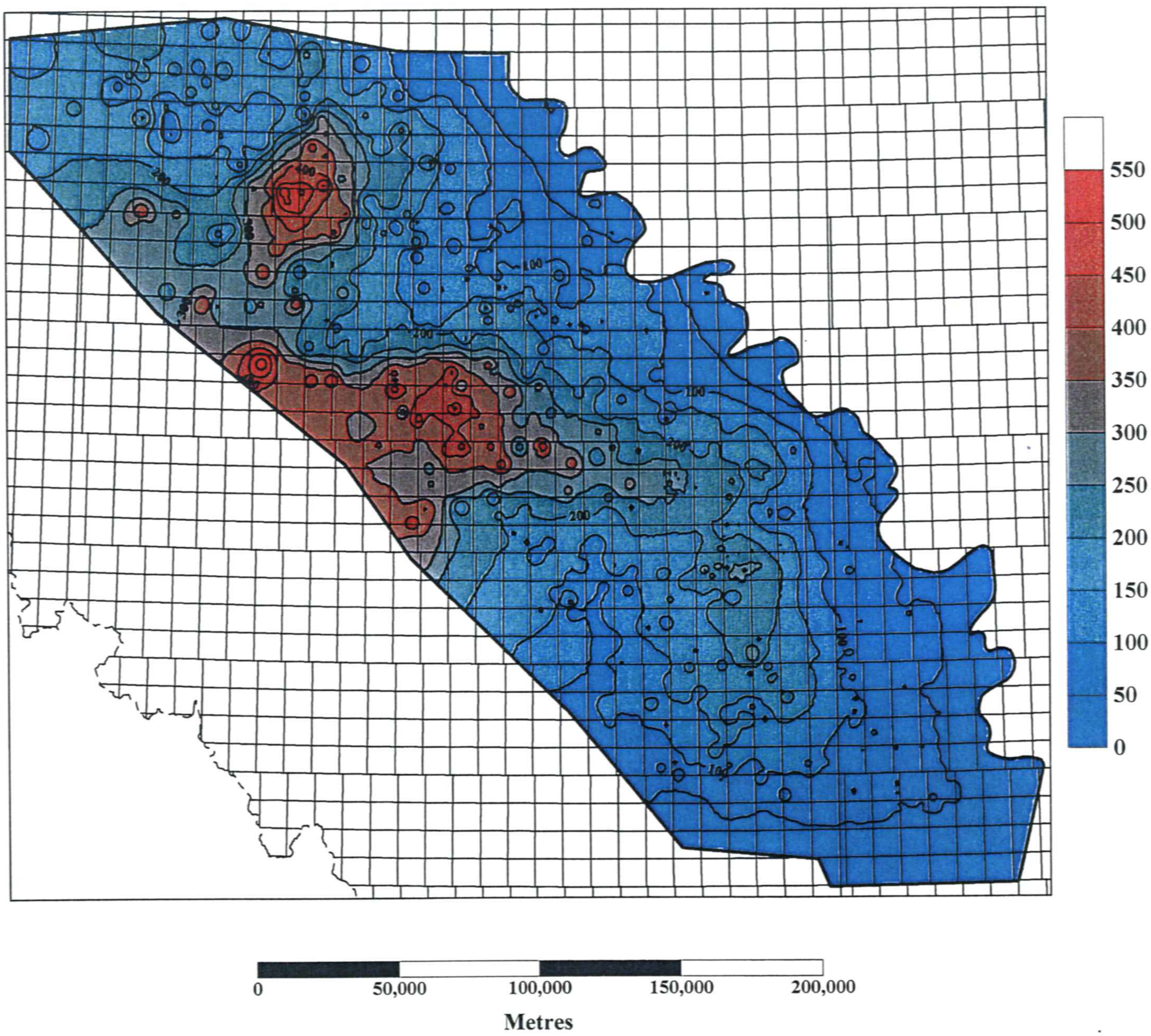

Figure 22 - CO_2 storage capacity concentration expressed as millions of cubic metres per square kilometre. CO_2 storage capacity concentration is the product of CO_2 storage capacity as determined from reservoir pressure and CO_2 adsorption isotherm analytical data, and the aggregate reservoir thickness.

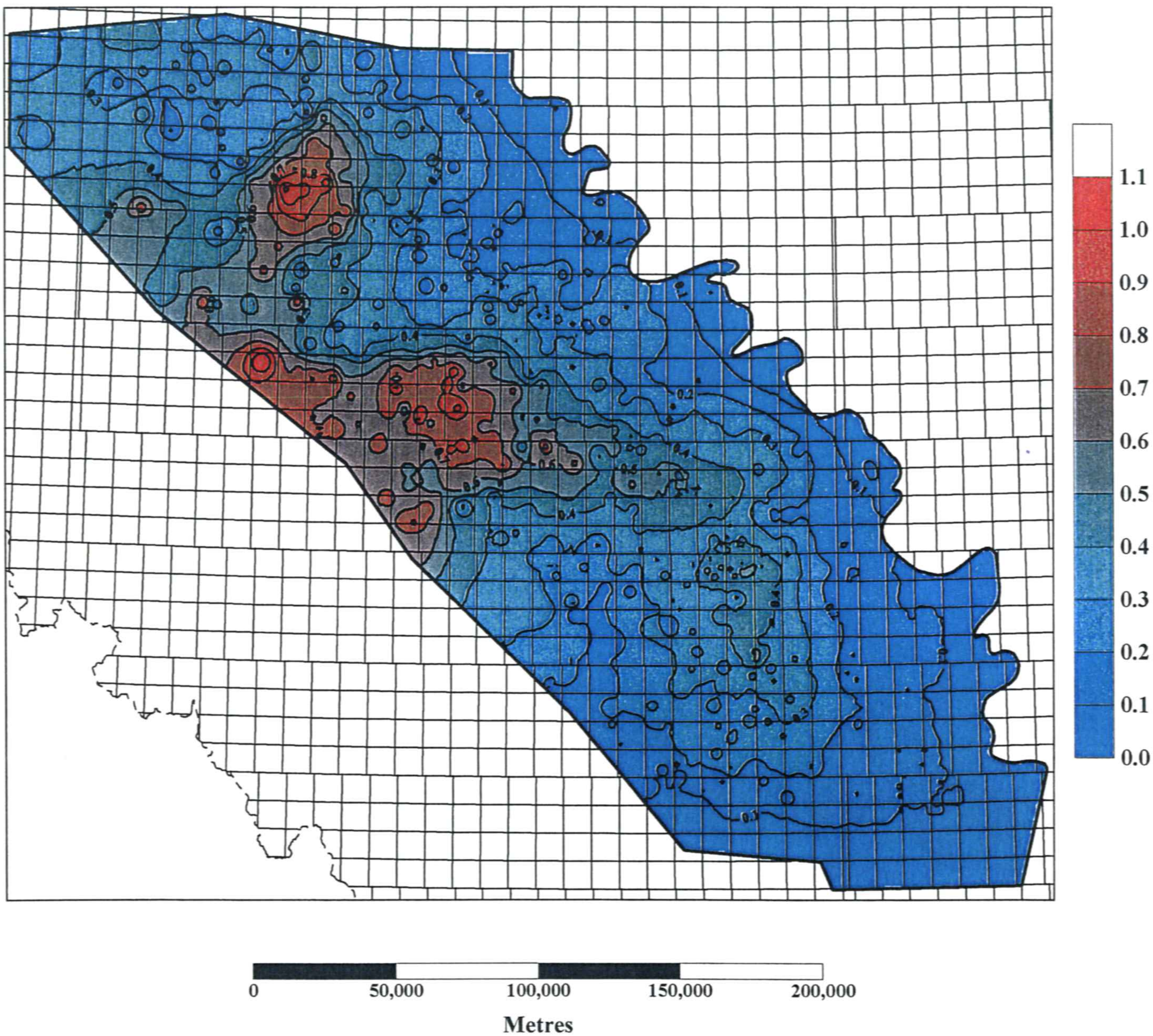

Figure 23 - CO_2 storage capacity concentration expressed as megatonnes per square kilometre.

Mean Depth from Surface (metres)	Incremental In Situ CO_2 Storage Capacity (millions of cubic metres)	Cumulative In Situ CO_2 Storage Capacity (millions of cubic metres)
25	19770	19770
75	71810	91580
125	90705	182285
175	128257	310542
225	222246	532788
275	314783	847571
325	365915	1213485
375	524479	1737964
425	676594	2414558
475	831364	3245922
525	1108241	4354163
575	1046116	5400279
625	796481	6196760
675	580097	6776857
725	540918	7317775
775	372682	7690457
825	358803	8049259
875	324705	8373964
925	93592	8467556
975	30685	8498241
1025	15211	8513452
1075	7622	8521074
1125	5340	8526414

Table 3 - CO_2 storage capacity concentration in the Ardley Coal Zone in the study area expressed as millions of cubic metres per square kilometre versus mean depth from surface.

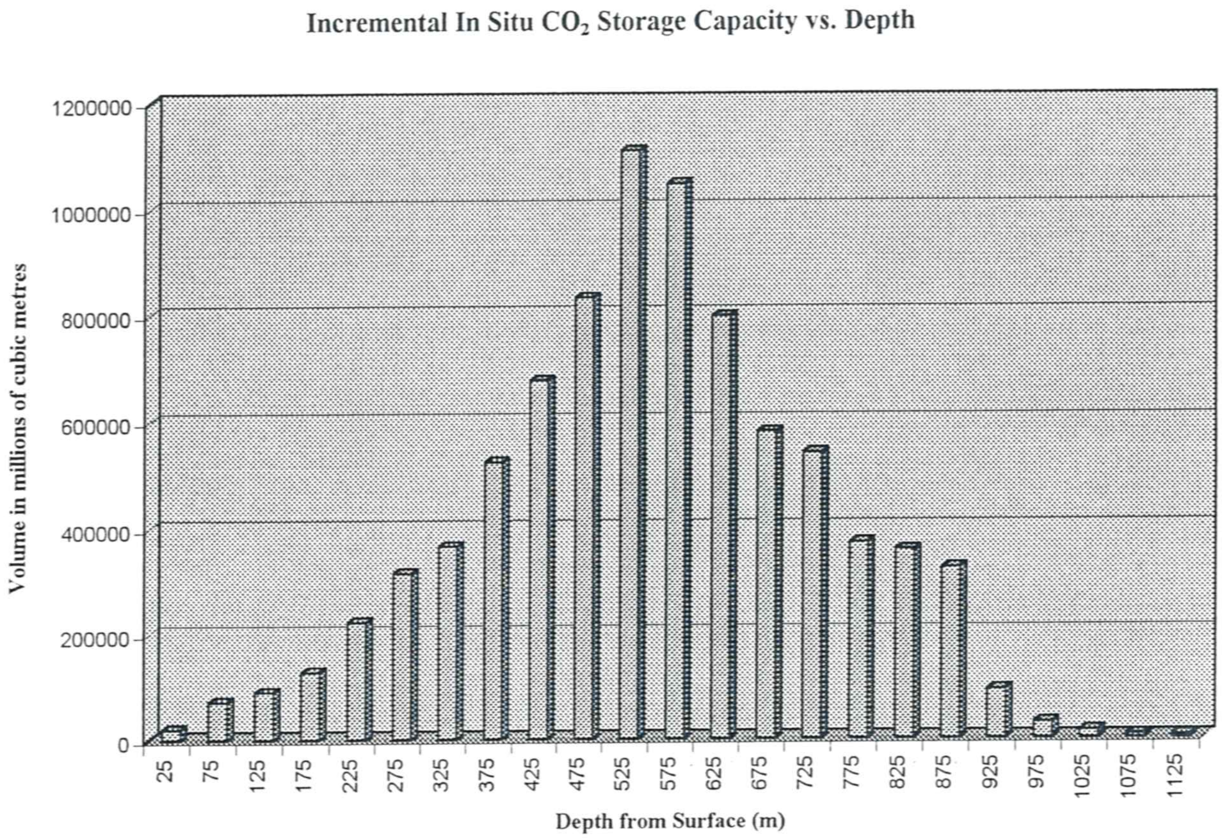

Figure 24 - Incremental in situ CO_2 storage capacity concentration in the Ardley Coal Zone in the study area expressed as millions of cubic metres per square kilometre versus mean depth from surface.

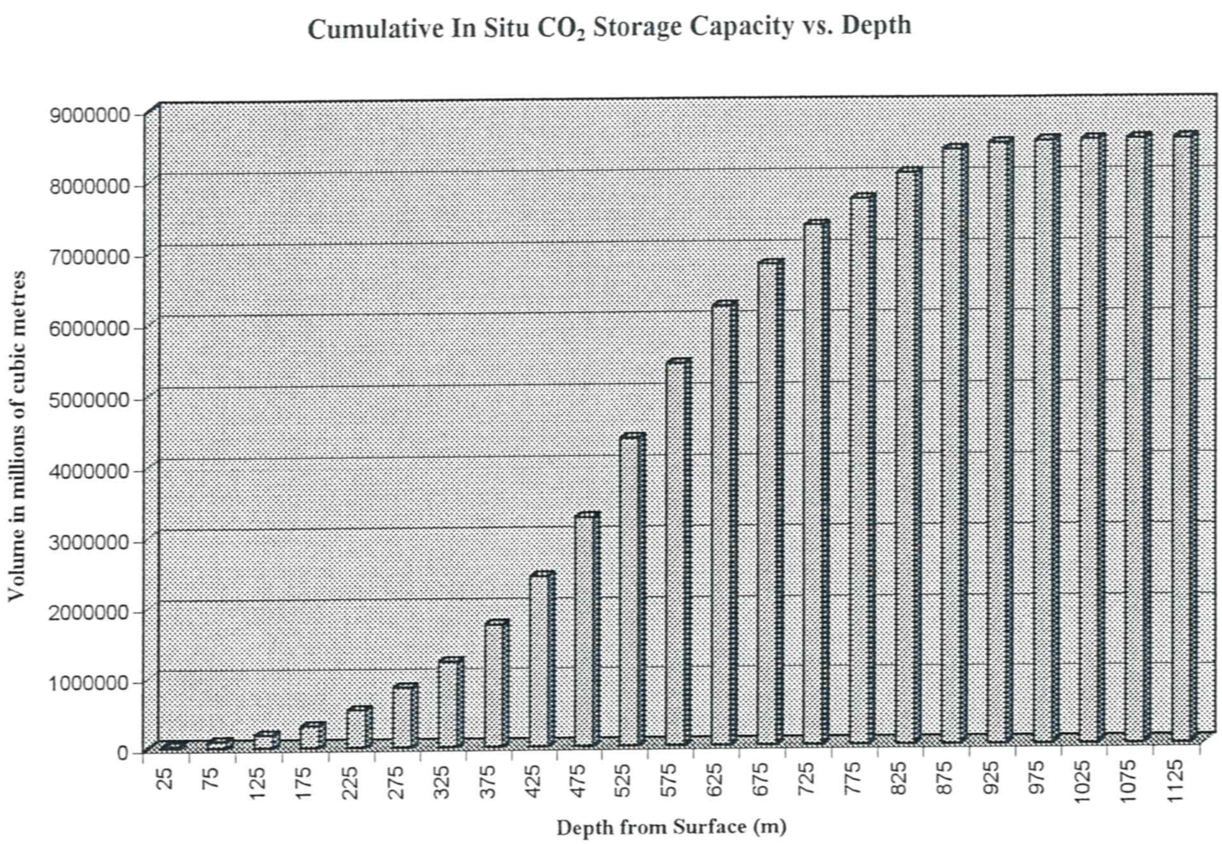

Figure 25 - Cumulative in situ CO_2 storage capacity concentration in the Ardley Coal Zone in the study area expressed as millions of cubic metres per square kilometre versus mean depth from surface.

In Situ CO_2 Storage Capacity Concentration (millions of cubic metres per square kilometre)	Incremental In Situ CO_2 Storage Capacity (millions of cubic metres)	Cumulative In Situ CO_2 Storage Capacity (millions of cubic metres)
12.5	40356	40356
37.5	169828	210184
62.5	271489	481673
87.5	396772	878445
112.5	522202	1400647
137.5	591315	1991962
162.5	979018	2970980
187.5	880496	3851476
212.5	829189	4680664
237.5	554156	5234820
262.5	481971	5716791
287.5	524933	6241723
312.5	419647	6661371
337.5	431701	7093071
362.5	641084	7734155
387.5	390388	8124543
412.5	206796	8331338
437.5	98099	8429437
462.5	50258	8479695
487.5	30092	8509787
512.5	15244	8525031
537.5	1597	8526628

Table 4 - CO_2 storage capacity versus CO_2 storage capacity concentration for the Ardley Coal Zone in the study area..

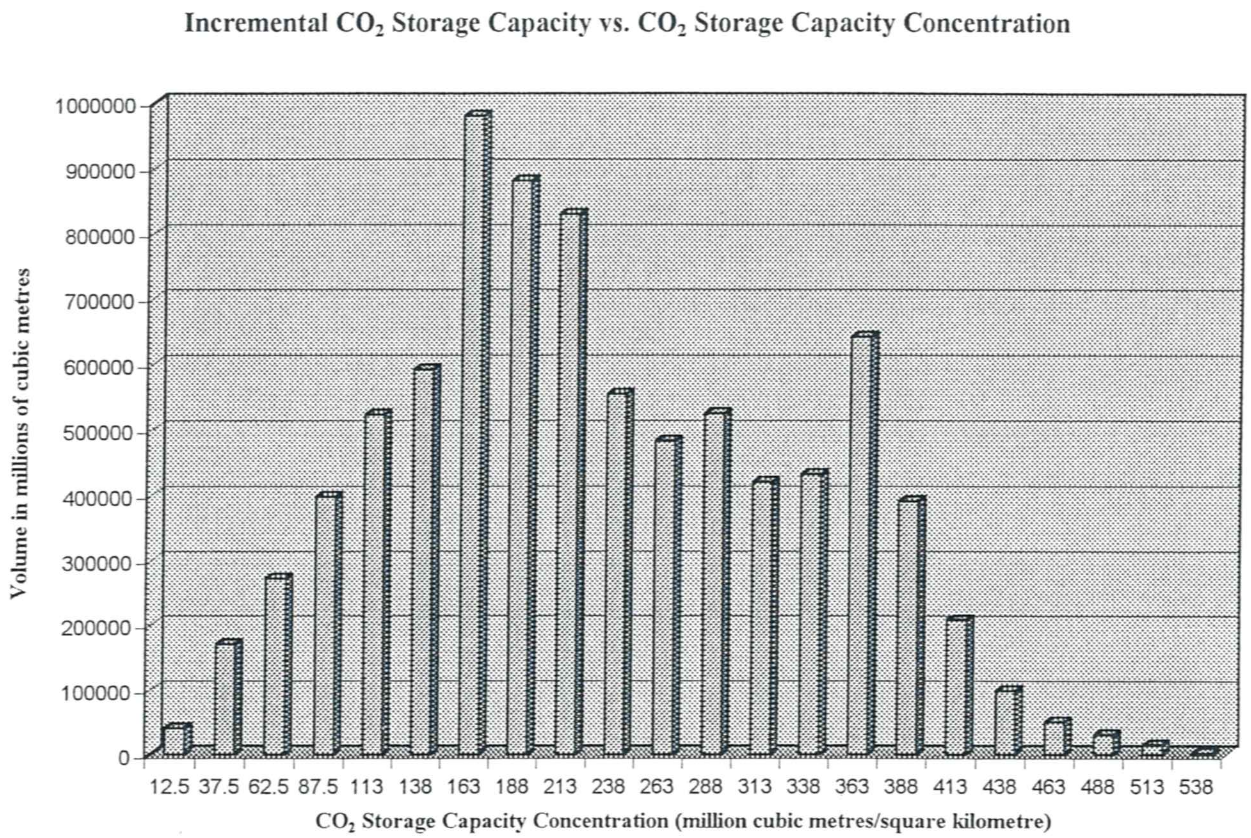

Figure 26 - Incremental in situ CO_2 storage capacity versus CO_2 storage capacity concentration for the Ardley Coal Zone in the study area.

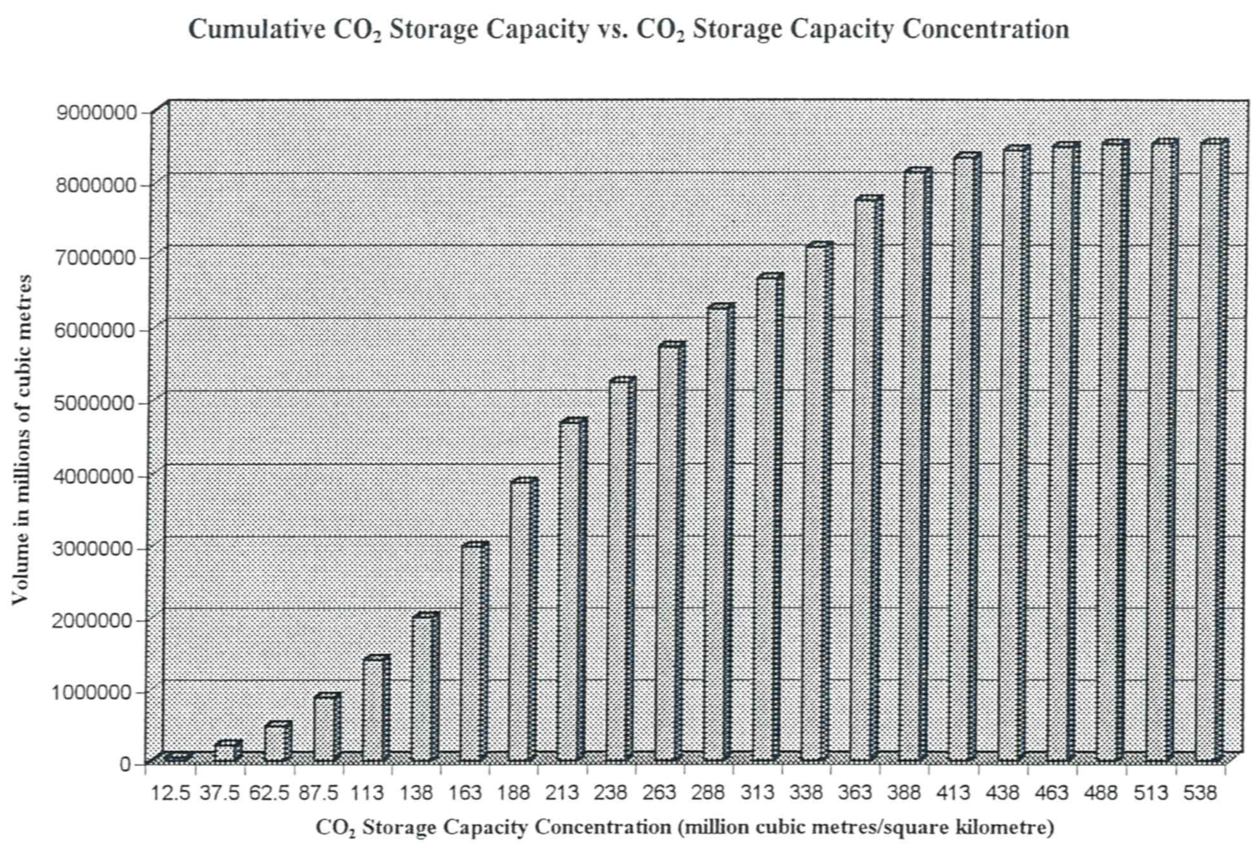

Figure 27 - Cumulative in situ CO_2 storage capacity versus CO_2 storage capacity concentration for the Ardley Coal Zone in the study area.

the cost of accessing the reservoir (determined by completion costs and spacing of production/injection wells) and, in the case of CO_2 sequestration, the distance from sources of CO_2. These parameters can be weighted according to their perceived importance and combined into a "favourability index" to select the most promising areas for further evaluation.

The reservoir properties of methane gas concentration and CO_2 storage capacity concentration have been discussed earlier. An estimate of the costs of accessing the reservoir can be made based on the type of drilling rig required, the associated mobilization and logging costs, and the depth of the reservoir which determines drilling and casing costs. Figure 28 is a map of estimated drilling costs based on the following assumptions:

- reservoirs at less than 500 metres depth can be accessed with a small drilling rig with mobilization and logging costs of $10,000. and drilling and casing costs of $70. per metre.

- reservoirs at greater than 500 metres depth will require a large drilling rig with mobilization and logging costs of $40,000. and drilling and casing costs of $300. per metre.

In situ coalbed methane resources and CO_2 storage capacity can be quantified according to the cost of accessing the reservoir as a preliminary assessment of some of the economic constraints associated with development. The distribution of coalbed methane versus the cost of accessing the reservoirs is given in Table 5 and illustrated graphically in Figure 29 (incrementally by cost) and Figure 30 (cumulatively by cost). The distribution of CO_2 storage capacity versus the cost of accessing the reservoirs is given in Table 6 and illustrated graphically in Figure 31 (incrementally by cost) and Figure 32 (cumulatively by cost).

Sources of CO_2 for sequestration include four thermal coal plants located west of Edmonton on the eastern edge of the study area (Wabamun, Sundance, Keephills, Genesee), five gas plants (Kabob South, Harlan-Robb, Strachan, Caroline, Harmattan), and two chemical plants (Fort Saskatchewan, Joffre). Figure 33 is a map showing the locations of these CO_2 sources and the distance of each part of the study area from the nearest point source, which can be used to estimate the relative cost of moving CO_2 to injection wells for sequestration.

Utilizing the above parameters, "favourability index" maps were created for coalbed methane production and CO_2 sequestration to locate optimal areas for detailed geological assessment as a precursor to the selection of drilling locations. The "favourability index" for coalbed methane production assigned a weight of 60 per cent to methane gas concentration and 40 per cent to cost of access to produce an index varying between 0 (no potential) and 1 (highest potential) (Figure 34). All reservoirs with a methane gas concentration of less than 25 million cubic metres per square kilometre were considered to be non productive and were eliminated from the analysis. The "favourability index" for CO_2 sequestration potential assigned a weight of 50 per cent to CO_2 storage capacity concentration, 25 per cent to cost of access and 25 per

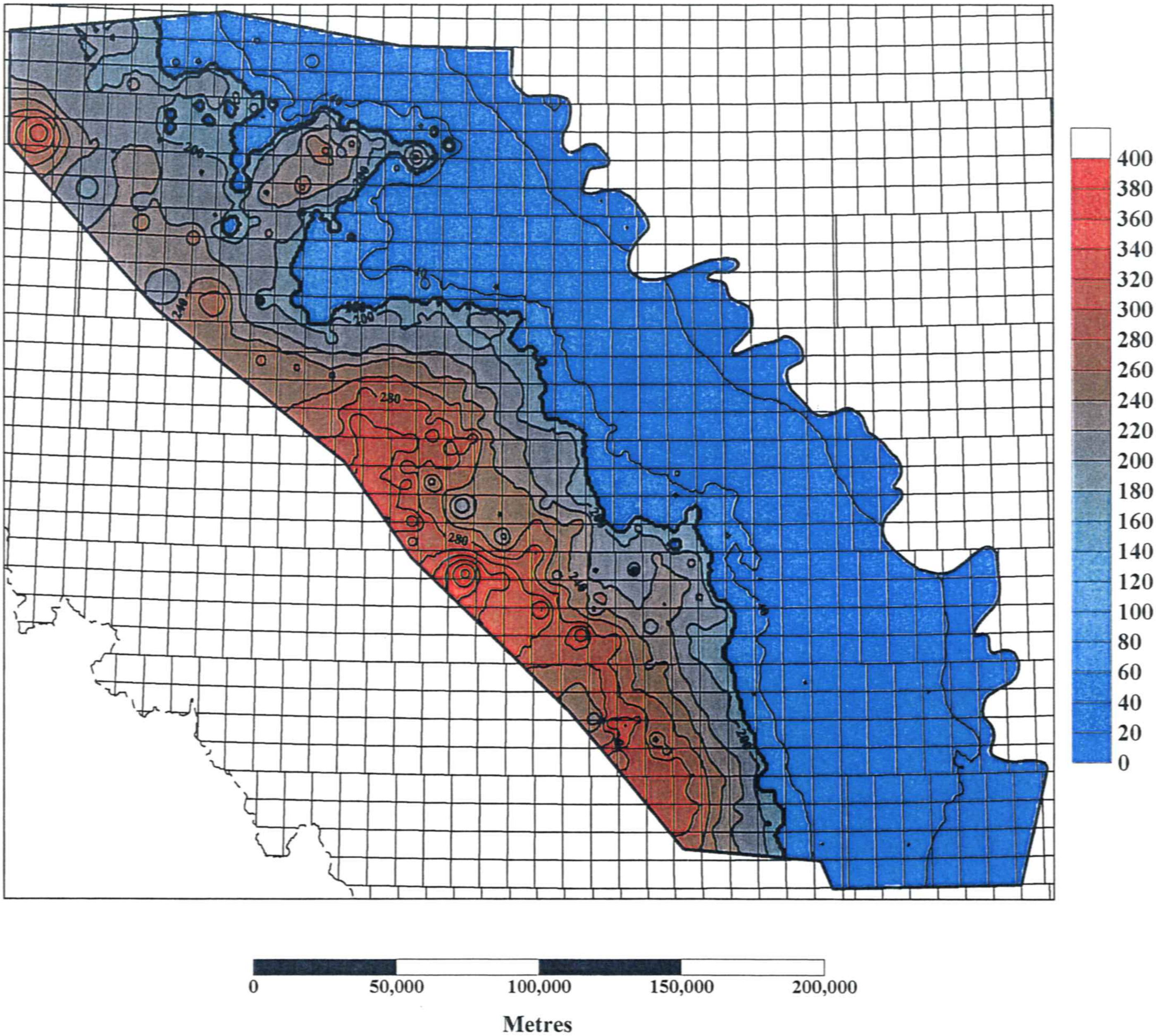

Figure 28 - Estimated drilling costs in thousands of dollars to complete a production well in the Ardley Coal Zone in the study area (see text for rationale).

Mean cost of access (thousands of dollars)	Incremental In Situ Coalbed Methane Resources (millions of cubic metres)	Cumulative In Situ Coalbed Methane Resources (millions of cubic metres)
10	126124	126124
30	545687	671811
50	254112	925924
70	0	925924
90	0	925924
110	0	925924
130	0	925924
150	0	925924
170	0	925924
190	149297	1075221
210	314863	1390084
230	214213	1604297
250	182035	1786332
270	116266	1902598
290	105543	2008141
310	71055	2079196
330	15120	2094316
350	5612	2099929
370	2520	2102449

Table 5 - In situ coalbed methane resources versus mean cost of access in the Ardley Coal Zone in the study area.

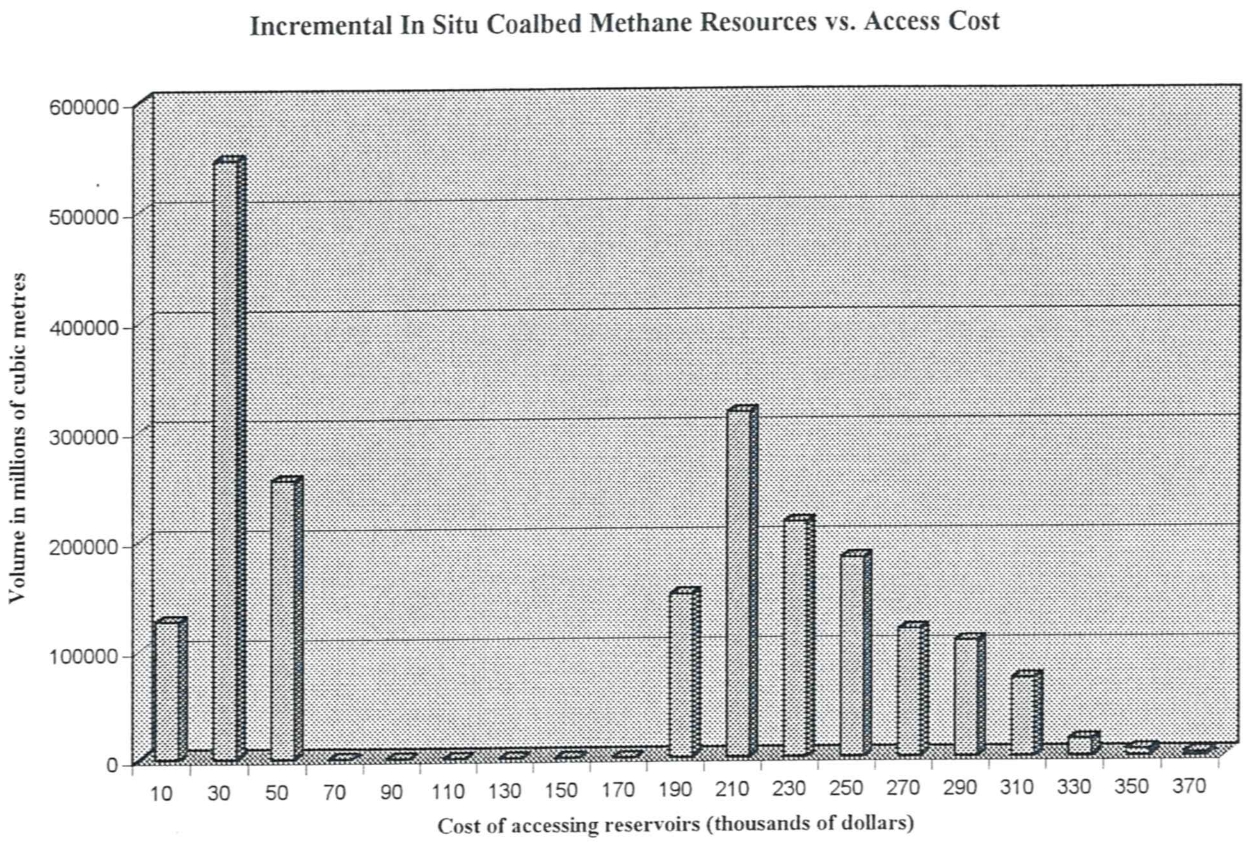

Figure 29 - Incremental in situ coalbed methane resources versus mean cost of access in the Ardley Coal Zone in the study area.

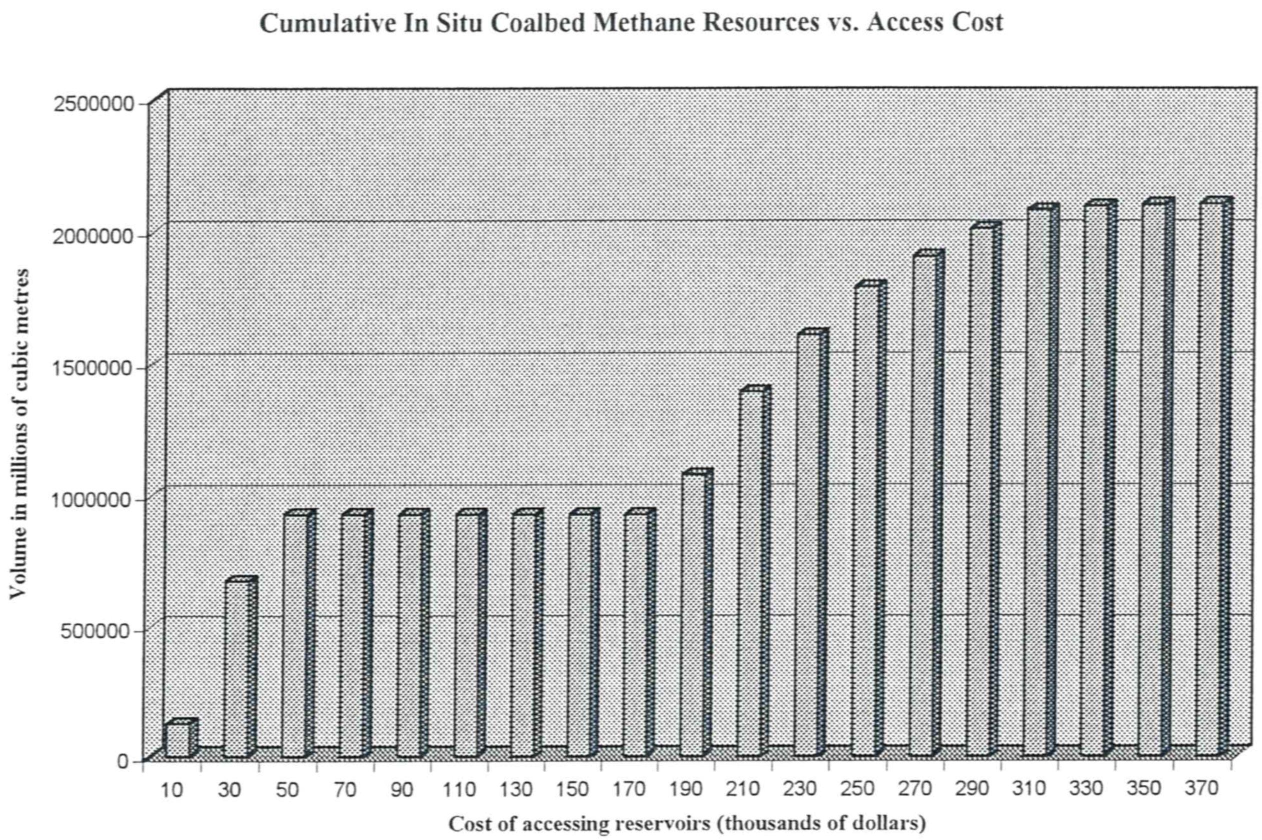

Figure 30 - Cumulative in situ coalbed methane resources versus mean cost of access in the Ardley Coal Zone in the study area.

Mean cost of access (thousands of dollars)	Incremental In Situ CO_2 Storage Capacity (millions of cubic metres)	Cumulative In Situ CO_2 Storage Capacity (millions of cubic metres)
10	163559	163559
30	1877395	2040954
50	1084747	3125701
70	0	3125701
90	0	3125701
110	0	3125701
130	0	3125701
150	0	3125701
170	0	3125701
190	662599	3788300
210	1411965	5200265
230	946260	6146525
250	774502	6921028
270	484592	7405621
290	446425	7852046
310	282533	8134579
330	48907	8183487
350	17804	8201291
370	7895	8209187
390	1634	8210821

Table 6 - In situ CO_2 storage capacity versus mean cost of access in the Ardley Coal Zone in the study area.

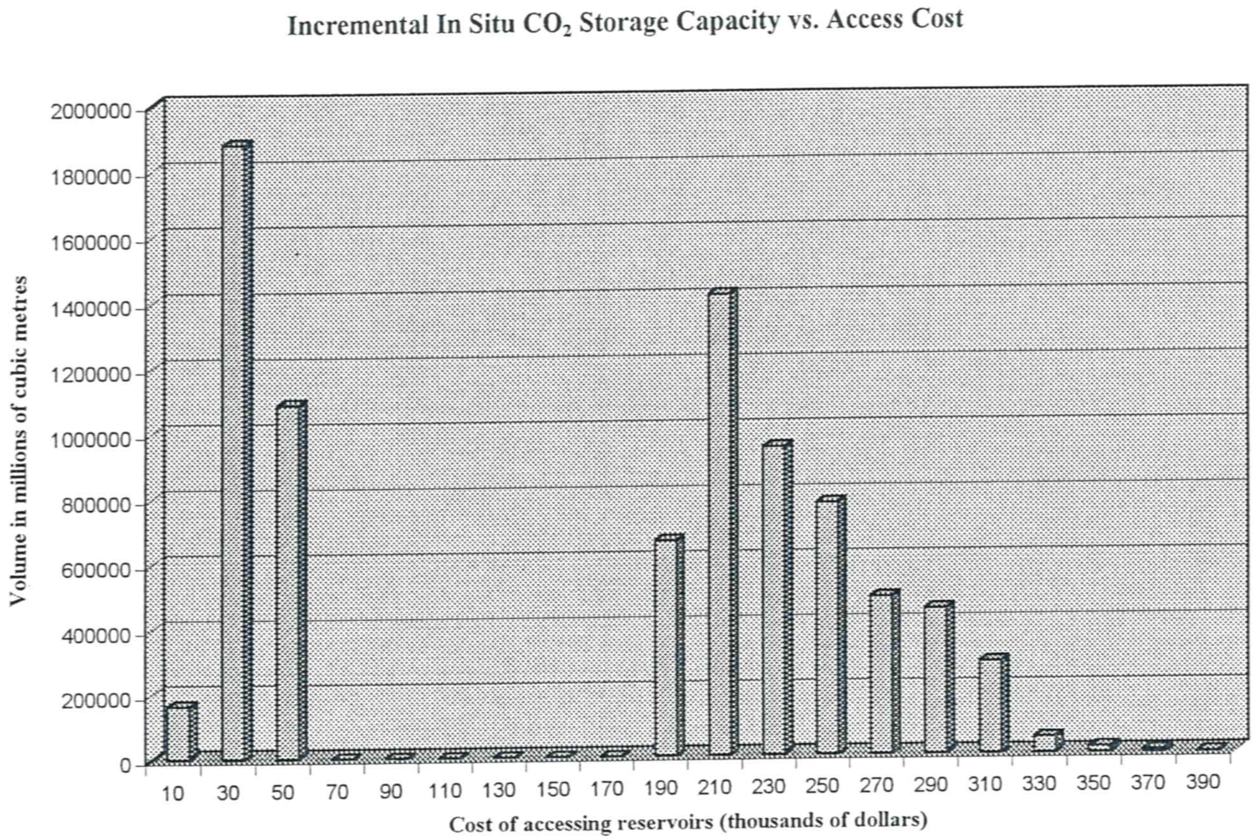

Figure 31 - Incremental in situ CO_2 storage capacity versus mean cost of access in the Ardley Coal Zone in the study area.

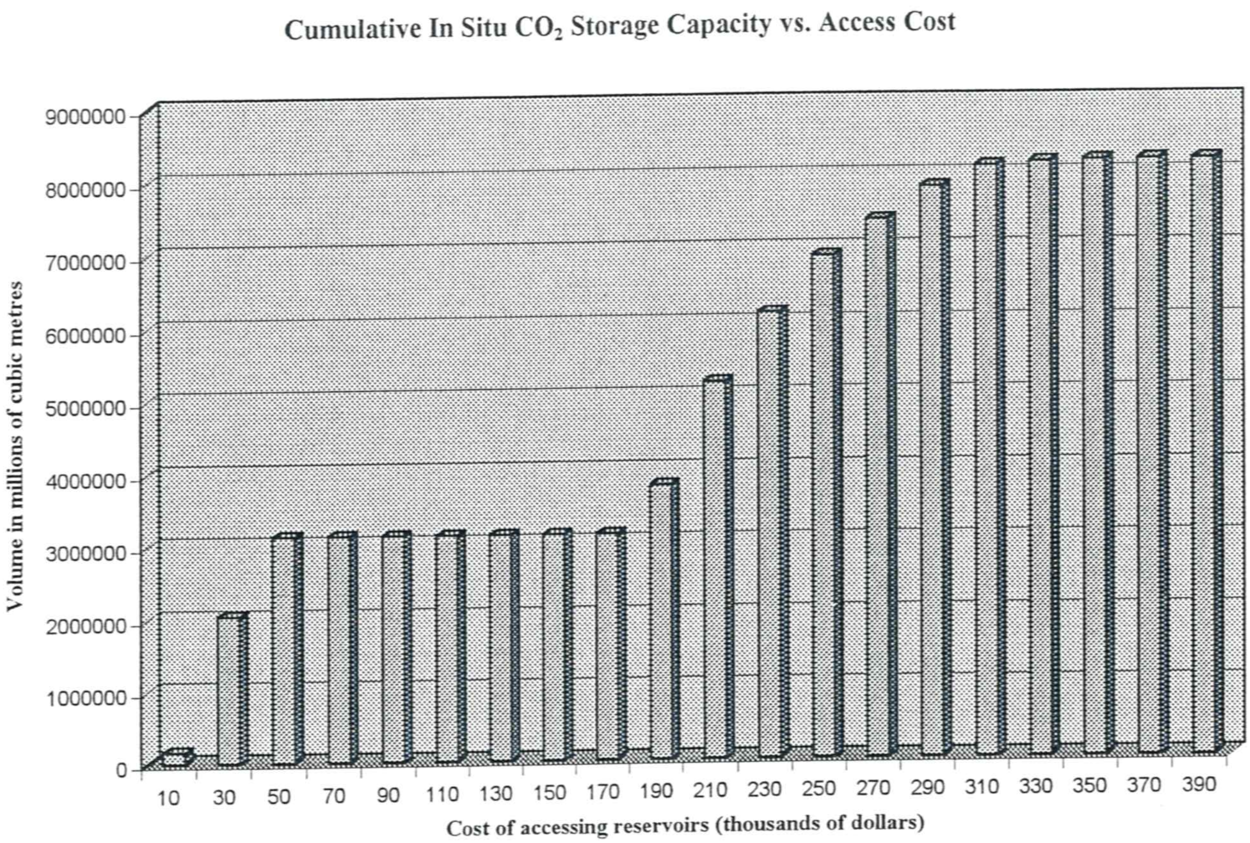

Figure 32 - Cumulative in situ CO_2 storage capacity versus mean cost of access in the Ardley Coal Zone in the study area.

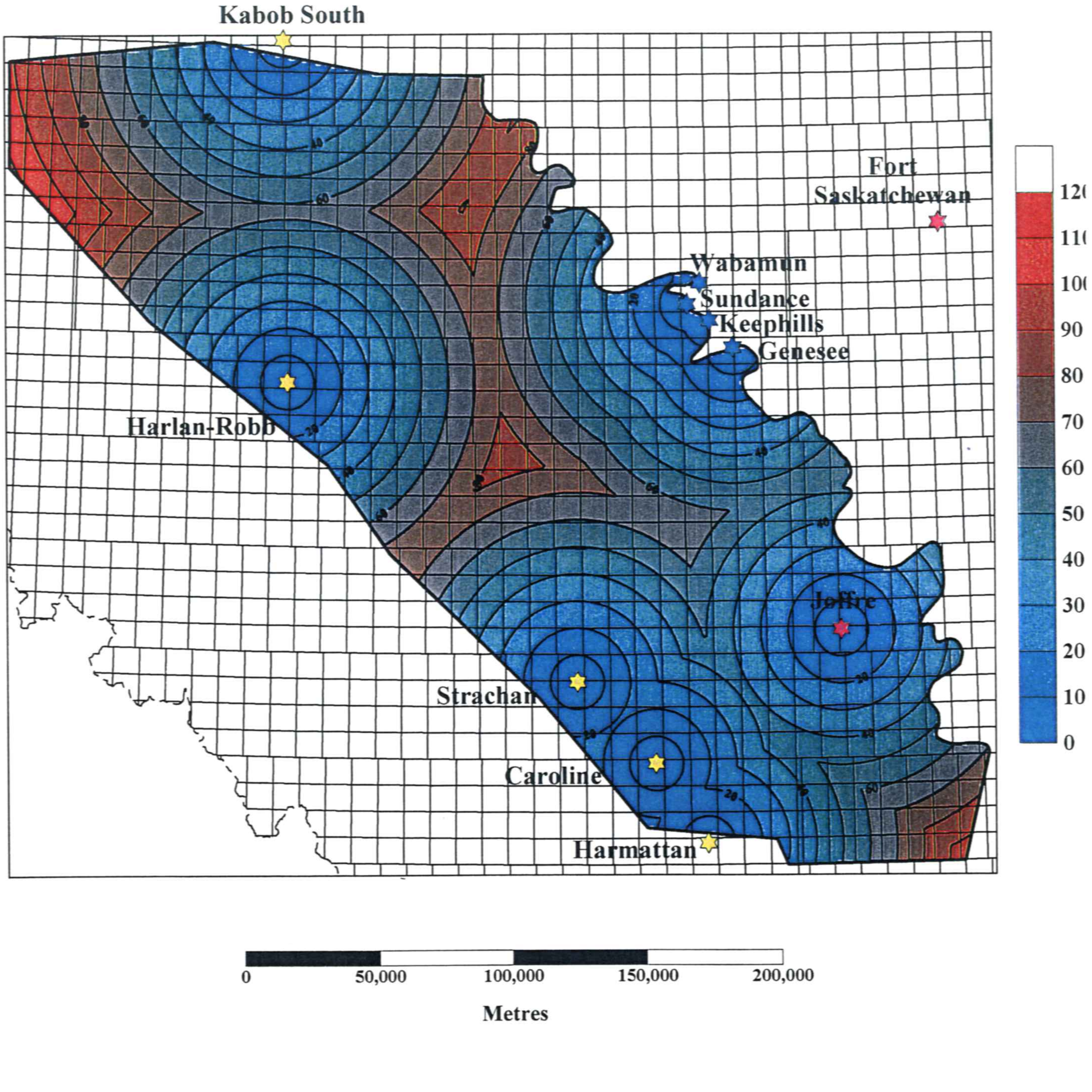

Figure 33 - Distance from point sources of CO_2 in kilometres. Yellow stars indicate gas plants, blue stars indicate coal plants and pink stars indicate chemical plants.

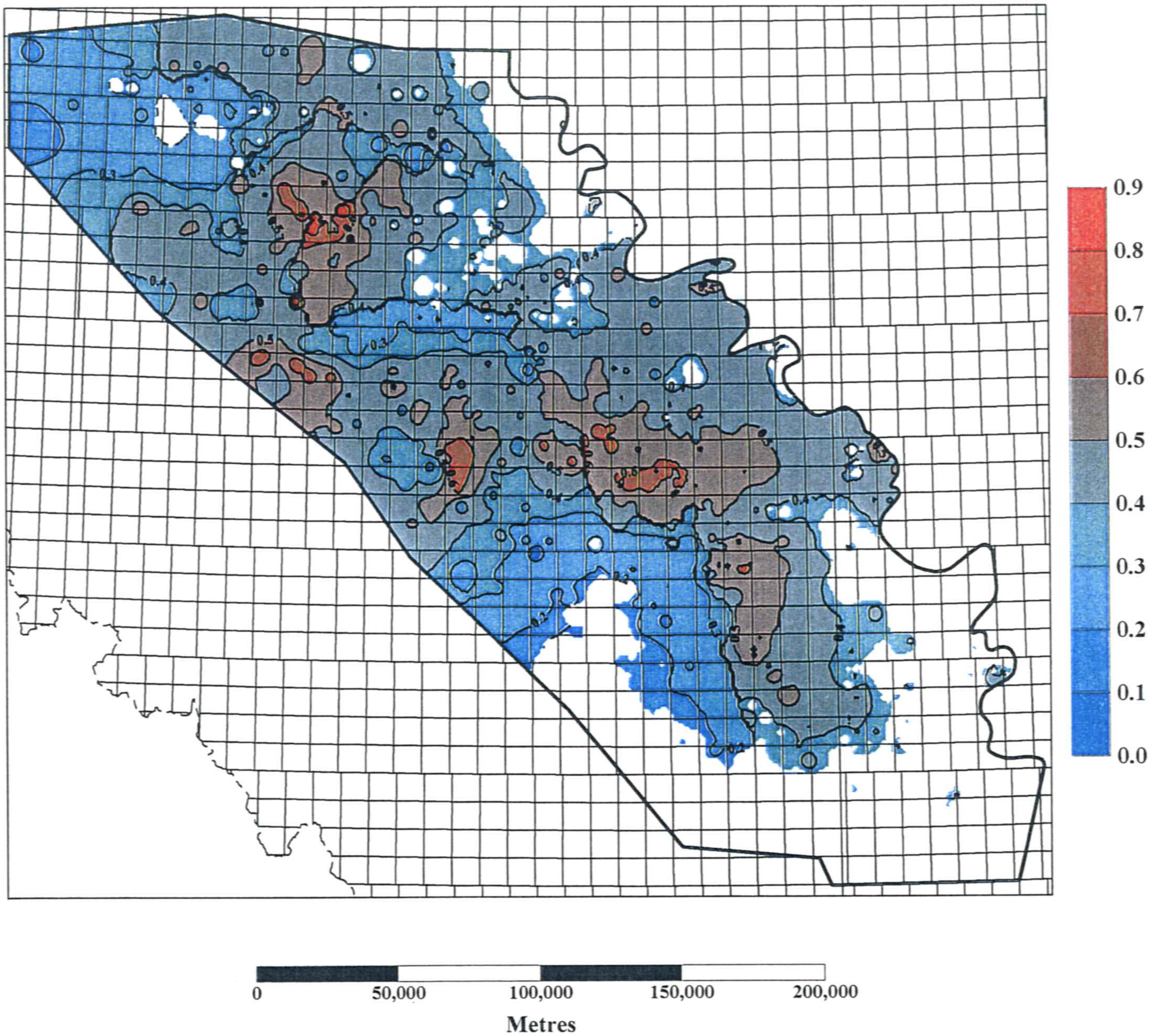

Figure 34 - Favourability index map for coalbed methane production. The most prospective reservoirs have a favourability index near 1.

cent to distance from point sources of CO_2 to produce an index varying between 0 (no potential) and 1 (highest potential) (Figure 35). All reservoirs with a CO_2 storage capacity concentration of less than 100 million cubic metres per square kilometre were considered to be non productive and were eliminated from the analysis.

This favourability analysis reveals that the southern portion of the study area has little or no potential for either coalbed methane production or CO_2 sequestration due to the lack of reservoir capacity (thin seams), and that the shallowest coal reservoirs along the eastern subcrop edge have potential for coalbed methane production but not for CO_2 sequestration. Areas with a high potential for both coalbed methane production and for CO_2 sequestration lie in the central, western and north-central part of the study area. Two of the most promising of these areas, which are indicated on Figure 35, warrant more detailed geological evaluation for the selection of optimal drilling locations. Each of these areas is reviewed at a larger scale, albeit with the same basic drilling information, in the following sections. In order to select optimal drilling locations, the best portions of each of these areas should be evaluated to define correlations of individual coal beds based on boreholes spaced at a kilometre or less (versus the minimum spacing of eight kilometres used in this study). This would permit mapping of permeability indicators and other reservoir properties including seals, thickness, methane content and CO_2 storage capacity within the best intervals defined for completion.

North Target Subarea

The north target subarea (see Figure 35 for location) contains more than 15 metres of aggregate coal thickness over a 1400 square kilometre area, and more than 19 metres of aggregate coal thickness over a 200 square kilometre area (Figure 36). The coal zone in these areas comprises 20 or more individual coal beds (Figure 37) spread over an 80 to 100 metre thick stratigraphic interval (Figure 38). The coal zone therefore contains between 15 and 30 per cent coal over the best parts of this subarea (Figure 39) and it can be expected that, with more detailed evaluation, areas can be located where many of these coal beds coalesce to form completion zones with ten or more metres of aggregate coal thickness.

The in situ coalbed methane resource concentration over the best parts of this subarea ranges from six to more than nine billion cubic feet per square mile (Figure 40) for an in place resource of approximately four trillion cubic feet. The CO_2 sequestration capacity concentration over this same area ranges from 325 to more than 500 million cubic metres per square kilometre (Figure 41) for a total in situ CO_2 storage capacity of about 560 billion cubic metres or 1065 megatonnes.

This subarea lies midway between, and 45 to 60 kilometres from, two major point sources of CO_2, the Harlan-Robb gas plant to the south and the Kabob South gas plant to the north (Figures 33 and 42). The coal zone in this subarea lies at a depth of between 400 and 600 metres, resulting in drilling costs per well of between \$50,000 and \$250,000 (Figure 43).

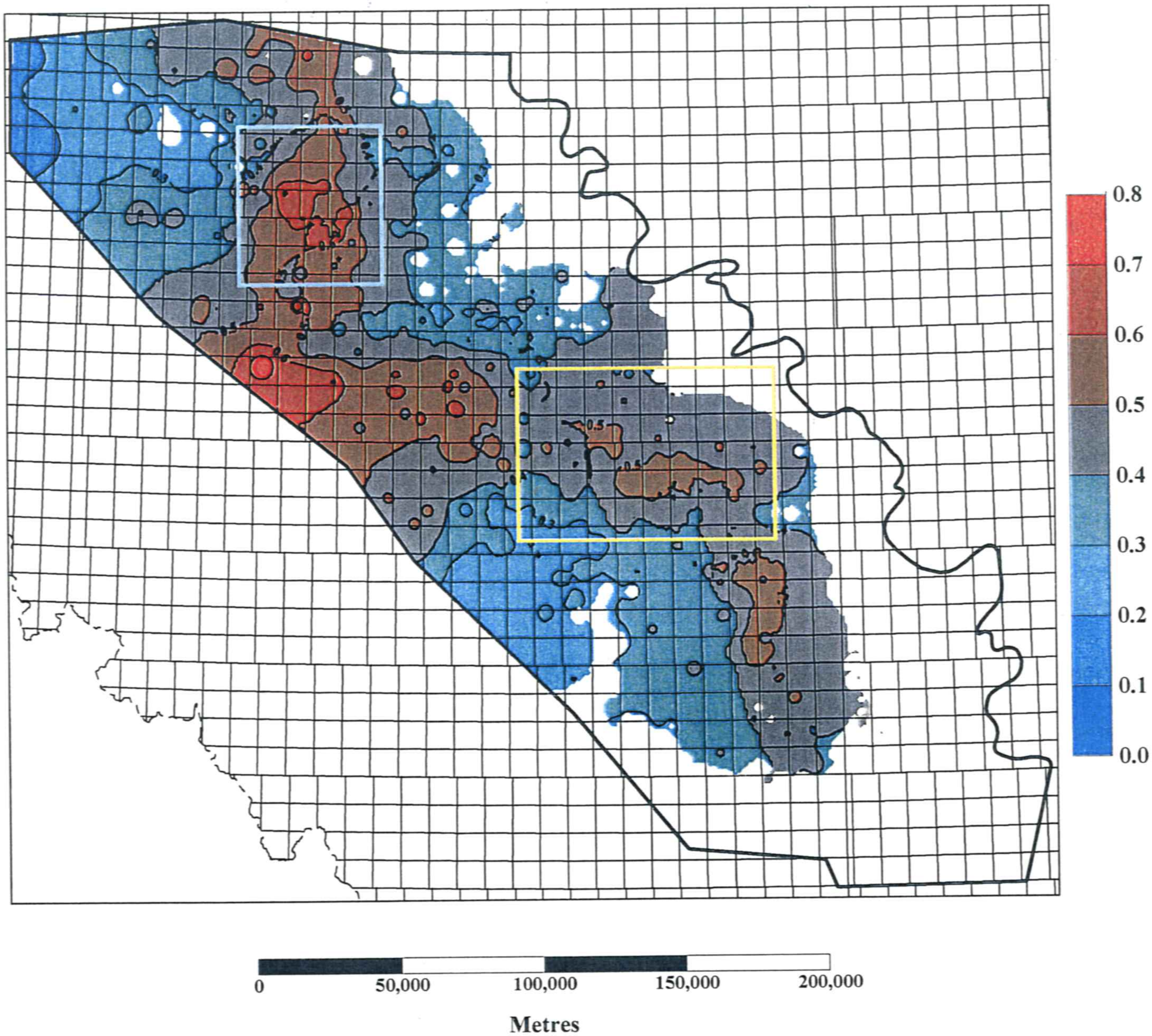

Figure 35 - Favourability index map for CO_2 sequestration. The reservoirs with the highest potential have a favourability index near 1. The two areas of interest which have a high potential for both coalbed methane production and CO_2 sequestration are outlined in blue ("north target subarea" - see text) and yellow ("south target subarea" - see text).

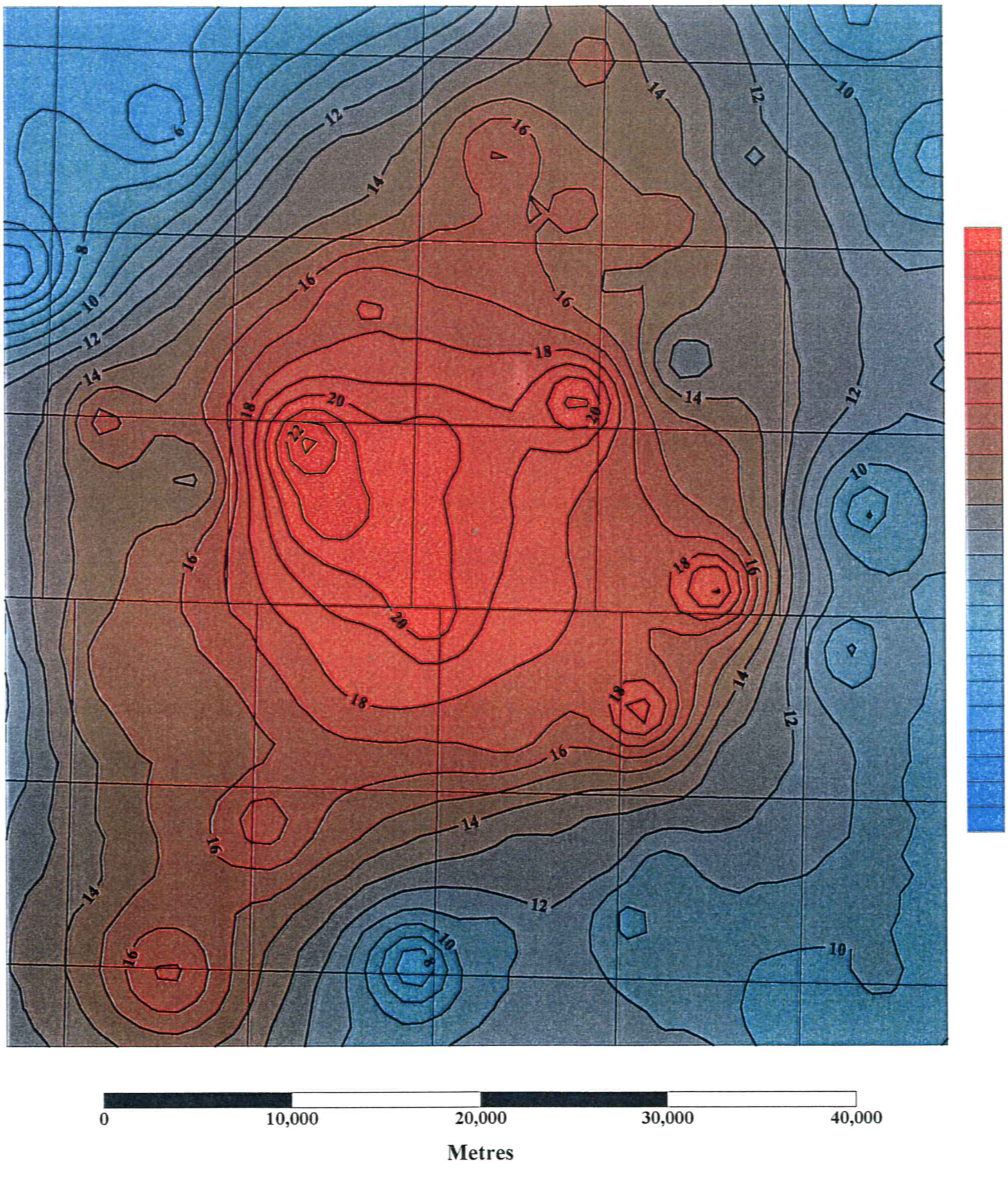

Figure 36 - Aggregate thickness of all coal beds in the northern target subarea, in metres. See Figure 35 for location.

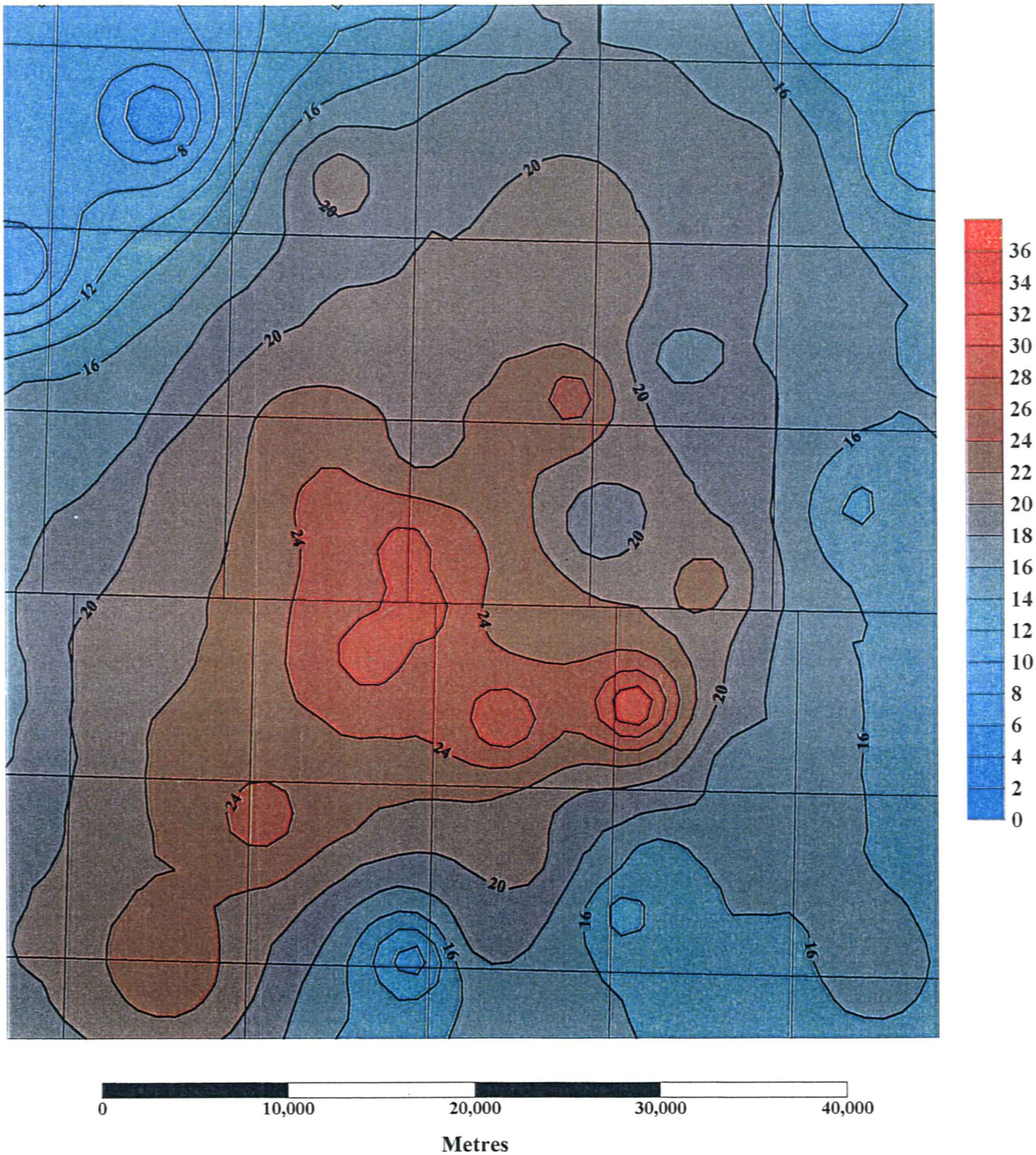

Figure 37 - Number of individual coal beds in the northern target subarea. See Figure 35 for location.

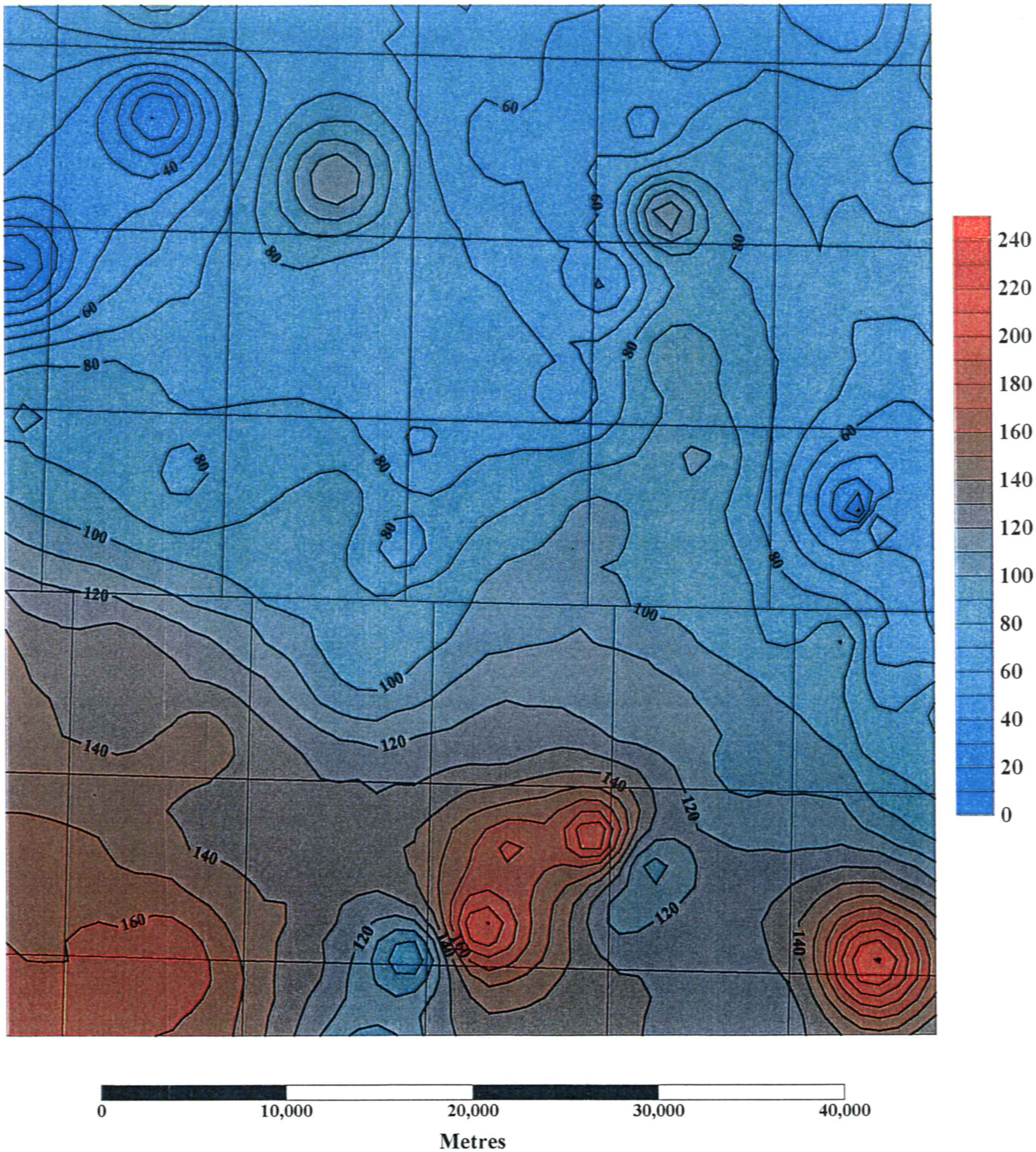

Figure 38 - Overall thickness of the Ardley Coal Zone, including all coal beds and rock partings, in the northern target subarea, in metres. See Figure 35 for location.

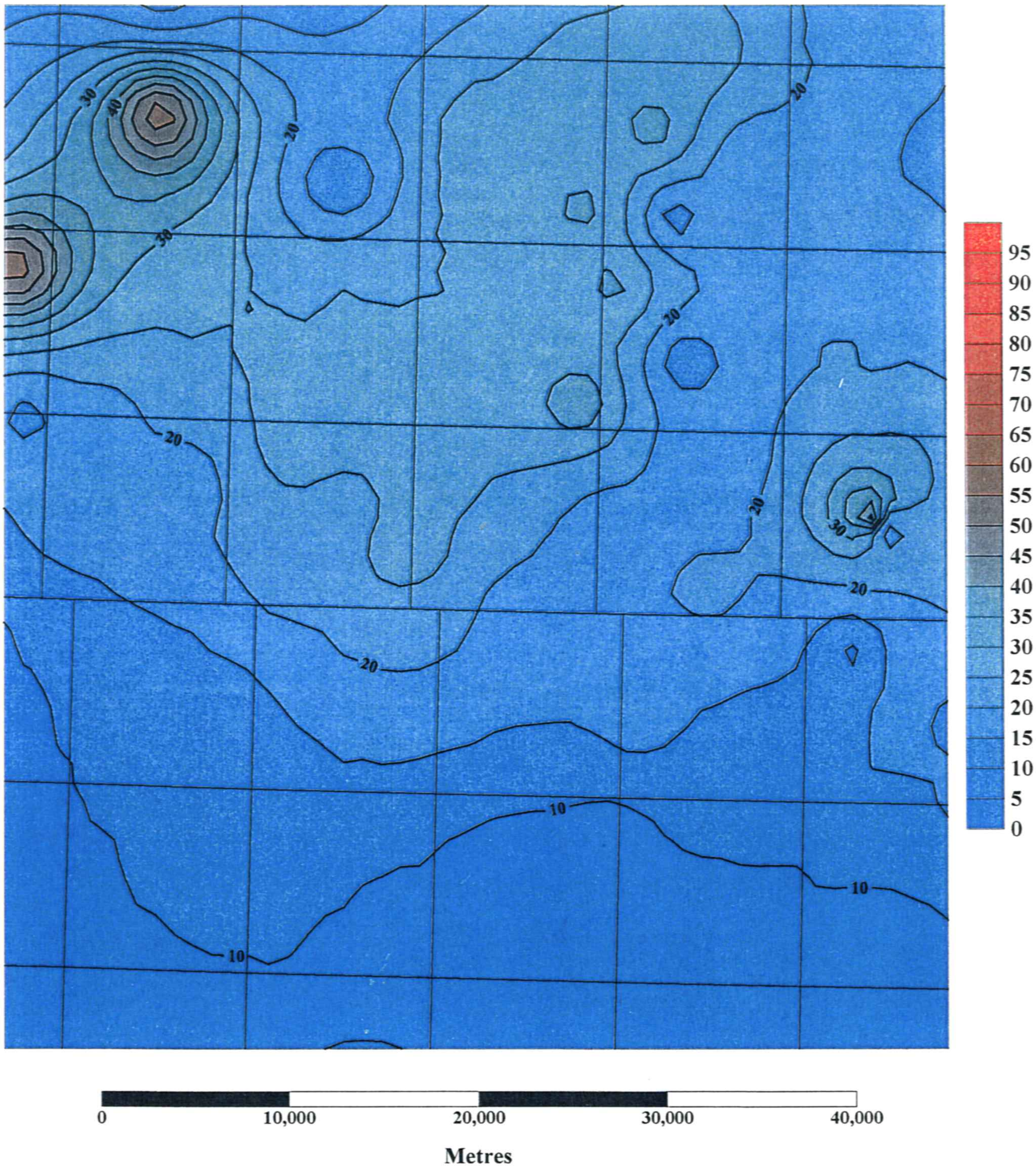

Figure 39 - Percentage of coal within the overall thickness of the Ardley Coal Zone in the northern target subarea. See Figure 35 for location.

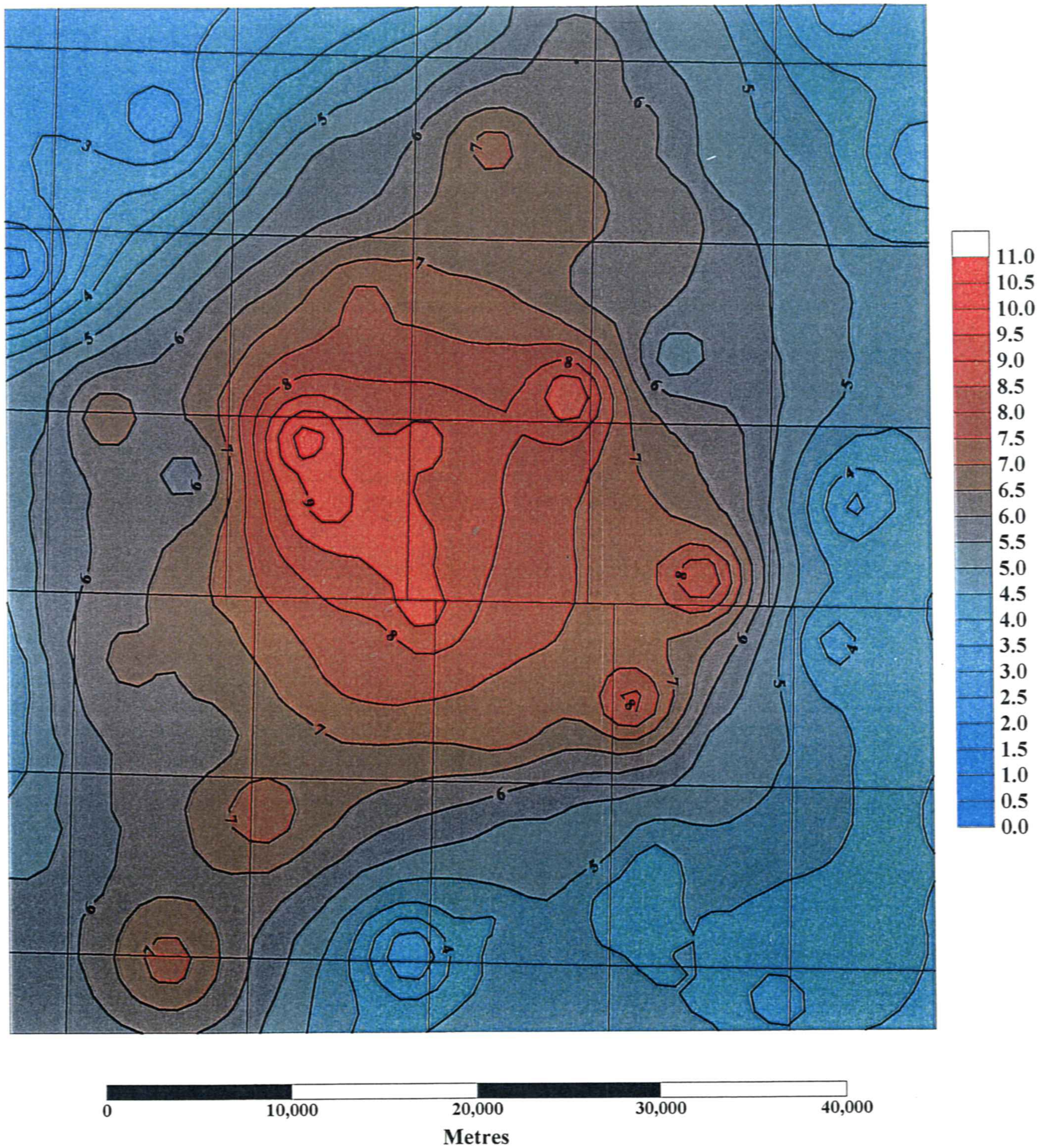

Figure 40 - In situ methane gas concentration in the northern target subarea, expressed as billion cubic feet per square mile. Methane gas concentration is the product of in situ gas content and aggregate reservoir thickness. See Figure 35 for location.

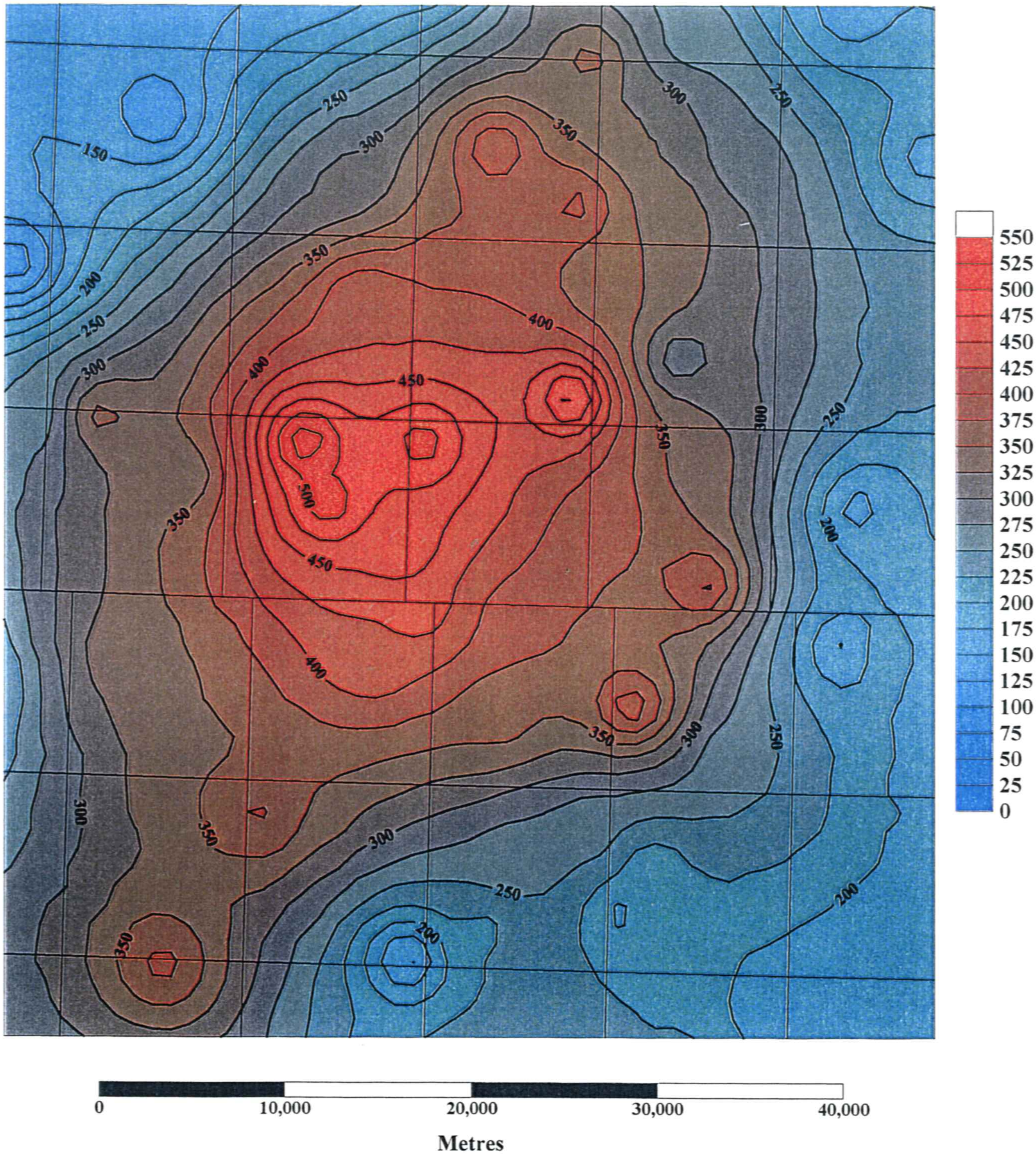

Figure 41 - CO_2 storage capacity concentration in the northern target subarea, expressed as millions of cubic metres per square kilometre. CO_2 storage capacity concentration is the product of CO_2 storage capacity as determined from reservoir pressure and CO_2 adsorption isotherm analytical data, and the aggregate reservoir thickness. See Figure 35 for location.

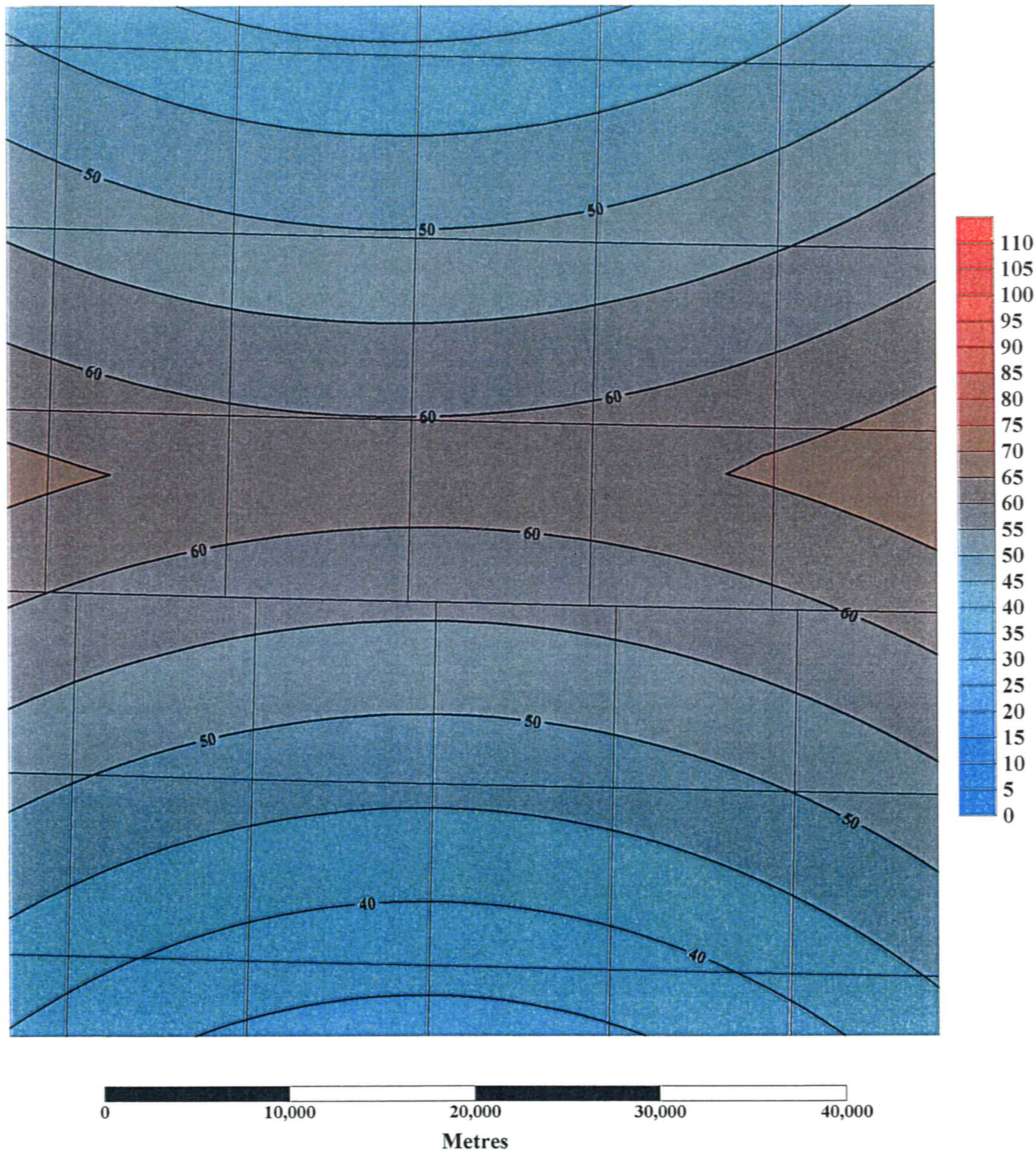

Figure 42 - Distance within the northern target subarea from the nearest point source of CO_2, in kilometres. The nearest sources are the Harlan-Robb gas plant to the south and the South Kabob gas plant to the north (see Figure 33 for location). See Figure 35 for location.

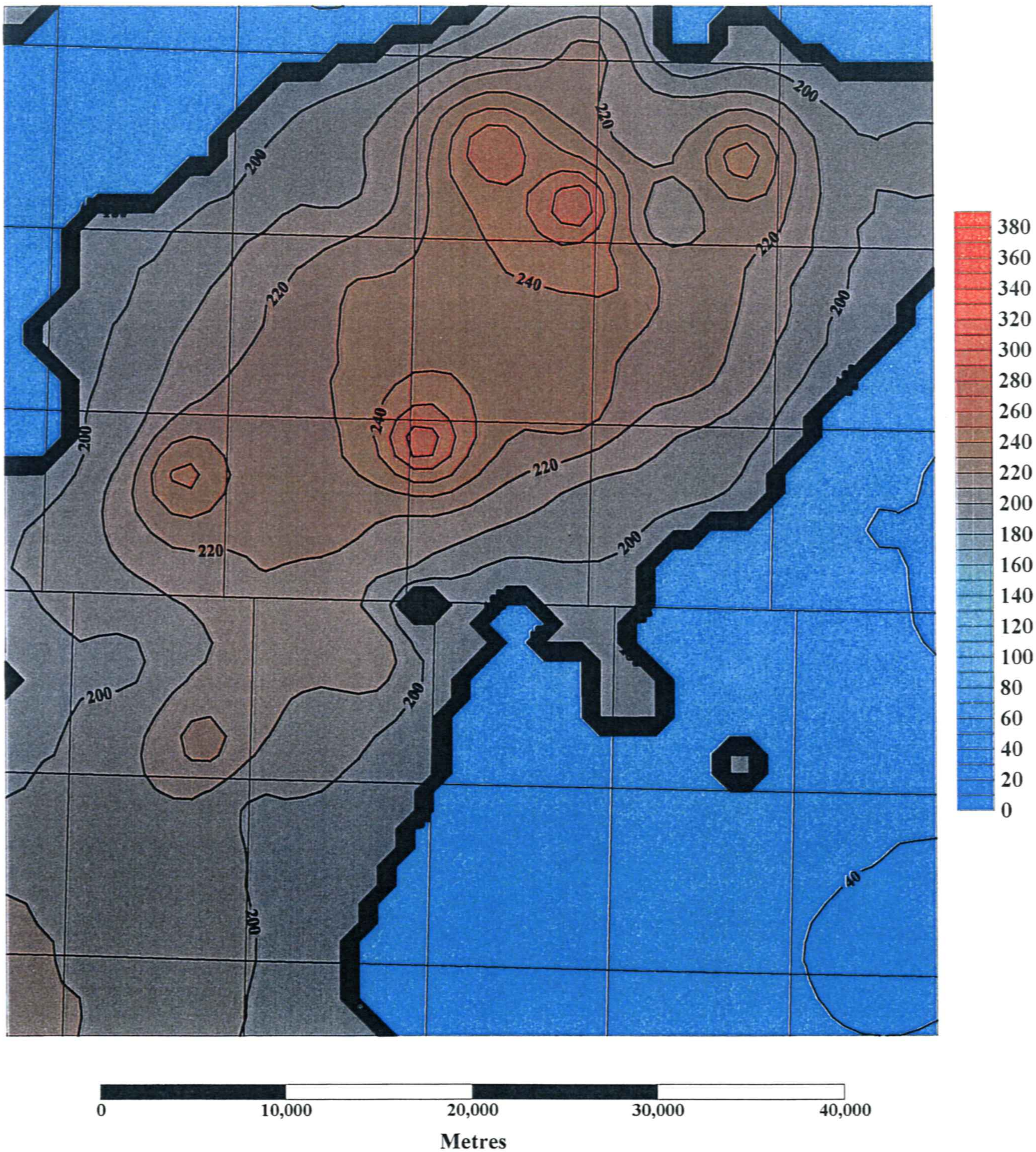

Figure 43 - Estimated costs of completing production/injection wells in the northern target subarea, in thousands of dollars. See Figure 35 for location.

South Target Subarea

The south target subarea (see Figure 35 for location) contains more than 11 metres of aggregate coal thickness over a 2300 square kilometre area, and more than 14 metres of aggregate coal thickness over a 500 square kilometre area (Figure 44). The coal zone in these areas comprises between 12 and 24 individual coal beds (Figure 45) spread over an 50 to 90 metre thick stratigraphic interval (Figure 46). The coal zone therefore contains between 15 and 20 per cent coal over the best parts of this subarea (Figure 47) and it can be expected that, with more detailed evaluation, areas can be located where many of these coal beds coalesce to form completion zones with eight or more metres of aggregate coal thickness.

The in situ coalbed methane resource concentration over the best parts of this subarea ranges from four to more than eight billion cubic feet per square mile (Figure 48) for an in place resource of approximately twelve trillion cubic feet. The CO_2 sequestration capacity concentration over this same area ranges from 200 to more than 350 million cubic metres per square kilometre (Figure 49) for a total in situ CO_2 storage capacity of about 575 billion cubic metres or 1094 megatonnes.

This subarea lies midway between, and 45 to 85 kilometres from several major point sources of CO_2 (Figures 33 and 50). The Joffre chemical plant lies to the southeast, the thermal coal plants at Lake Wabamun to the northeast, the Harlan-Robb gas plant to the west, and the Strachan, Caroline and Harmattan gas plants to the south. The coal zone in this subarea lies at a depth of between 300 and 600 metres, resulting in drilling costs per well of between $50,000 and $250,000 (Figure 51).

Conclusions

The Ardley Coal Zone offers considerable potential as an exploration target for coalbed methane production and as a potential reservoir for CO_2 sequestration. It is the shallowest and thickest of the eight major coal zones underlying the Alberta Plains and, by analogy to coals of similar maturity in the Powder River Basin of Wyoming, should contain substantial amounts of biogenic and lesser amounts of thermogenic gas. Areas with the highest potential are relatively restricted geographically, however, and considerable additional geological evaluation will be required to map reservoir characteristics including coal bed geometry and permeability required to select optimal completion intervals and drilling locations. The best portions of the Ardley Coal Zone offer aggregate reservoir thicknesses of greater than 20 metres, in situ methane gas concentrations of greater than nine billion cubic feet per section, and CO_2 storage capacities of greater than 500 million cubic metres per square kilometre or one megatonne per square kilometre. The Ardley Coal Zone lies adjacent to many potential point sources of CO_2 and can be accessed at relatively low cost because of its shallow depth.

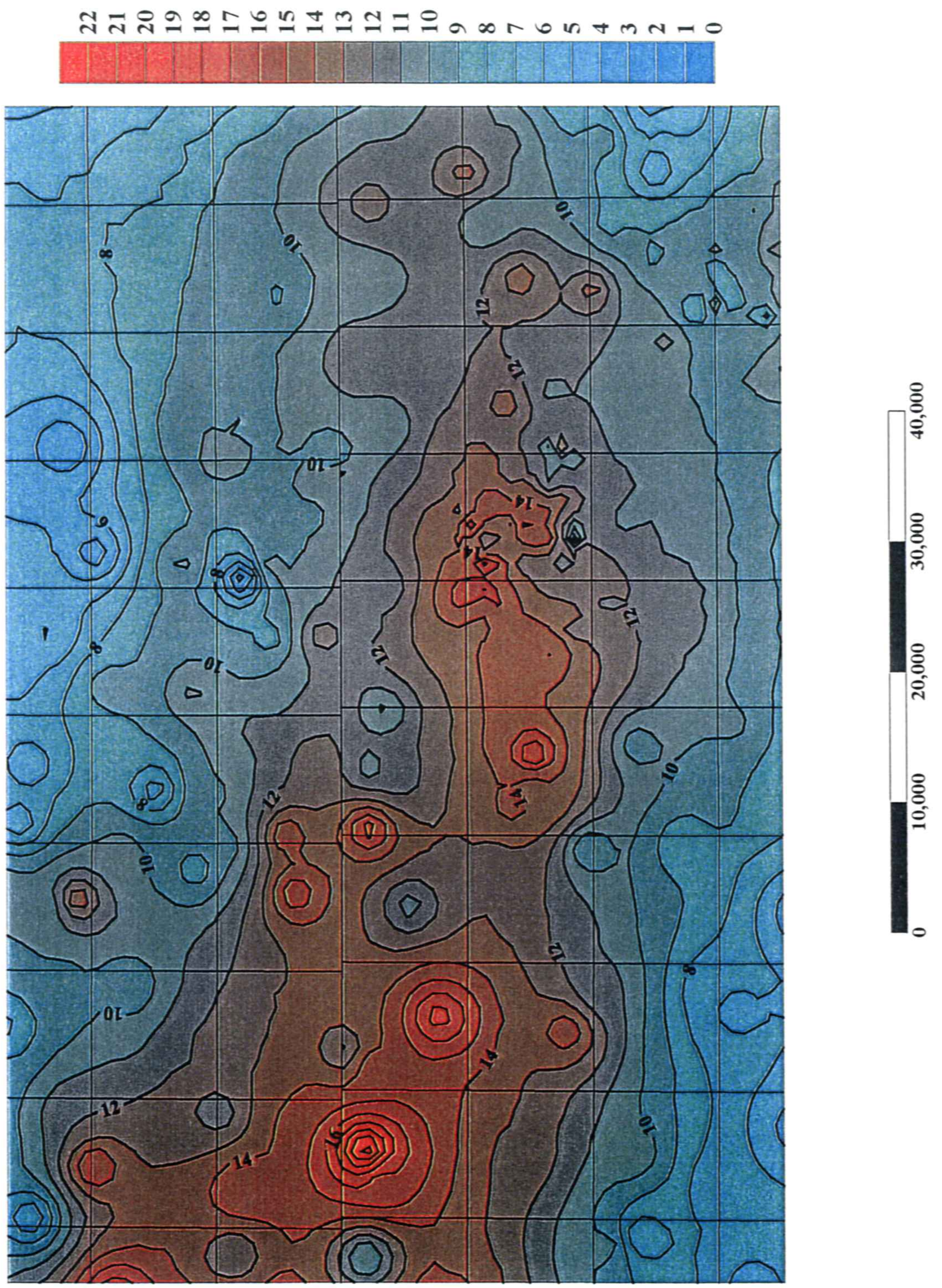

Figure 44 - Aggregate thickness of all coal beds in the southern target subarea, in metres. See Figure 35 for location.

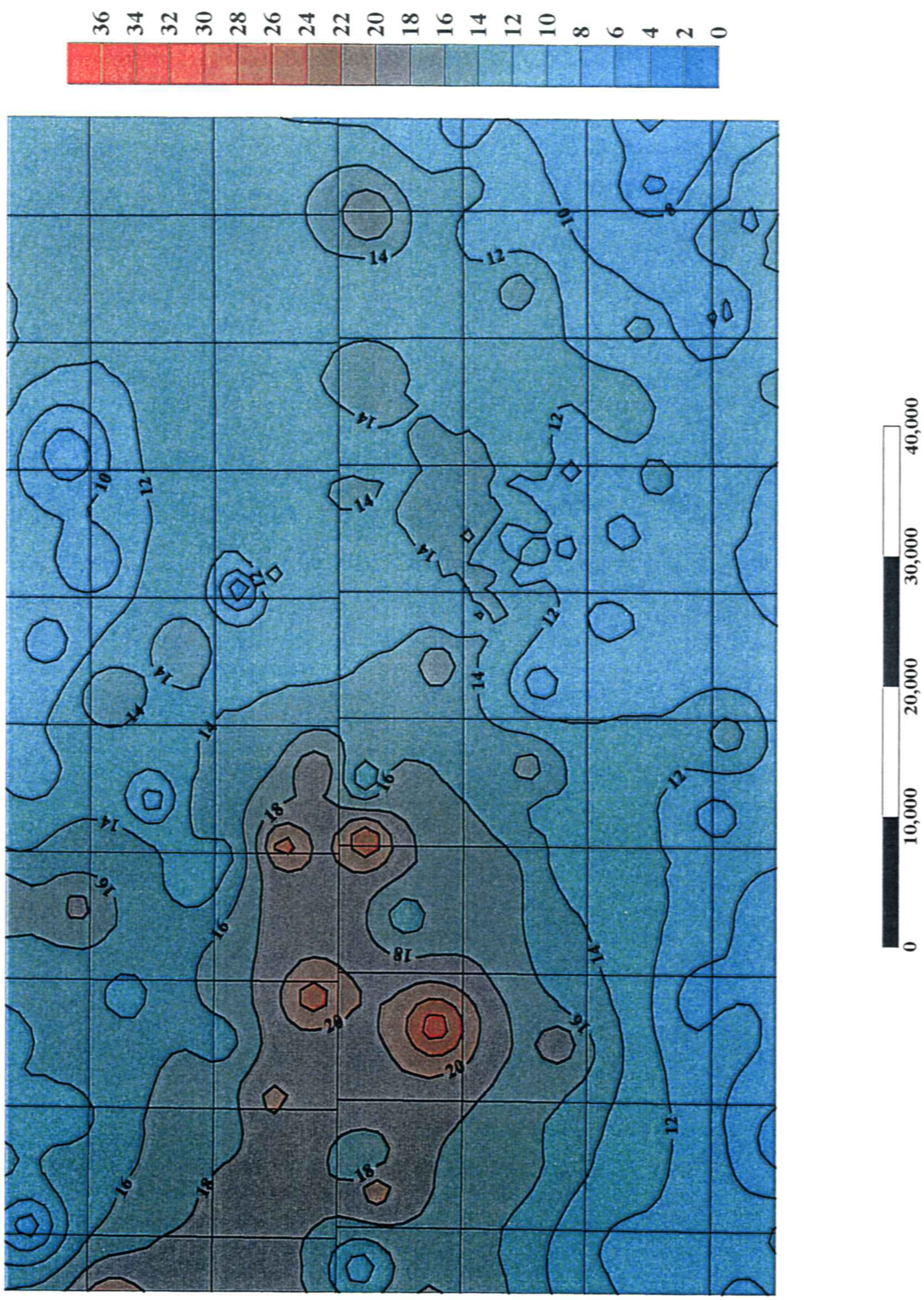

Figure 45 - Number of individual coal beds in the southern target subarea. See Figure 35 for location.

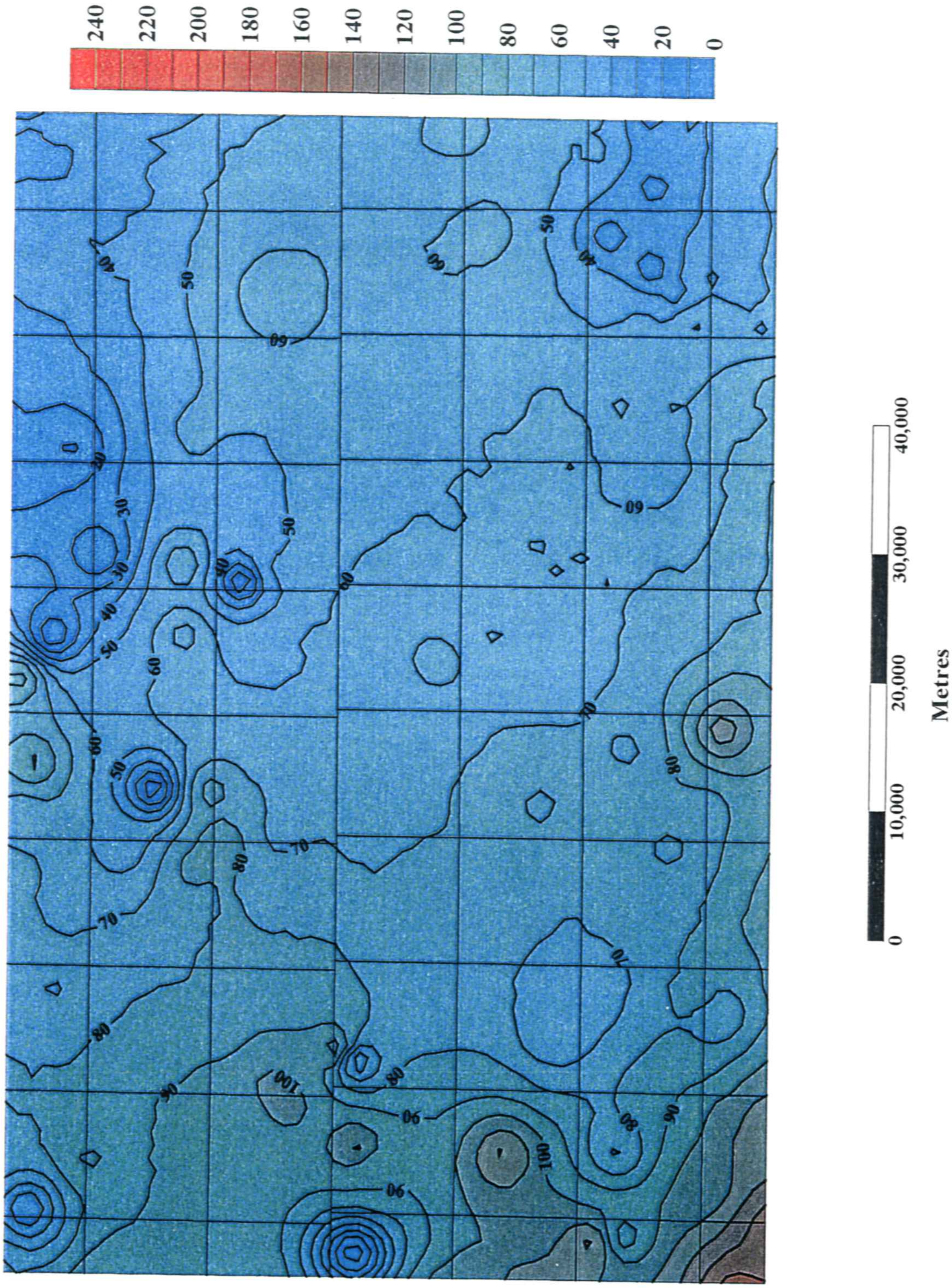

Figure 46 - Overall thickness of the Ardley Coal Zone, including all coal beds and rock partings, in the south target subarea, in metres. See Figure 35 for location.

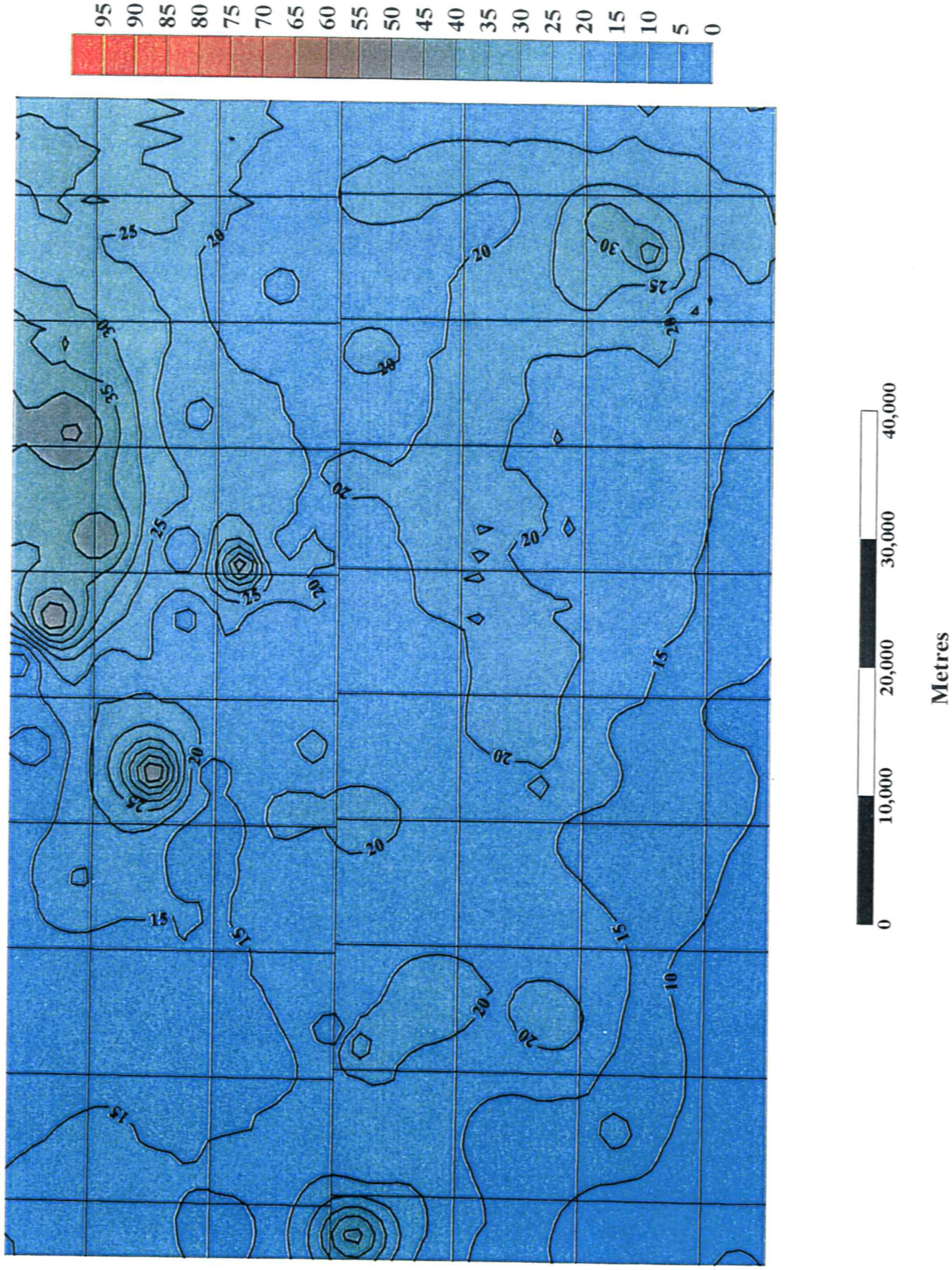

Figure 47 - Percentage of coal within the overall thickness of the Ardley Coal Zone in the southern target subarea. See Figure 35 for location.

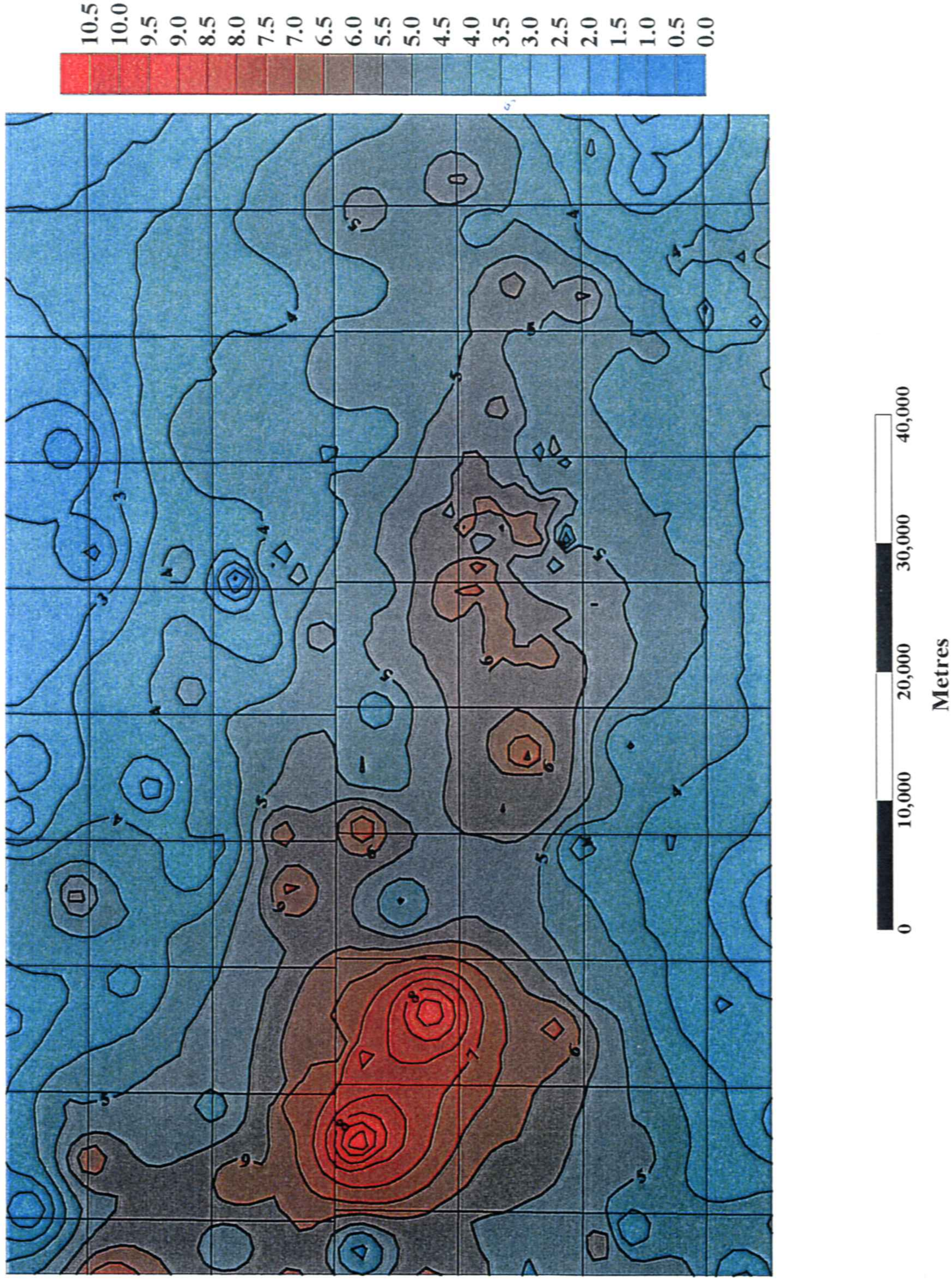

Figure 48 - In situ methane gas concentration in the southern target subarea, expressed as billion cubic feet per square mile. Methane gas concentration is the product of in situ gas content and aggregate reservoir thickness. See Figure 35 for location.

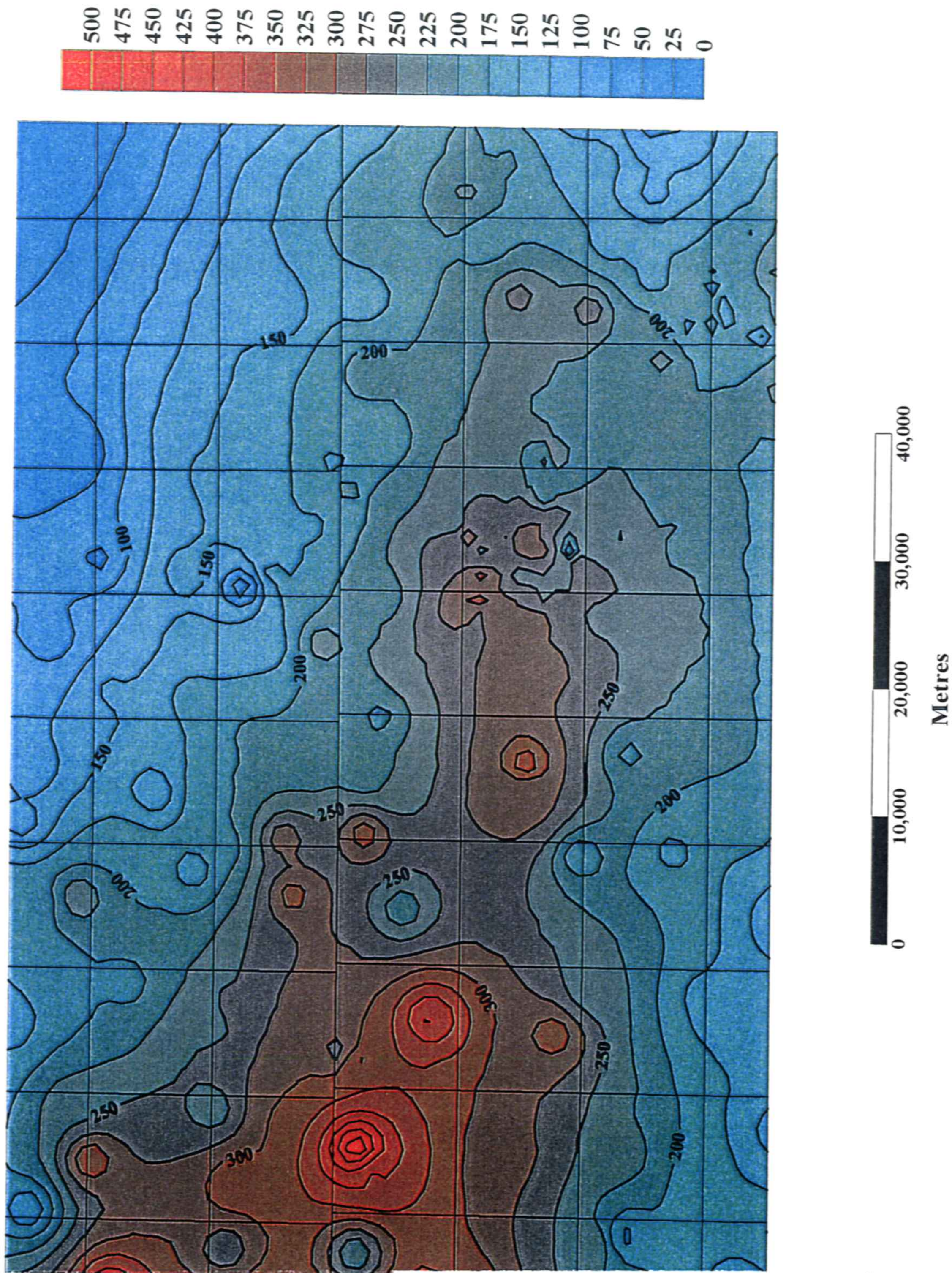

Figure 49 - CO_2 storage capacity concentration in the southern target subarea, expressed as millions of cubic metres per square kilometre. CO_2 storage capacity concentration is the product of CO_2 storage capacity as determined from reservoir pressure and CO_2 adsorption isotherm analytical data, and the aggregate reservoir thickness. See Figure 35 for location.

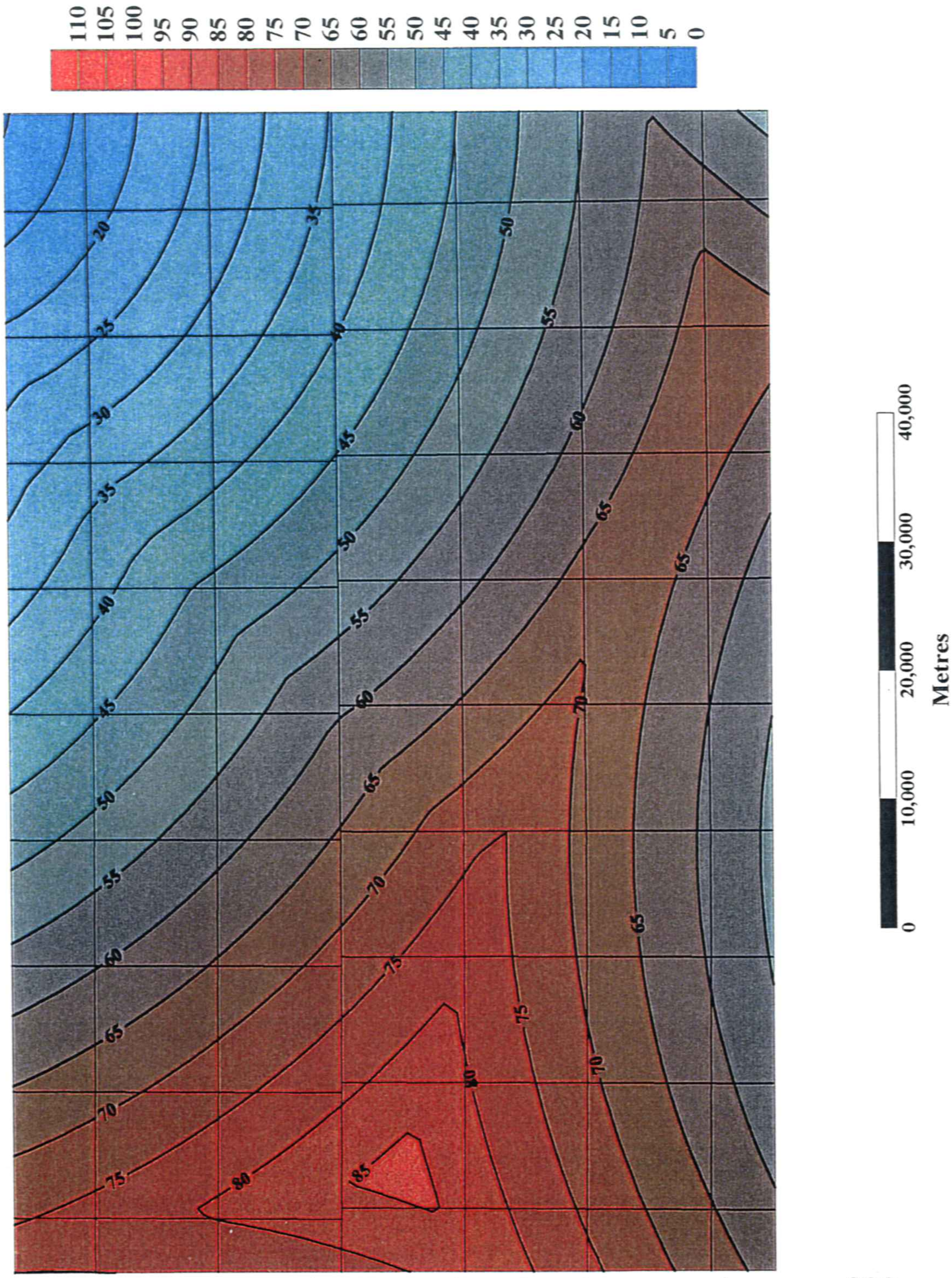

Figure 50 - Distance within the southern target subarea from the nearest point source of CO_2 in kilometres. The nearest sources are the thermal coal power plants at Lake Wabamun to the northeast, the Joffre chemical plant to the southeast, the Strachan, Caroline and Harmattan gas plants to the south, and the Harlan-Robb gas plant to the west (see Figure 33 for locations). See Figure 35 for the location of the southern target subarea.

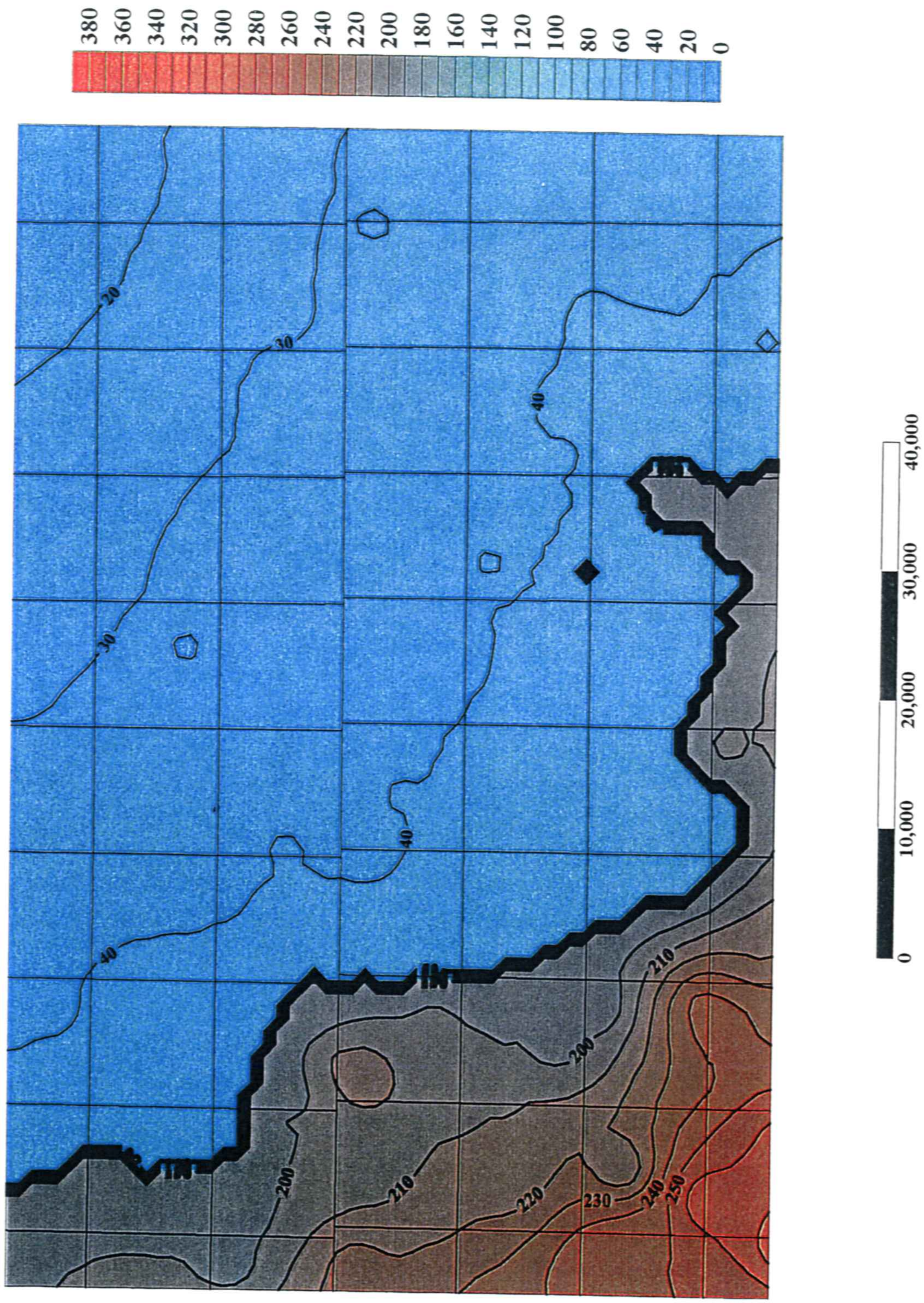

Figure 51 - Estimated costs of completing production/injection wells in the southern target subarea, in thousands of dollars. See Figure 35 for location.

Acknowledgments

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