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APPLICATION OF HRAM SURVEYING TO CAMBRIAN EXPLORATION IN THE APPALACHIAN BASIN

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ABSTRACT

High resolution aeromagnetic surveying has been done in an area located in the northwestern flank of the Appalachian Basin. The surveying was done for Cambright Gas Corporation of London, Ontario, for purposes of exploration for hydrocarbons in Cambrian strata overlying the Precambrian basement. A number of oil fields have been developed in these rocks, e.g., the Innerkip, Gobles and Clearville Pools.

From a detailed analysis of the magnetic data, using a rather conventional method of analysis, based on modelling, four Precambrian lithologic units were distinguished according to magnetic susceptibility and also sense of magnetization. The distribution of known hydrocarbon reservoir rocks was found to be highly correlated with the contacts separating these magnetic/lithologic units. Some of the magnetic contacts were, in places, identified as faults as reflected in seismic data. Also, zones of increased reservoir thickness were correlated with rocks of higher magnetization/iron content and thus could be expected to be less resistant to erosion.

The magnetic data were found to be useful in providing information about the potential location of structural as well as stratigraphic traps. It is concluded that seismic surveying over "magnetic structure prospects" would be a cost effective means of hydrocarbon exploration in this region.

INTRODUCTION AND GEOLOGICAL SETTING

This paper presents a case history in the application of high resolution aeromagnetic data to hydrocarbon exporation. The setting is southwestern Ontario.

Figure 1 shows the location of the study area from the perspective of the regional geology of Canada. Most, if not all, of the geological material referenced in this paper, including Figure 1, are taken from Sanford et al. (1985). The study area is located on the flank of the Algonquin Arch; a major positive basement structure that separates the Michigan and Appalachian Basins. The study area is located on the updip edge of the Appalachian Basin which to the east thickens to over 13 000 m of Paleozoic rocks. Underlying SW Ontario, the 800 to 1500 m thick sedimentary succession hosts hydrocarbon pools in distinct levels described in Figure 2; in shallow Devonian structures, in Silurian pinnacle and patch reefs, in Ordovician dolomitized limestones and in Cambrian sandy dolomites overlying the Precambrian – the focus of this paper.

Figure 3 shows the "conceptual fracture framework" for SW Ontario proposed by Sanford et al. (1985); an idealized system of faults proposed to be associated with the development of the Algonquin Arch. This structural model is fairly consistent with known faulting and with a great deal of well geological data.

Figure 3 also shows the location of Cambrian gas pools, namely the Innerkip, Gobles and Clearville Pools. The location of all of these pools appear to be associated with the proposed structure model. Figure 4 shows an isopach map which defines the north limit of Cambrian deposition/hydrocarbon reservoir development. This map is taken from Bailey and Cochrane (1984). Virtually all of the development is in Cambrian intervals of sandy dolomite less than 10 m thick. Figure 5 describes the Innerkip and Gobles Pools in section. These pools are located at depths less than 900 m below ground or 1100 m below the aeromagnetic survey altitude. The Innerkip Pool, currently developed by Cambright Gas, has produced over 20 Bcf gas. The Gobles Pool produced 1.5 million barrels of oil and 5 Bcf gas.

MAGNETIC DATA AND ITS ANALYSIS

Aeromagnetic Data

Figure 6 is a Vertical Gradient Aeromagnetic Map of the Innerkip-Gobles area. The data was obtained from a high resolution survey conducted by Terraquest Survey Corporation of Toronto in 1997, on behalf of Cambright Gas. The "grid" survey consisted of both NW and NE directed lines at 500 to 700 m spacing and 500 m barometric altitude (about 200 m above ground). The data, measured using a Cesium vapour magnetometer, has a system noise component of less than 0.1 nT. To this is added a 2 to 10 nT cultural noise component associated with man-made objects such as well casing, pipelines, culverts, etc.

Survey products included Total Intensity and Vertical Gradient (calculated) maps as well as composite profiles of this data together with diurnal magnetic and altimeter data, all at 1:30,000 scale. Figure 7 shows a sample of this

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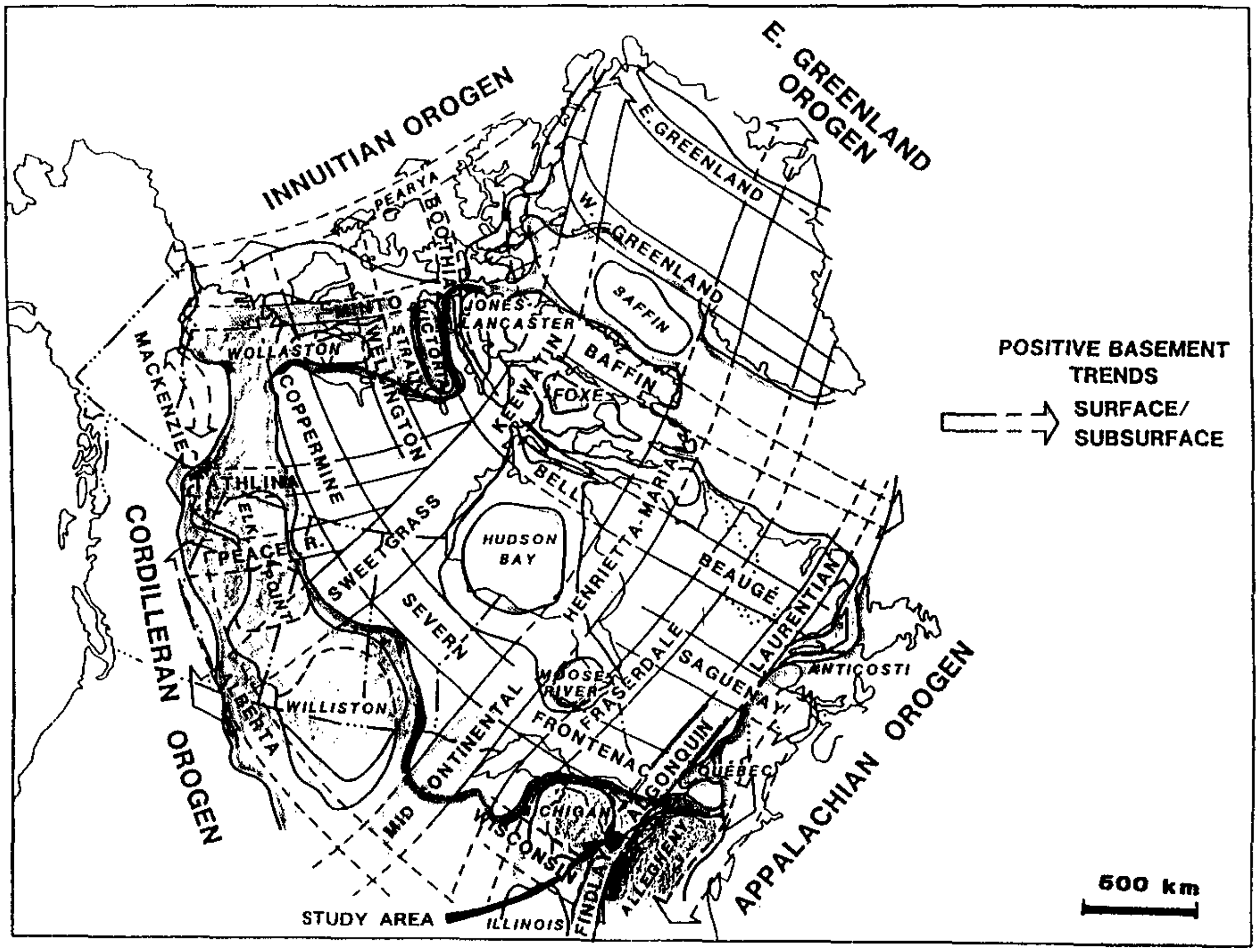

Fig. 1. Regional geological setting of project area, from Sanford et al. (1985).

composite profiling as well as analysis annotations describing anomaly discrimination, location of magnetic contacts, depth determination, etc. Experience has shown the author (A.S.) that only about half the geological data that is extractable from survey data are expressed in magnetic contour maps and their derivatives. To achieve full productivity the data must be examined in profile form.

Magnetic Modelling

The magnetic data analyses were done with reference to model anomaly profiles. Figure 8 shows a few of the suite of 21 model anomaly profiles that were plotted for this study. To compute the profiles, we used the following geomagnetic field characteristics for the area;

declination: 6 degrees west
inclination: 73 degrees north
intensity: 57,000 nT

The model profiles simulate anomalies created by various prismatic bodies (infinite strike length, vertical dip, infinite depth extent and flat top) which comprise *infrabasement* lithologic units. Also, profiles were computed over plate-like bodies that approximate topographic structures or *suprabasement* features. Induced magnetization only was presumed; susceptibility contrast of 1000 x 10^{-6} cgs units. The model profiles provide a basis for locating magnetic contacts and estimating depth of burial. Because the model profiles are computed for *vertically dipping* bodies, they provide a reference for determining direction of magnetic bedding dip in cases where observed anomalies display clear asymmetry. Computation of the model profiles was done using a FORTRAN program which utilizes the expression for the magnetic anomaly due to a vertical step given in Grant and West (1965, p. 319-320).

An important observation from modelling is that the minimum resolvable width of a magnetized zone is the depth to

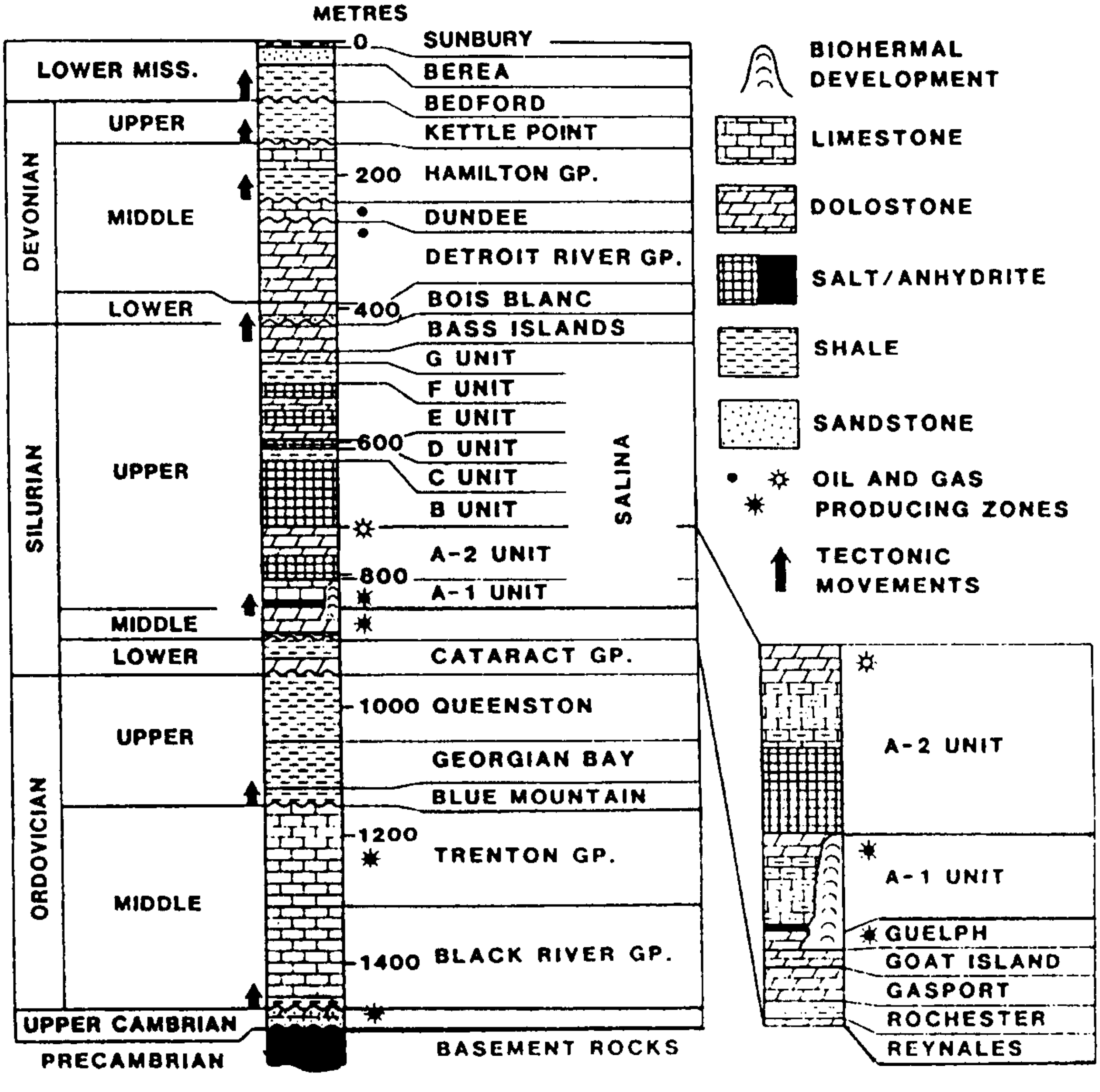

Fig. 2. SW Ontario stratigraphy and hydrocarbon development, from Sanford et al. (1985).

that zone. In the study area, this width is about 1200 m. The anomaly due to a 20 m wide zone is not distinguishable from that of a 1200 m wide zone. This has important implications in the resolution of structural mapping, e.g., the minimum separation of adjacent structures.

Suprabasement anomaly amplitudes as seen in the lower four inserts of Figure 8, are observed to be much smaller; 8 to 10 nT than those due to corresponding infrabasement features; 100 nT, even though topographic relief is about 100 m.

Assuming magnetization by induction only, the modelling can also be used to estimate magnetic susceptibility from anomaly amplitude and estimated body size. Using an empirical relationship shown on page 367 of Grant and West (1965) we can convert susceptibility to an estimate of magnetite content of the rock unit that is the source of the magnetic anomaly.

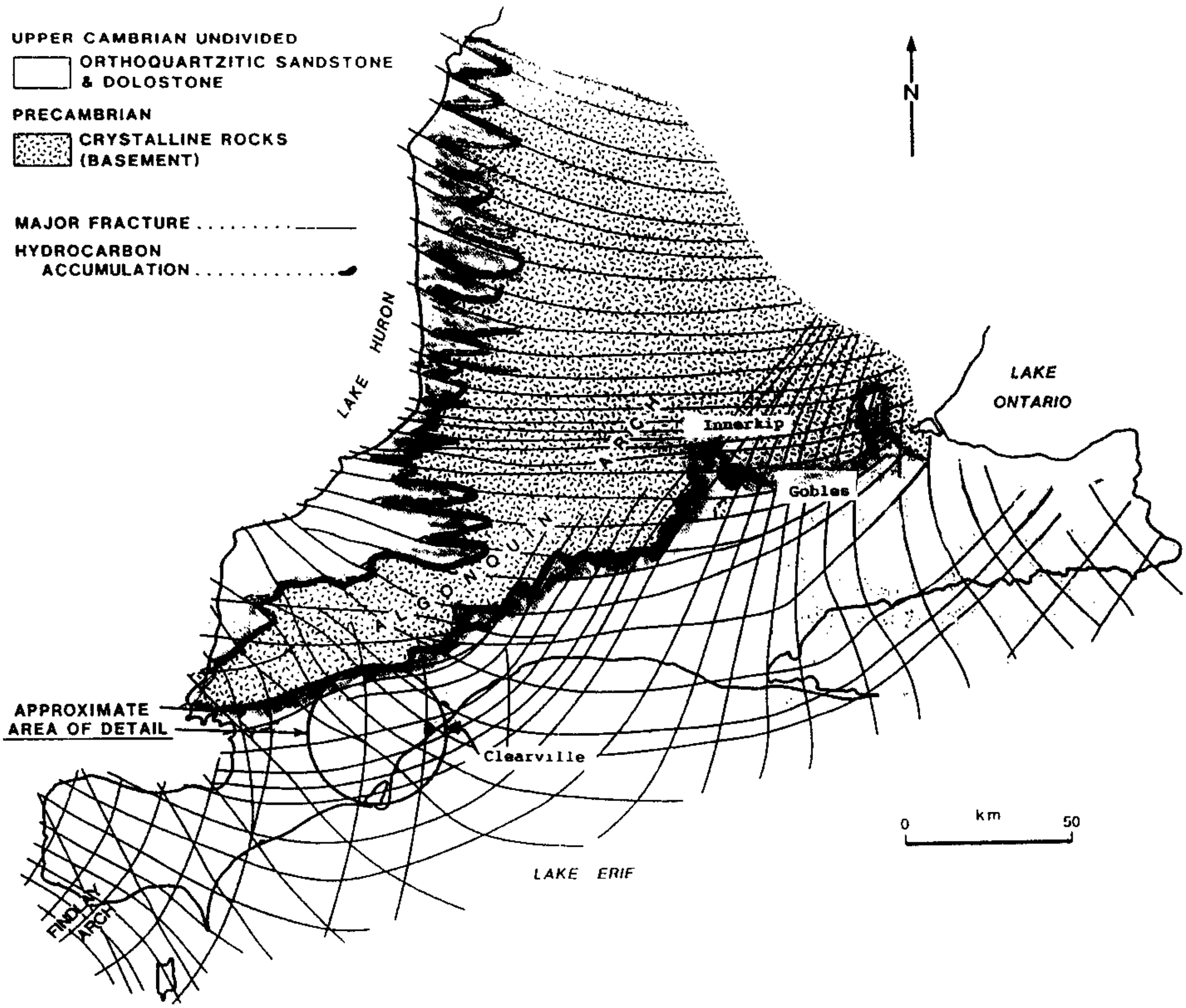

Fig. 3. Sanford's conceptual structural framework.

Magnetic Depth Determination

The empirical "straight-slope" method (SSM) of determining depth to magnetic basement was employed because of its simplicity, proven reliability and versatility. This hands-on approach permits the analyst to more readily distinguish noise features (conspicuous wavelength composition) and also deal with the problem of overlapping anomalies. The method is less likely to produce spurious results that so often emanate from computer-automated processing.

Having identified at least part of an anomaly, the analyst examines that part of the anomaly exhibiting steepest gradient and then marks the length of the straight slope portion, as seen in Figure 8. The horizontal projection of this interval (S) serves as an estimator of depth (H). S is independent of anomaly amplitude. For further evaluation of the SSM, the reader may be directed to Rao and Babu (1984). Results observed from the model anomaly study are summarized below;

For anomalies that are infrabasement in origin;

S = 0.5 H	thin bodies	(W < 2S)
S = 0.6 H	"normal" bodies	(2S < W < 4S)
S = 0.7 H	thick bodies	(W > 4S)

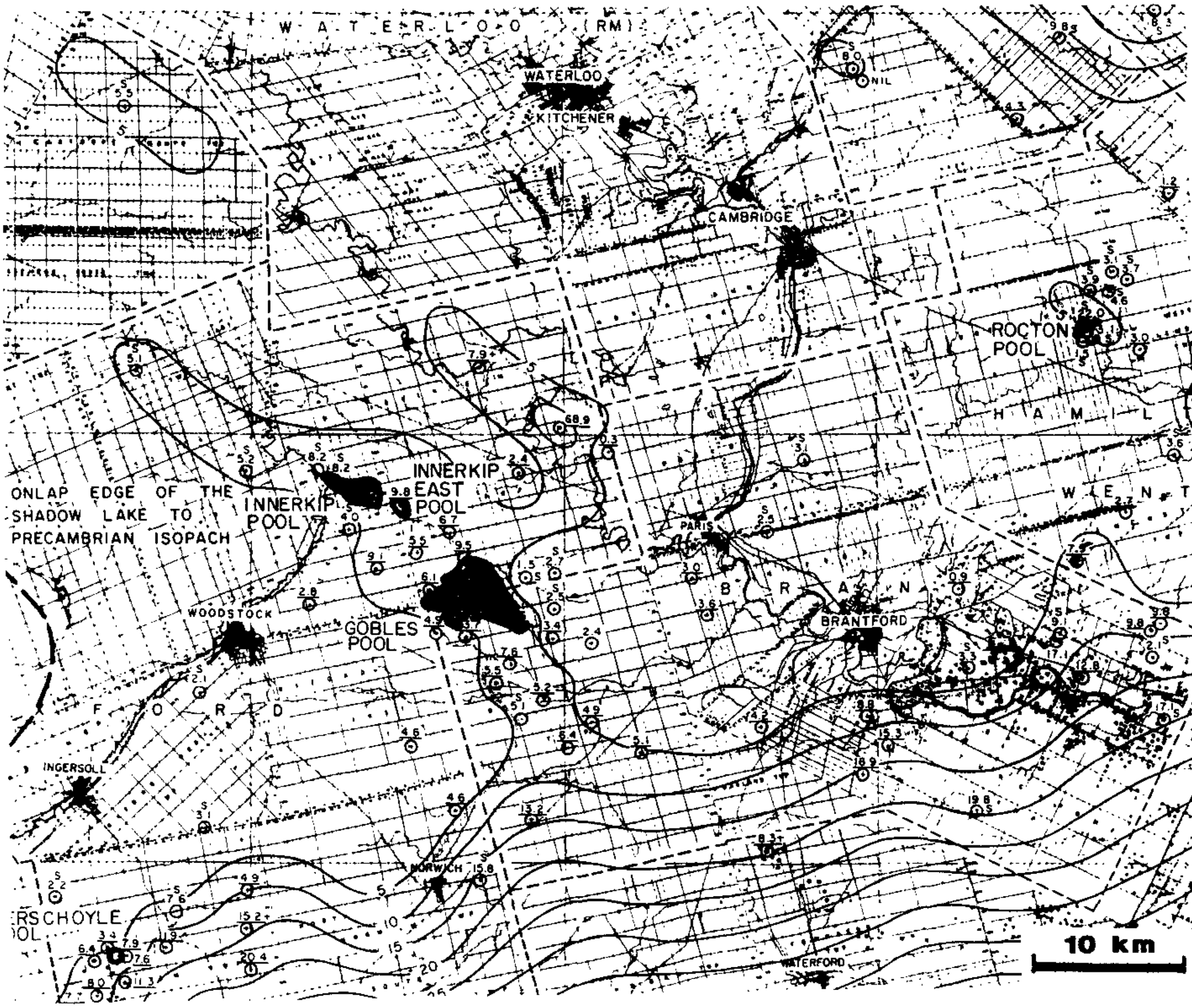

Fig. 4. Shadow Lake – Cambrian isopach map, from Bailey and Cochrane (1984).

For anomalies that are suprabasement in origin; S = 0.45 H.

W is a measure of apparent body width; the distance between inflection points. The inflection point is located midway in the delimited straight-slope interval. By comparison, Rao and Babu (1984) estimated S = 0.6 H (thin body) and S = 0.8 H (thick body).

It has been the author's experience that the SSM method produces results that have a reliability of ± 20%. This is equivalent to ± 240 m in the study area. Steenland (1963) demonstrated a similar result in the Peace River area of Alberta.

The SSM is part of a first pass "phase" of operation that permits virtually all detectable gradients to be used for magnetic contact and depth mapping. In the second phase, the digital data together with available gravity data, in selected areas of interest, were modelled using a published, interactive modelling software package called GRAMA (Seeman, 1990) to create structure sections.

Magnetic Contacts

Figure 7 shows, as an example, the analysis of a data interval. Magnetic data at coarse and fine scales, radar altimeter and magnetic monitor data are plotted. The analysis results include anomaly resolution, magnetic contact location, depth determination and the discrimination of non-geologic, cultural features (C).

The magnetic contacts mark transitions between rock units of differing magnetization as well as possible basement

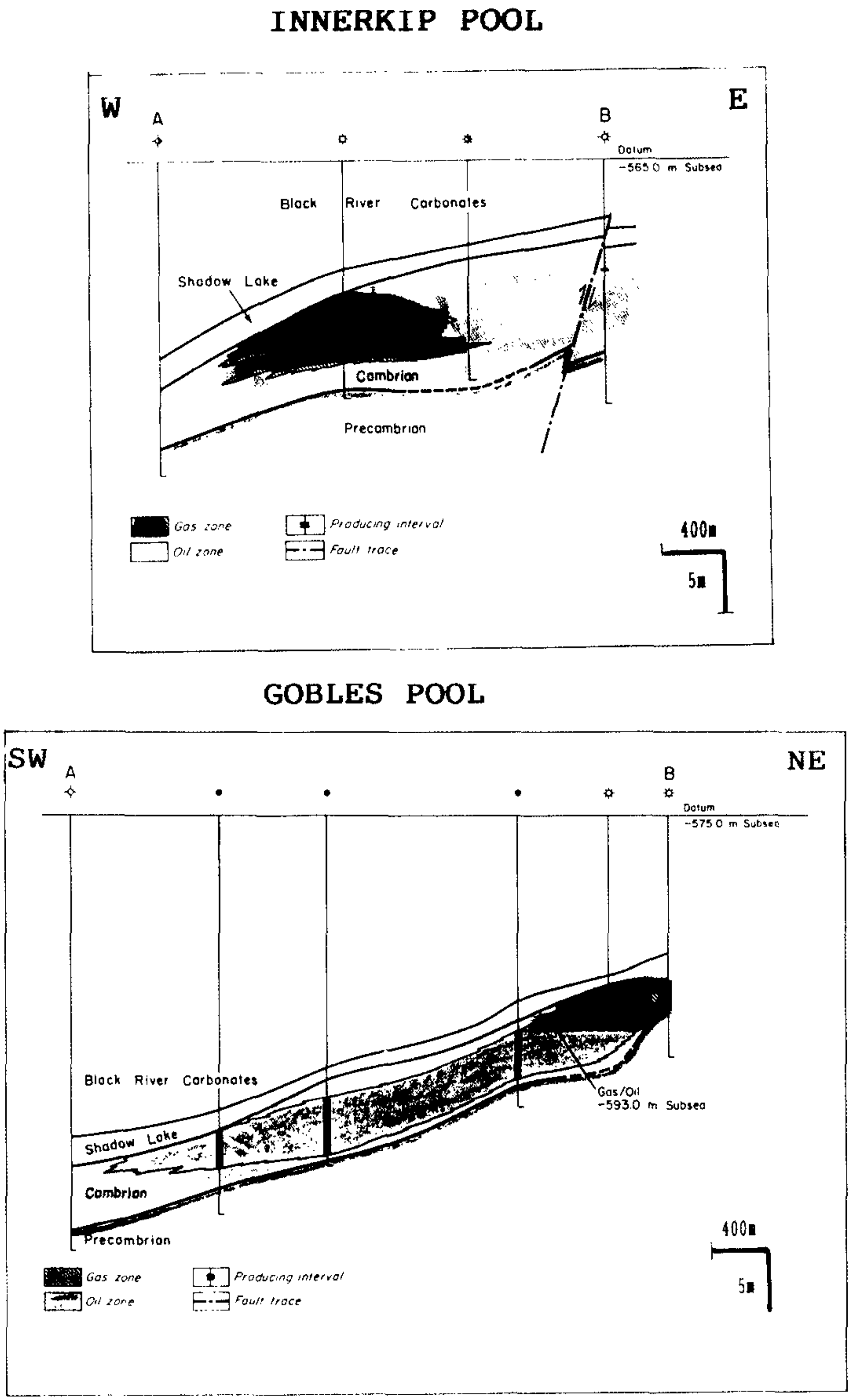

Fig. 5. Sections across Innerkip and Gobles Pools, from Bailey and Cochrane (1984).

Fig. 6. Vertical gradient aeromagnetic map of study area.

structures. The first rock type to most readily identify is that exhibiting relatively minimal magnetization. If the profile is sufficiently long, we may discern those units exhibiting nil magnetization; the "neg" zones. Secondly, rock units associated with anomalies of reversed polarity may be identified. Two or three of these units were mapped in the northeast part of the study area. These "rem" zones are indicative of rocks that either have appreciable remanent magnetization or exhibit diamagnetism, a less likely phenomenon. Lastly, rocks exhibiting moderate magnetization (magnetic relief under 100 nT) and rocks exhibiting relatively high magnetization (relief exceeding 200 nT) are discriminated.

The magnetic contact together with anomaly amplitude information are compiled in a Magnetic Contacts Overlay. This map is superimposed on the Total intensity Map (Fig. 9) and subsequently onto the Vertical Gradient Map and the Bouguer Gravity Map (Fig. 11) to map structures.

Magnetic contact mapping is similar to the "terracing operator" which Cordell and McCaffery (1989) used on magnetic data that had been transformed to pseudogravity data, to define boundaries between rock units of contrasting magnetization. However this approach suffers from the loss in resolution that results from using gridded data as opposed to viewing the basically unprocessed or unadulterated data profiles. Also, the magnetic contacts approach allows simultaneous depth-to-basement mapping and also permits the integration of results from other datasets, e.g., magnetic contacts taken from other, overlapping surveys and even ground survey data.

Geological Interpretation

Figure 10 shows the Precambrian geology of the project area as inferred from the aeromagnetic data analysis. Figure

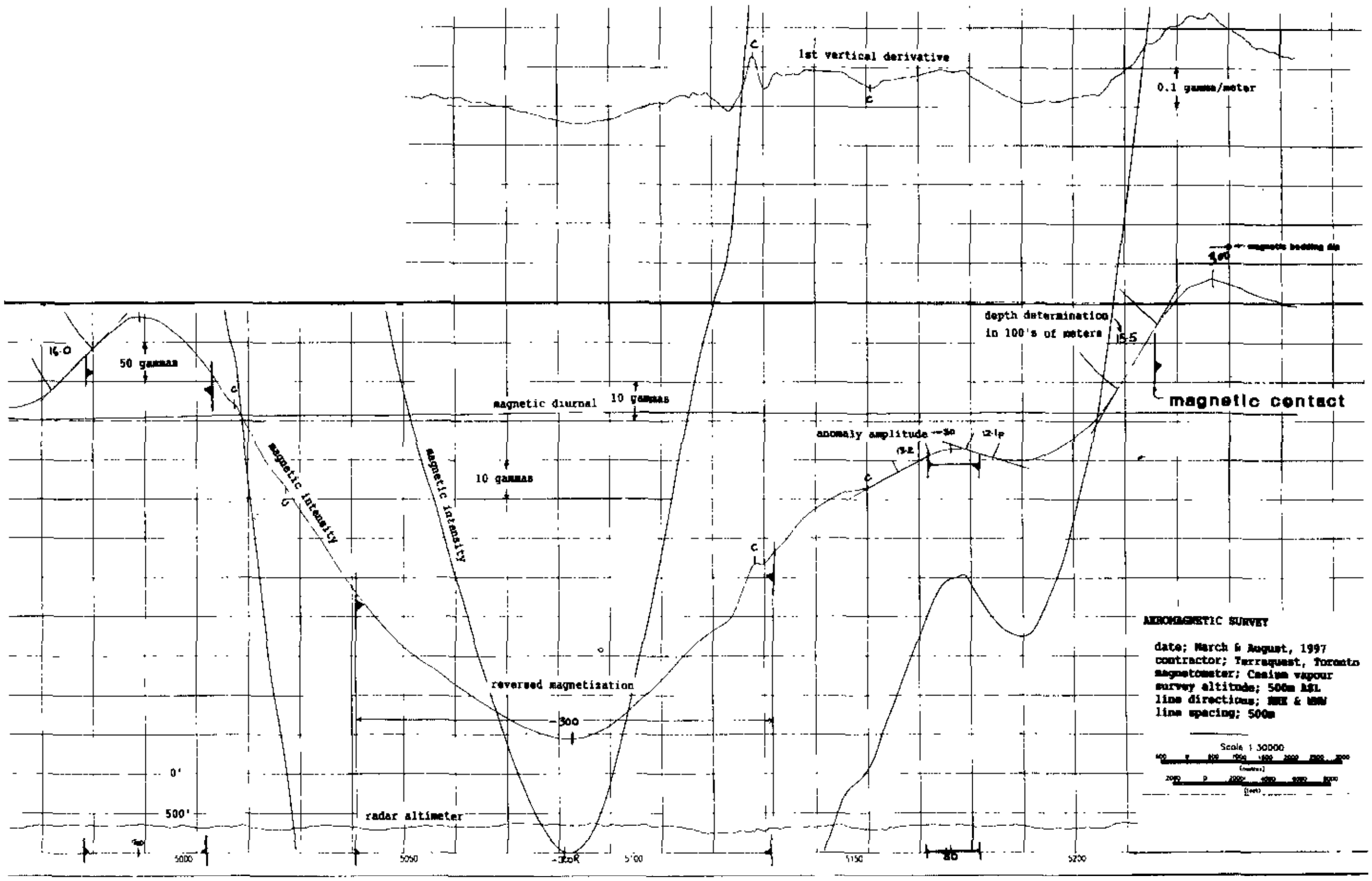

Fig. 7. Sample of aeromagnetic profile analysis to locate anomalies, contacts and determine depth to basement.

10a includes the legend for this map. Various magnetic/lithologic units and structures are represented in this map. For purposes of correlation, well locations are shown in the map. Also included is the six metre Shadow Lake-Cambrian isopach. This is the minimum thickness to permit economic pool development.

Rocks of High Magnetite Content

These rocks have an estimated magnetite content of 0.2 to 0.5% and are reflected by magnetic relief of 100 to 300 nT. They are distributed in two north-trending, arcuate-shaped zones. We might expect that these ferromagnesium-rich rocks would be less resistive to erosion. In fact we can, in places, correlate an increase in the thickness of the Shadow Lake-Cambrian interval with these zones.

Rocks of Moderate Magnetite Content

These rocks (0.1 to 0.3% magnetite) are reflected by 5 to 100 nT relief. They are distributed in a series of narrow, north-trending belts in the east half of the area and in a rather discordant, west-trending broad zone to the west.

Non-Magnetic Rocks

As seen in profile form, magnetic intensity values over these rocks are at minimal level. We might expect that these rocks have relatively higher silica content (least ferromagnesium content). These rocks occupy much of the west quarter of the area.

Reversely Magnetized Rocks

These rocks are identified in the survey data by anomalies that are reversed in sign. These rocks are mapped in two narrow, north-trending belts in the east half of the map. *Remanent magnetization and, possibly, diamagnetism are* explanations for these anomalies. Remanent magnetization is sometimes associated with rocks having very high magnetite content and can also be the result of metamorphism. Diamagnetism is associated with certain igneous rock types such as anorthosite. As an aside, it should be noted that quartz, marble, rock salt and anhydrite are known to be diamagnetic.

Deduced Fault Structures

Having mapped the contacts of these magnetic/lithologic

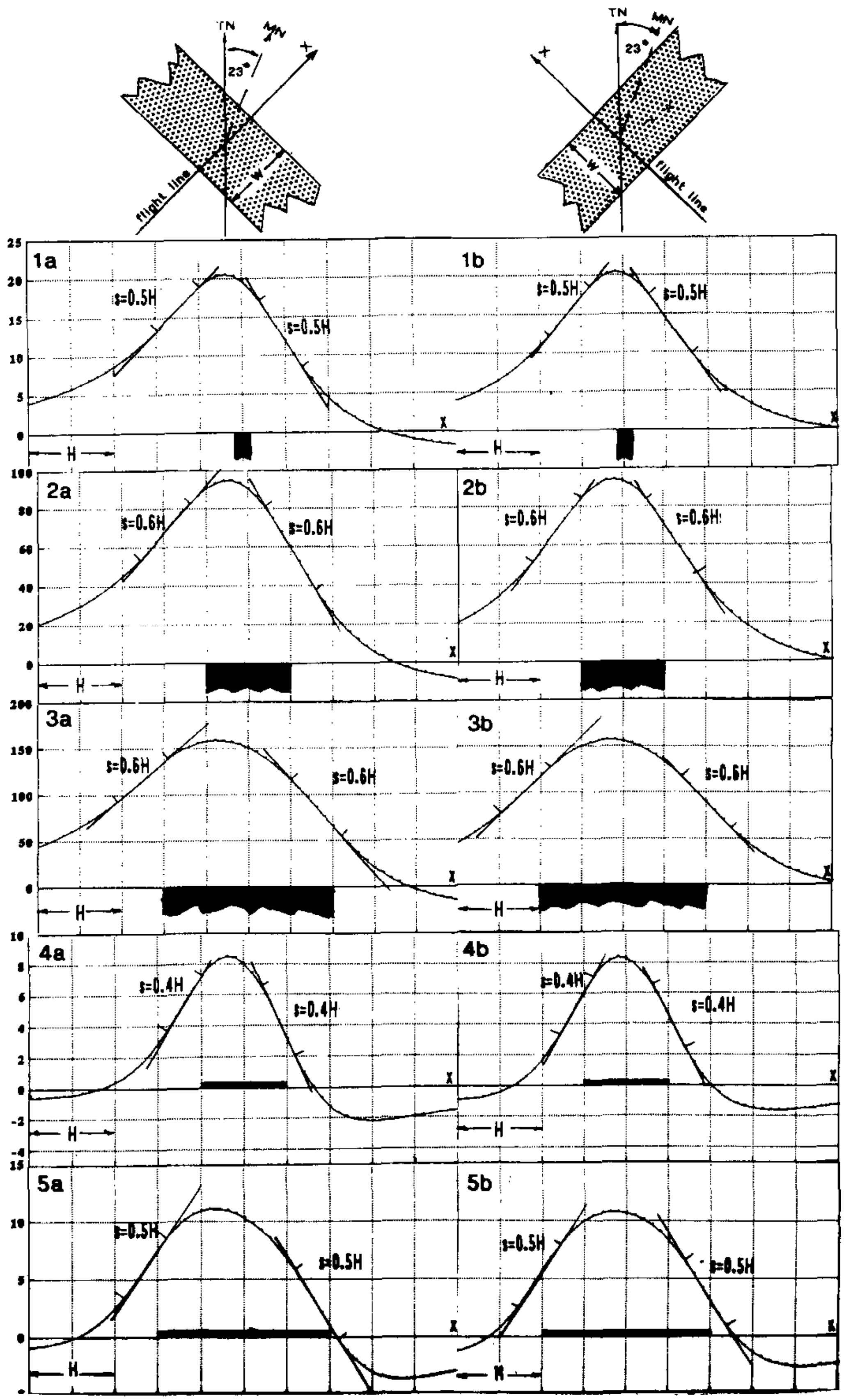

Fig. 8. Magnetic model profiles. W is distance between inflection points, H is depth of burial and S is the horizontal width of the zone of maximum gradient (straight slope).

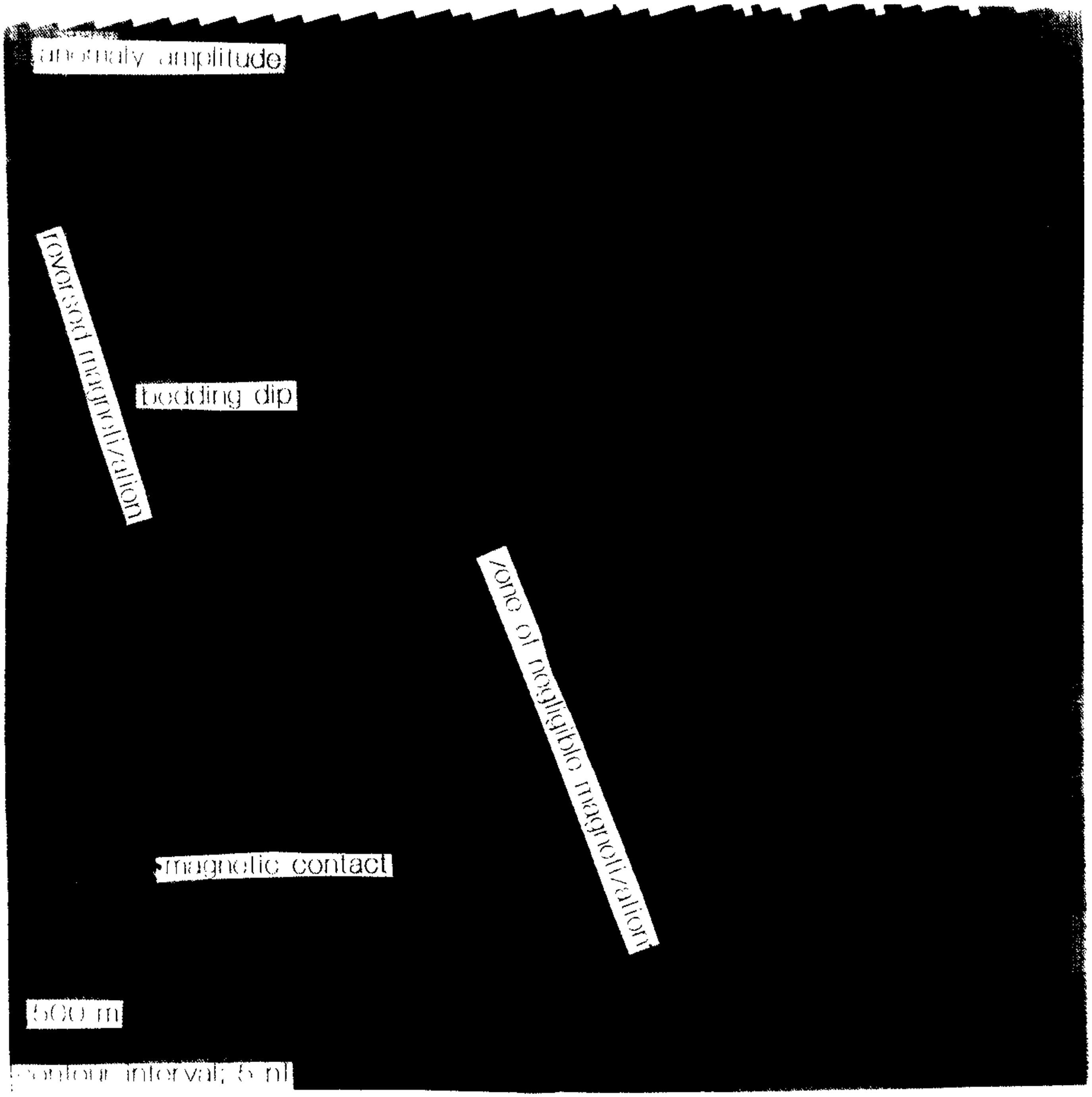

Fig. 9. Magnetic contacts overlay; contacts, anomaly amplitudes, bedding dip and depth determinations. Overlay is superimposed on total intensity magnetic map, contour interval is 5 nT.

units, we may now examine the possibility that some of these contacts are faults that in places have affected sedimentary rocks overlying the basement. We may deduce faults on the basis that a contact is characterized by one or more of the following features;

(a) magnetic trends across the contact are discordant,

(b) there is an apparent offset in the location of a magnetic unit,

(c) a magnetic zone is terminated,

A number of fault systems are discerned;

- System I includes F1, F1a and F1b which are north-trending faults that mark a major discordancy in magnetic trend,
- System II comprised of WNW-trending F3a, F3b, F3c and F3d which are associated with noticeable dislocations of magnetic units,
- System III includes faults F5, F5a, F6 and F6d associated with noticeable N-trending lineation.

Fig. 10. Inferred Precambrian geology map including drill hole locations.

Both the Innerkip and Gobles Pools are seen to be associated with the intersection of System II and System III faults. Gravity data (see Fig. 11) appear to corroborate this interpretation. We note that fault Systems II and III can be correlated with fault lines depicted in the "conceptual fracture framework" proposed by Sanford et al. (1985).

Correlation With Seismic Data

Prior to the aeromagnetic surveying, about 300 km of seismic data had been acquired in the area. Surveying was done by Signature Geophysical and Trace Exploration with 16 m shot and receiver interval.

Figure 12 shows an example of the seismic data in a line that crosses a magnetic contact. The magnetic contact is coincident with a half graben clearly represented in the seismic data. A vertical break of 40 m is indicated. Where seismic data are available, a high correlation was observed, about 80% of the time, between faults that were resolvable on seismograms and magnetic contacts. Thus aeromagnetic data provide a means of projecting fault structures expressed in seismic data or for locating structural leads for follow-up seismic surveying.

Clearville Pool and Aeromagnetic Data

The clearville Pool is located 100 km southwest of the Innerkip-Gobles area. This Cambrian pool, discovered in

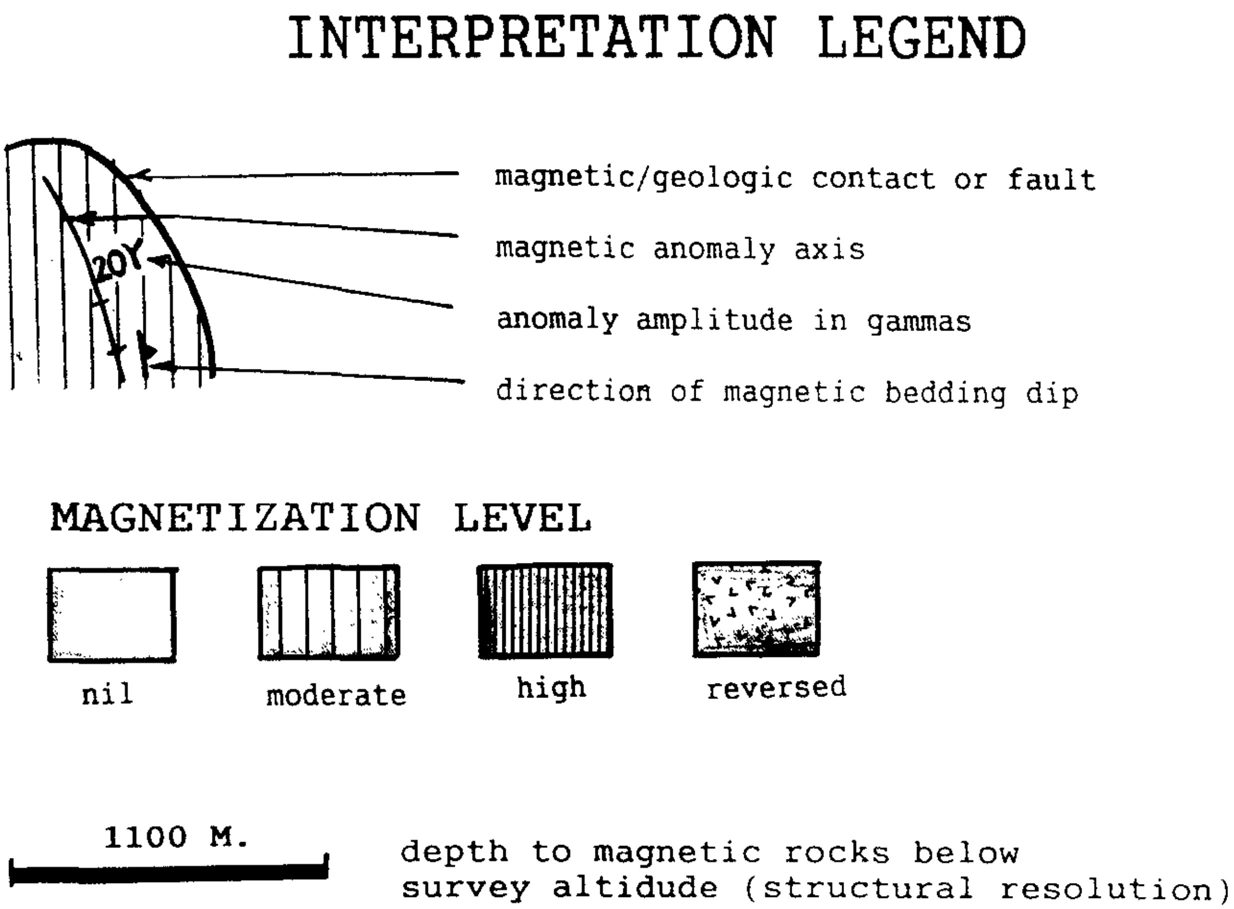

Fig. 10a. Interpretation legend accompanying Figure 10.

1962, is at a depth of 1180 m below ground and produced about 1.4 million barrels of oil. Figure 13a describes the available magnetic data over this pool. The 1954 survey consisted of east-west lines at 1600 m spacing (one mile), 500 m ASL. Because of the wide line spacing, the 15 nT anomaly associated with this Precambrian structure is observed on only one survey line. Unquestionably a HRAM survey is needed to effectively prospect for other structures like Clearville.

Faults and Exploration in Younger Strata

The focus of this paper has been an examination of the relation between fault structure mapping from aeromagnetic data and the localization of Cambrian pools. In addition to vertical displacement of strata, faulting may also play a role in pool development through increased rock permeability and the creation of pressure barriers. According to Sanford et al. (1985), faulting plays important roles in the development of both stratigraphic and structural traps in *younger strata*, as portrayed in Figure 14, parts A, B and C;

- dolomitization of Ordovician limestones,
- localization of Silurian pinnacle and patch reefs,
- development of Devonian structure resulting from leaching of underlying Silurian salt beds.

Acknowledgment

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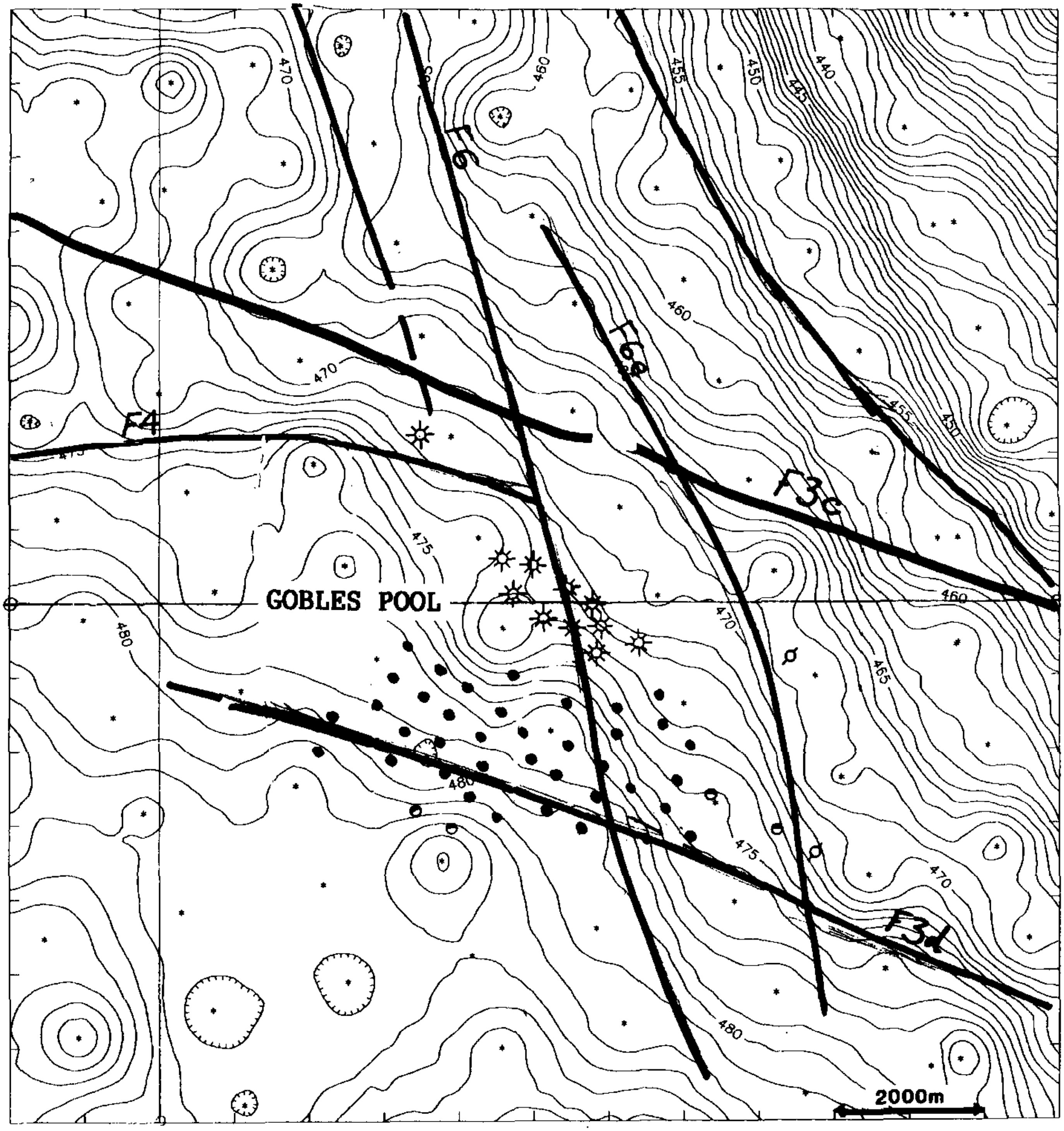

Fig. 11. Bouguer gravity map, contour interval is 0.1 mgal.

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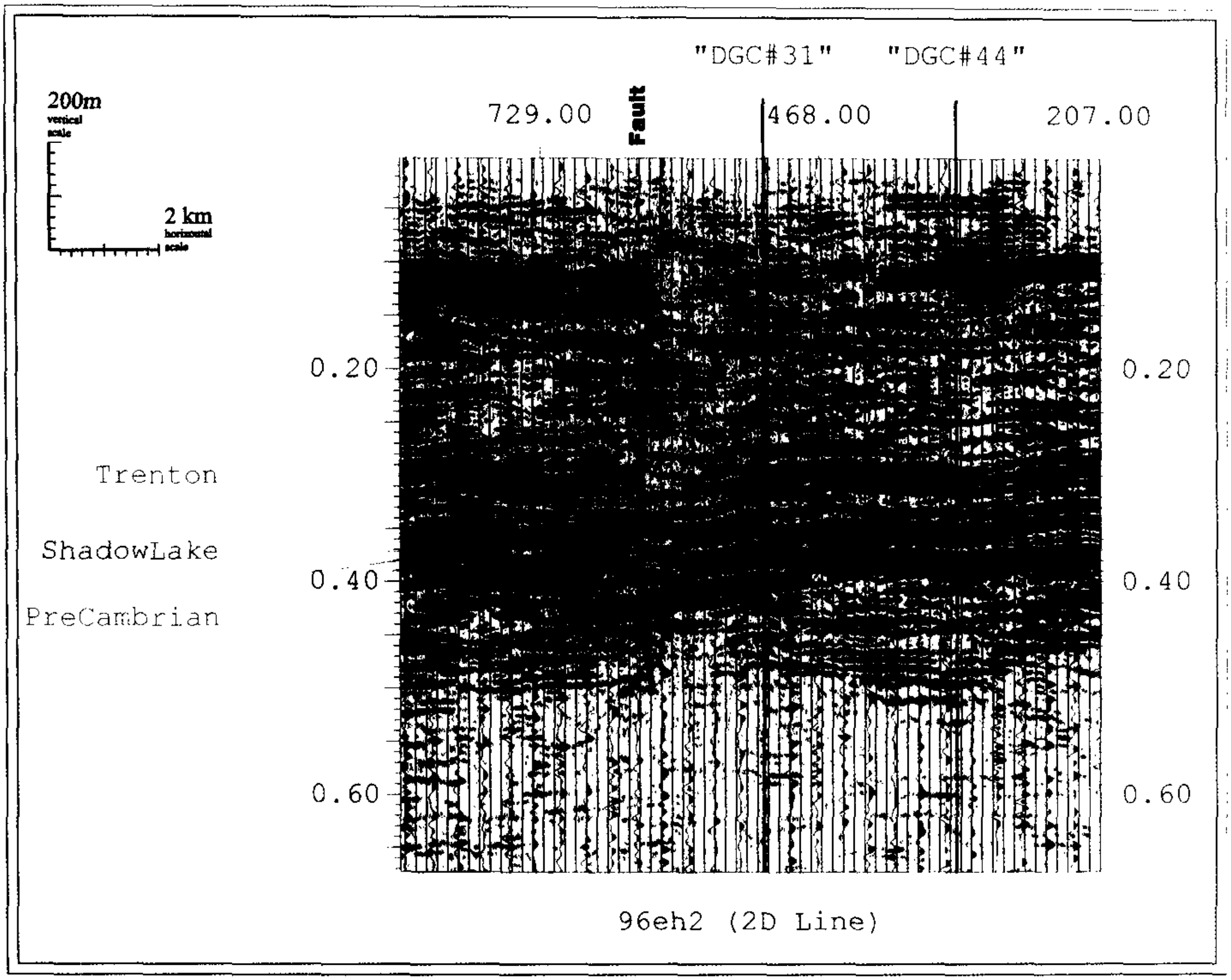

Fig. 12. Correlation of seismic data and magnetic contact.

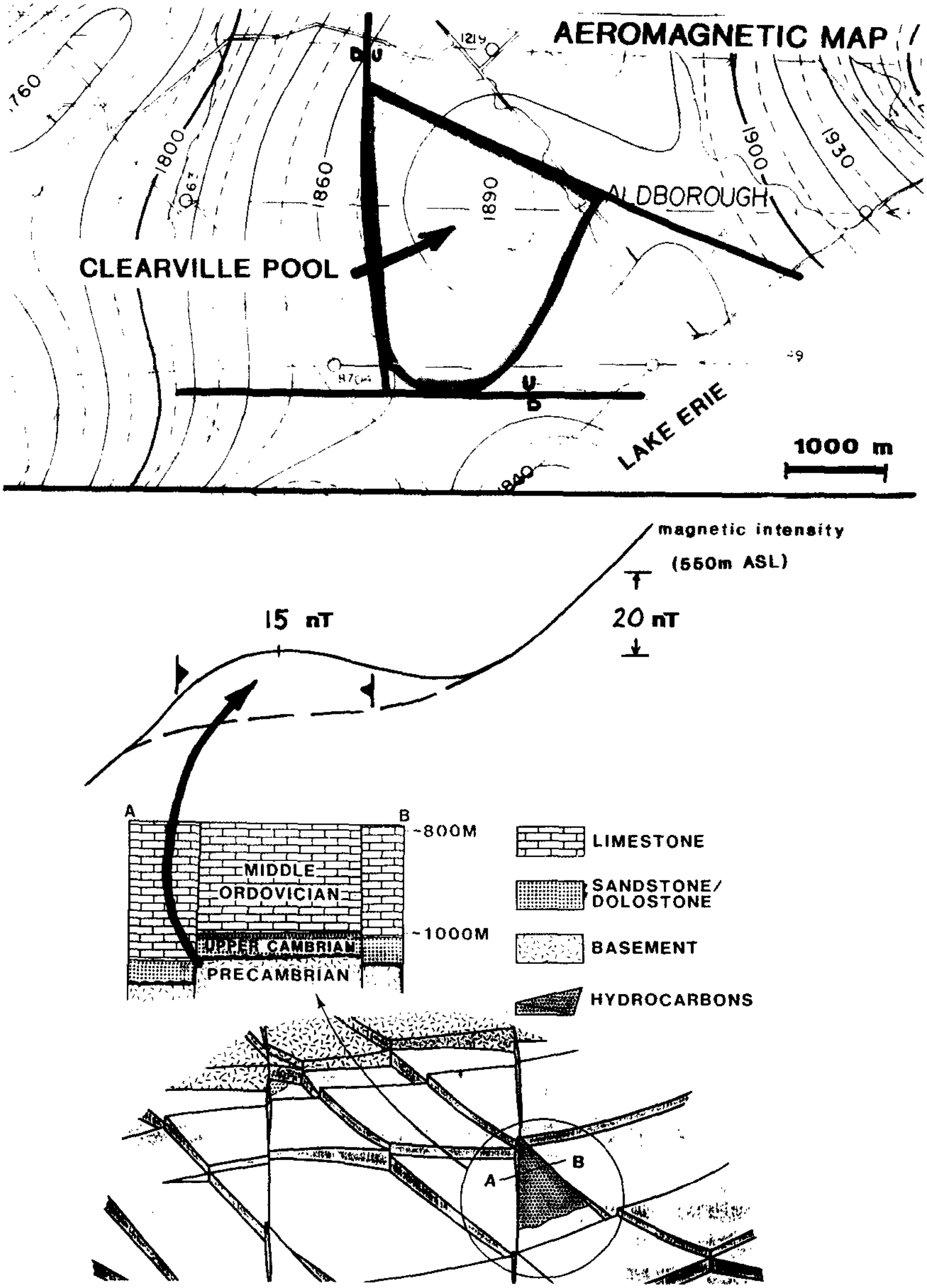

Fig. 13. Clearville Pool and its magnetic expression.

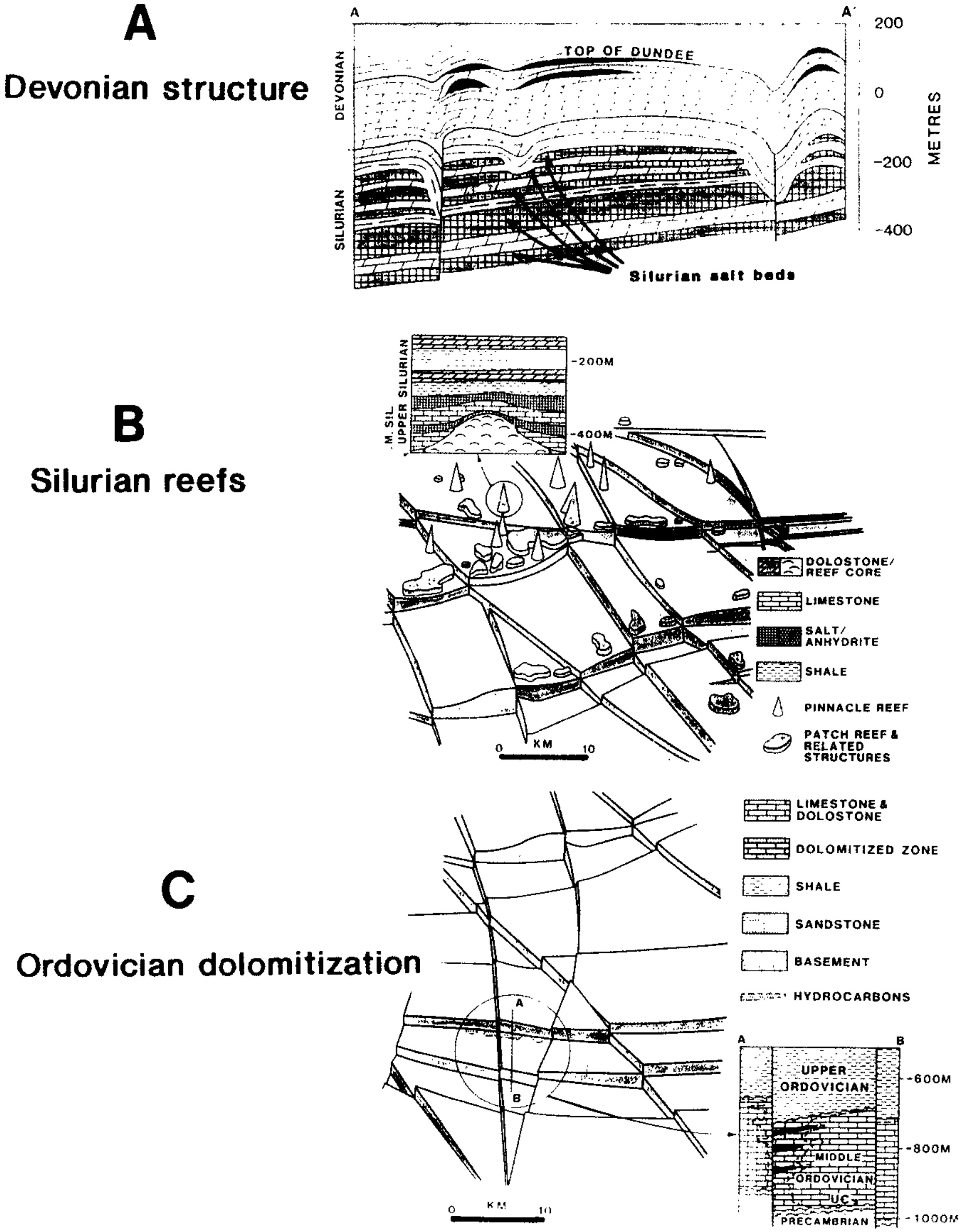

Fig. 14. Faulting and development of (A) Devonian structure, (B) Silurian reefs and (C) Ordovician dolomitization.