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The relationship between uranium distribution and some major crustal features in Canada

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ABSTRACT. The availability of reconnaissance scale geochemical maps for large areas of Canada enables spatial associations between major crustal structures and surface uranium content to be identified. Maps of the distribution of uranium for an area greater than 2 million km^2 compiled from airborne gamma-ray spectrometry data are supplemented by maps for uranium, based on stream and lake sediment and some bore hole sampling. These are examined in relation to gravity, aeromagnetic and geological maps.

The radioelement distribution can be related in detail to exposed bedrock and surface geology, but in addition there is evidence of the control of uranium distribution by major structural features which are marked by granitoids containing elevated levels of radioelements; several of these granitoids are associated with large negative Bouguer gravity anomalies. The distribution of such granitoids appears to be related to 'megashears', as in the case of the South Mountain batholith in Nova Scotia, or zones of tension. A belt of uranium enrichment, the Athabasca axis which is characterized by uraniferous granitoids with negative Bouguer gravity anomalies and associated tension faulting extends 2500 km northeastward from Edmonton, Alberta to the Melville Peninsula. This structure passes under the Athabasca basin which contains many large uranium deposits. Recent evidence that granitoids enriched in radioelements can provide low-grade heat sources over periods of hundreds of millions of years, capable, in favourable situations of maintaining low-temperature hydrothermal circulation is considered to account for uranium and other mineralization in the basin. It is suggested that the transfer of radioelements into the crust at the end of the Lower Proterozoic, was a factor in the stabilization of North American craton.

ABNORMALLY radioactive granitoids have been sought as part of uranium exploration programmes for several decades because of their potential importance both as a host and a source rock for uranium mineralization.

Recent work in Britain (Brown *et al.*, 1979) suggests that such granites are characterized by negative gravity anomalies and are also associated with high heat productivity and heat flow. Examples include the Cornubian batholith of SW England, the north Pennine batholith, and the Cairngorm granite in Scotland. These granites are enriched in potassium and have approximately three times the uranium content and up to 2.5 times the thorium content of average granite (Brown *et al.*, 1979). The high levels of radioactivity of the granitoids have been known for many years, but the significance of their large negative Bouguer gravity values (up to 30 or 40 mGal) has not been generally appreciated. Such negative Bouguer anomalies are most readily explained by a mass deficiency for approximately one-third of the continental crust (typically about 35 km thick) so that the simplest interpretation is that the granitoids extend to considerable depth. The large Bouguer anomalies distinguish such intrusions from granitoids of comparable horizontal dimensions but with no similar evidence of deep roots.

The high radioactivity and deep source of such granitoids raises questions of theoretical and practical interest. The purpose of this paper is to draw attention to the occurrence of granitoids of this type in Canada, and to comment on their structural and economic significance.

Canadian data. Anomalously radioactive granitoids of the type recognized in Britain are large, outcropping over areas of tens to hundreds of km. Thus they can be detected by reconnaissance surveys in which the distance between sampling or observation points is of the order of a few km. Various types of geophysical and geochemical surveys have been carried out over Canada which has an area of approximately 10 million km^2. The percentage of the land area covered by the different surveys is as follows: gravity—85%; aeromagnetic—60%; airborne gamma-ray spectrometry—20%; and multi-element geochemistry—10%. Airborne gamma-ray spectrometry, with selective ground control, has been used as the principal method of measuring the mean surface concentration of potassium, uranium, and thorium, supplemented by regional geochemical surveys using surface water, stream or lake sediment samples for uranium

(Darnley *et al.*, 1975). In mountainous areas, sediment and water samples provide the only data on uranium distribution.

The Precambrian Shield, northwest of Lake Superior, is the largest area for which gravity, aeromagnetic, and geochemical data are available, with sparser coverage over the adjacent Prairies. There are also several smaller areas for which all these types of data are available, including parts of the Atlantic Provinces.

Deep crustal structure. Magnetic and gravimetric maps provide information on the structure and distribution of certain properties of the crust in three dimensions. Aeromagnetic maps primarily

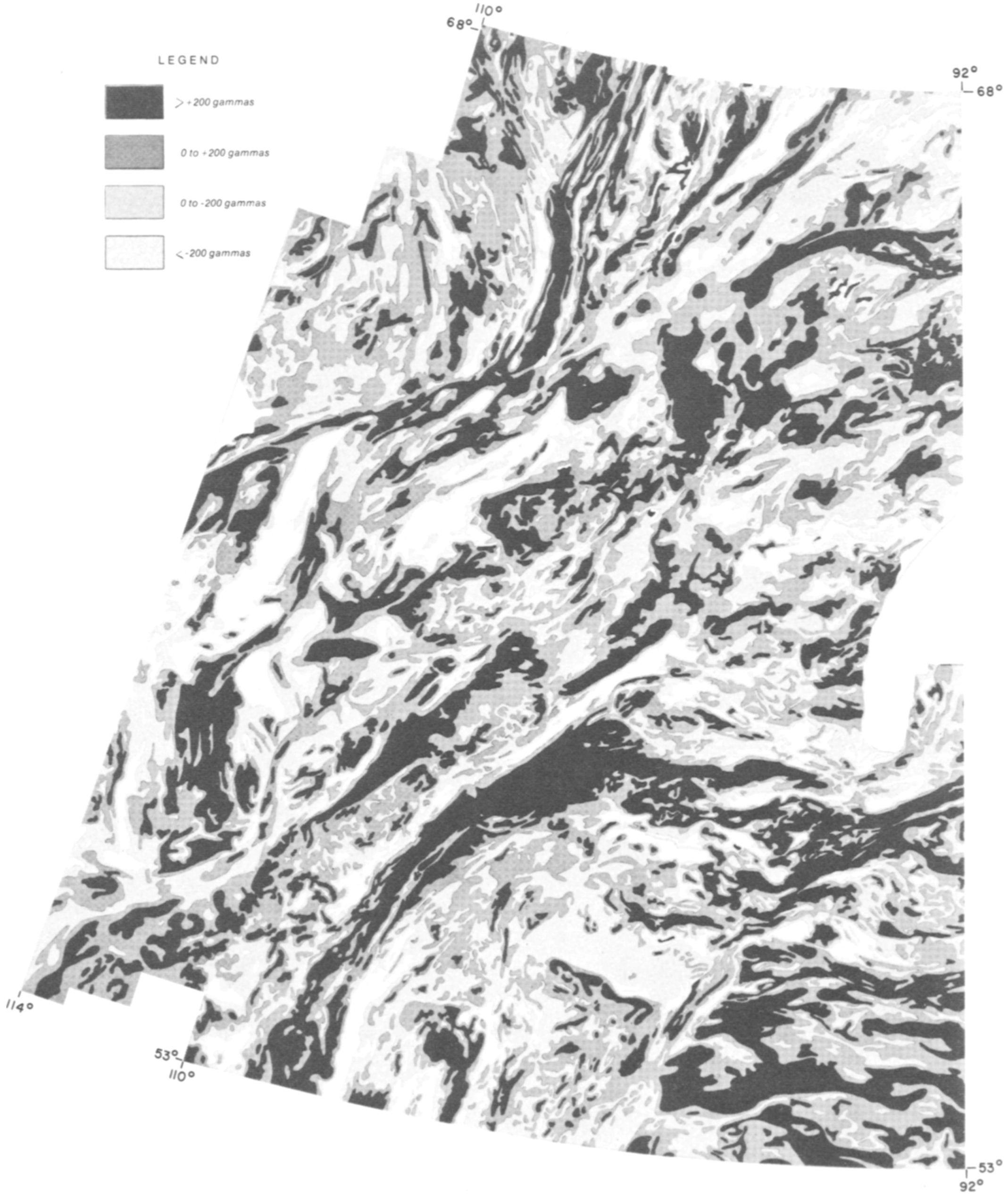

FIG. 1. Magnetic anomaly map. North-central Canada; adjoining parts of NWT and provinces of Manitoba and Saskatchewan.

reflect the distribution of magnetite (Garland, 1979) and by removing the regional magnetic gradient due to the Earth's core and filtering the data to remove short wavelengths caused by near-surface geology, variations in the bulk magnetism of the upper crust can be identified. No response is obtained from depths greater than 20 km where temperatures exceed the Curie point for magnetite of 580 °C. The 1 : 5 million scale magnetic anomaly map of Canada (Hood *et al.*, 1977) shows dicontinuities traceable for hundreds of km which mark major crustal discontinuities reflecting differences in lithology and/or metamorphic history. A portion of the magnetic anomaly map bounded by latitudes 53° N. and 68° N. and longitudes 92° W. and 114° W., and covering an area of approximately 1.75×10^6 km^2 is shown in fig. 1. A strong northeasterly trend is apparent. The major magnetic linears derived from an unpublished magnetic anomaly map compiled for the whole of mainland Canada are given in fig. 2*. These show the western and eastern limits of the Shield and the continuity of several major lineaments across the exposed Shield and beneath the Prairies. Between the 49th and 56th parallels they can be traced west as far as the Rocky Mountain Trench to the west of the Rocky Mountain Thrust Belt. Most of the prominent magnetic linears of central and eastern Canada including the Grenville front trend northeastwards and such topographic features as the St. Lawrence Valley, the Appalachians and the present Atlantic continental margin parallel this trend.

Regional gravity maps of Bouguer anomalies, for example EPB Map 74-1 1974, provide information about the entire thickness of the crust. The Bouguer anomaly map of Canada provides less detail than the magnetic map at the same scale because of the lower density of data points. Nevertheless it is clear that the dominant trend for gravity anomalies over most of Canada is NE. The NE-trending gravity features include a discontinuous high close to the northwestern margin of the Appalachian orogen, the Grenville front low between the Grenville and Superior provinces and the Nelson River high in Manitoba. The longest northeasterly trending gravity feature is shown in fig. 3; it transects the Churchill province and can be traced for more than 1500 km, from the Cordillera southwest of Edmonton, Alberta to Baker Lake, NWT. This feature is referred to here as the

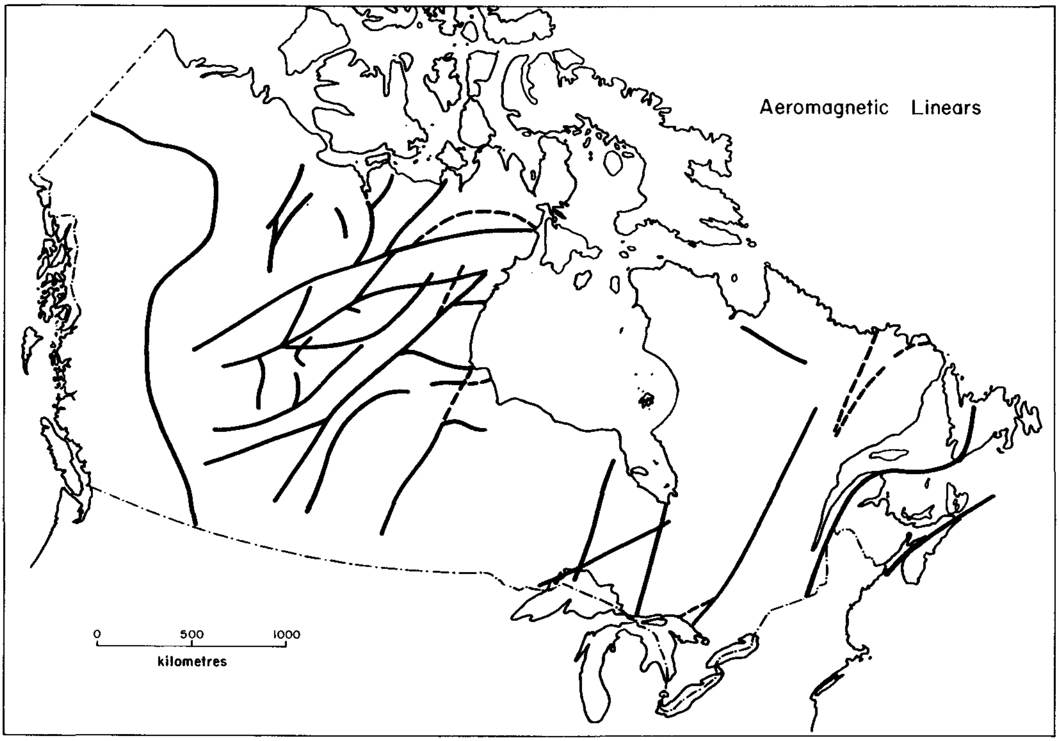

FIG. 2. Major magnetic linears: Canada east of the Cordillera.

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* Based on Hood *et al.* (1977) and Coles *et al.* (1976).

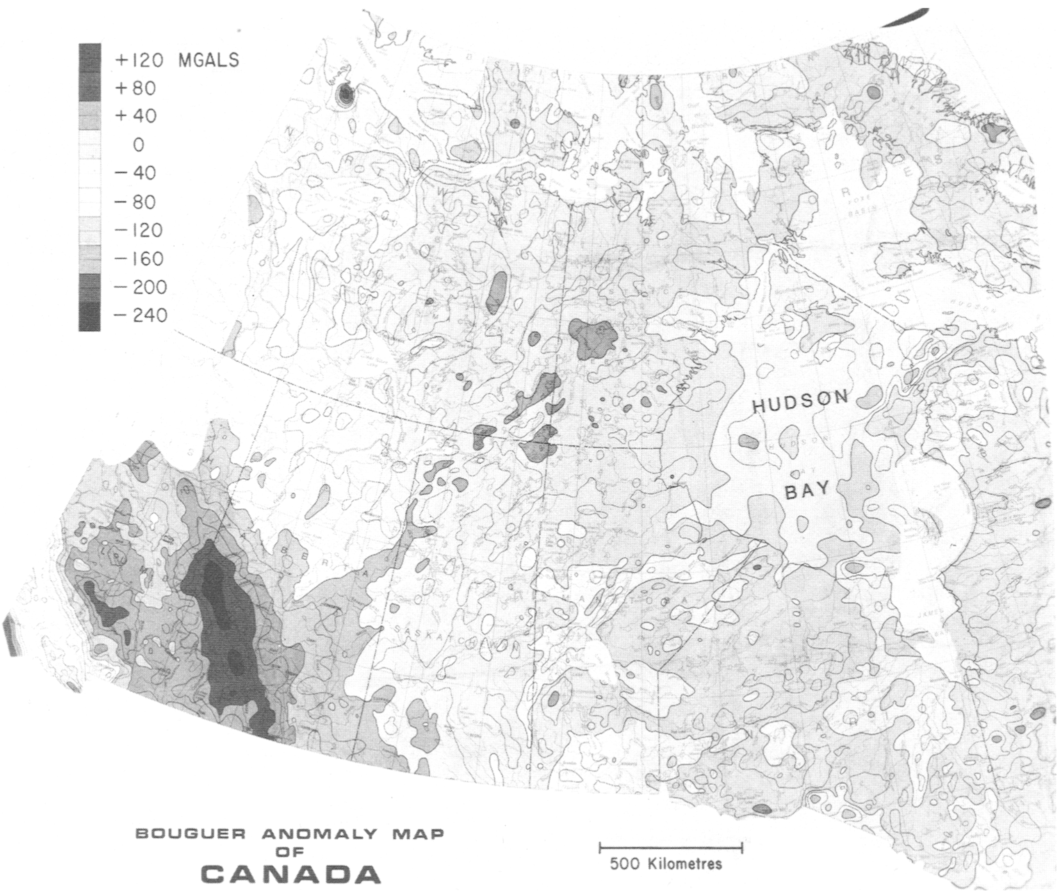


FIG. 3. Gravity map: west central Canada.

Athabasca axis although portions of it have previously been called the Fond du Lac gravity low (Walcott, 1968) and Kasba Lake–Edmonton gravity low (Burwash and Culbert, 1976).

Thus, although other trends are present, the magnetic and gravity data indicate the importance of northeasterly trends related to the deep structure of the crust of Canada east of the Cordillera; and the regional uranium distribution, which is mapped largely from surficial data, also relates to them.

Uranium distribution in western Canada. The distribution of uranium is shown in fig. 4 based on three types of geochemical mapping. Over the Precambrian Shield the data were obtained by airborne gamma-ray spectrometry (GSC Open File reports 1971 to 1979). The uranium distribution over the Prairies is from a map by Burwash and Cumming (1976) who used delayed neutron analysis of borehole samples from the underlying Precambrian basement. The uranium distribution over southeast British Columbia (GSC Open File 736, 1981) and the north shore of Lake Superior (GSC Open File 746, 1981), is based on the delayed neutron method of analysis of stream and lake sediment samples. Airborne gamma-ray spectrometry techniques used for mapping have been described by Darnley and Grasty (1971); Darnley *et al.* (1977); and Charbonneau (1980). The relationship between the mean surface uranium content measured from the air, and the uranium concentration measured using a portable gamma-ray spectrometer at outcrop, is described in Charbonneau *et al.* (1976). The airborne data can be extrapolated to predict probable bedrock heat productivity (Richardson and Killeen, 1980). The redistribution of bedrock by glaciation may obscure or smear the distribution pattern although large-scale displacement is seldom more than one or two kilometres (see also Shilts, 1976) and is not important in maps at the scale discussed.

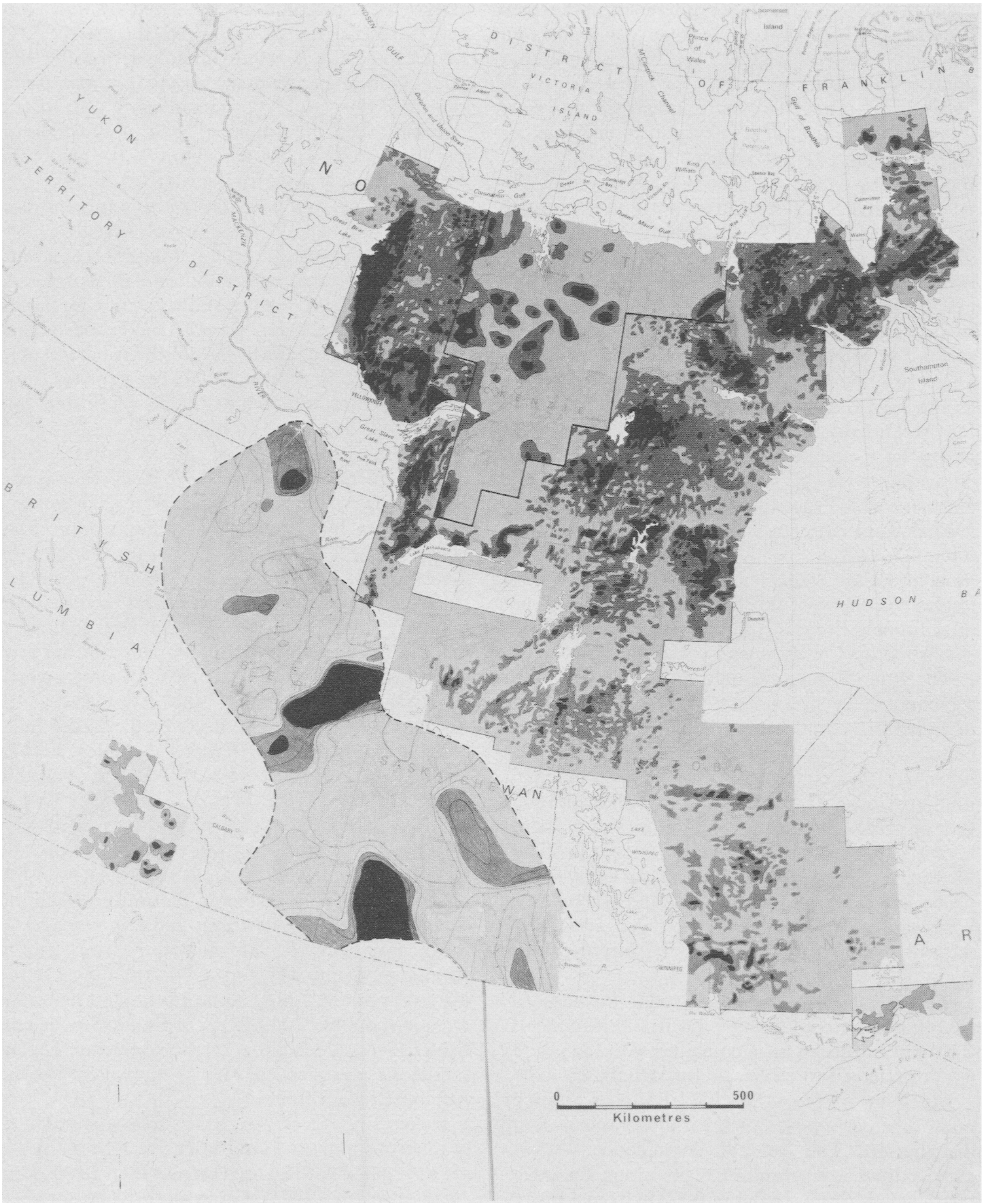


FIG. 4. Uranium distribution: west central Canada.

The main features of the uranium distribution (fig. 4) are first a zone of high uranium along the western edge of the Shield extending from the northwest near Great Bear Lake southwards into NE Alberta, and secondly the broad northeasterly trending zone of uranium enrichment extending from central Alberta to the Melville Peninsula at about latitude 68° N.

The first feature, which has a sinuous strike length of about 1000 km, crosses the Bear and Slave structural provinces and extends into the Churchill province. The geophysical 'signature' of the high uranium zone shows differences in the three provinces. Most of the Bear province has an elevated uranium content, the highest uranium content coinciding with the Great Bear batholith of Hudsonian age. This batholith is defined only weakly on the regional gravity map, but it coincides with a strong positive magnetic anomaly. Across the Slave province the zone of high uranium can be correlated in some areas with late potassic granites of uncertain but probably Archaean age (McGlynn, pers. comm.). There is no clear association with gravity or magnetic features, nor with mapped structural trends other than the contacts of individual intrusions. In the Churchill province to the south of the east arm of Great Slave Lake, an apparent continuation of the same zone, known as the Fort Smith belt, is present to the south of the McDonald fault. High contents of uranium occur in a foliated porphyritic granite, which coincides with a strongly negative magnetic anomaly which extends for more than 200 km in a north-south direction and 50 km in an east-west direction. In the Fort Smith belt, thorium is the most abundant radioelement and most uranium is in the periphery of the body. A detailed account of radiometric investigations in this area has been published by Charbonneau (1980).

The zone of high-uranium granitoids along the relatively well exposed western margin of the Shield demonstrates that not all such bodies are associated with prominent gravity lows. There is, however, a general coincidence between magnetic domains and surface uranium distribution although the apparent continuity of the uranium zones across structural province boundaries is probably fortuitous. The variation in other parameters suggests that zones of high uranium in each province were caused by separate events. The ages of the various uraniferous granitoids are important but these data are incomplete.

The Athabasca axis. The broad northeasterly trending zone containing high uranium which is the main feature of fig. 4 coincides with the gravity feature referred to earlier as the Athabasca axis.

Fig. 5 shows the -80 mGal Bouguer anomaly contour superimposed on the maps of the uranium distribution. The general coincidence between gravity lows and uranium highs along the Athabasca axis can be traced for 2000 km from approximately latitude 65° N., longitude 91° W. northeast of Baker Lake, NWT southwestwards under the Athabasca basin and the Prairies to the foothills of the Cordillera at about latitude 53° N., longitude 116° W. Here it cuts the prominent northwest-southeast gravity low caused by crustal thickening under the Cordillera. The Bouguer Anomaly Map also shows a weak cross cutting feature in southeastern British Columbia indicated by the -120 and -140 mGal contours on the east of the Rockies and the -140 mGal contour on the west side which aligns with the Athabasca axis trend, although this could be coincidental. SE British Columbia and the adjoining area of Washington and Idaho states, USA which are on the line of the Athabasca axis contains several economic (e.g. Midnite Mine) and potentially economic uranium deposits and many uranium occurrences. The above-average uranium content of the stream sediments is associated with granites of Mesozoic age and Eocene alkali syenites and volcanics; phonolite and trachyte averages 8 ppm U (Boyle and Ballantyne, 1980) and the Battle batholith averages 9 ppm eU, 27 ppm eTh (Lewis, 1976). The exposed basement in the region includes rocks of Proterozoic age.

For half the length of the Athabasca axis, the basement is concealed. Within the Shield gravity lows defined by the -80 mGal contour generally enclose granitic rocks mapped as Aphebian or remobilized Archaean but for much of the area north of the Athabasca basin only reconnaissance geological, geophysical, and geochemical mapping has been carried out. Detailed geological mapping has recently been completed in the area southwest of Baker Lake, NWT however, which is at the north end of the Athabasca axis. Lecheminant *et al.* (1979) describe the Baker Lake basin as a northeast trending complex graben associated with basement uplift and volcanic activity at about 1800 Ma and extending for 300 km with an average width of 50 km. It is filled with continental sediments and volcanics of the Dubawnt group and alkaline volcanism was followed by acid volcanism and plutonism. Uranium occurs in a variety of settings and in many ages of rocks. For example, late fluorite-bearing granite contains 19 ppm eU and a NE trending syenite dyke 40 ppm eU. After an appreciable interval of erosion (possibly 200 Ma according to Curtis and Miller, 1980) deposition of the overlying Thelon sandstone commenced; this is equivalent to the Athabasca sandstone.

Hence, in the Baker Lake area a variety of uraniferous extrusive and intrusive igneous rocks are associated with an area greater than 10 000 km^2 enclosed by the -80 mGal contour. The enriched levels of uranium are apparent from fig. 4 of the Baker Lake region. The NE trend of the geology and uranium occurrences is also apparent from the work of Curtis and Miller (1980).

No systematic ground-based gamma-ray spectrometry or bedrock sampling has been carried out along the Athabasca axis but by analogy with results in other areas such as the Fort Smith belt and Elliot Lake area (Darnley *et al.*, 1977) where both airborne and ground data are available, within the gravity lows bedrock concentrations are of the order of 15 ppm eU which coincide with the gravity lows. This is significant as will be indicated below.

The Athabasca axis underlies the Athabasca basin which is of middle Proterozoic age (about 1450 Ma according to Bell, this volume). It contains continental arenaceous sediments in the lower part, with a maximum depth of about 2 km below the present erosion surface. The thickness immediately following deposition is estimated to have been about 4.8 km (Hoeve *et al.*, 1980). Fig. 6 shows the position of the gravity lows in relation to the outline of the Athabasca basin. The Athabasca axis as defined by the −80 mGal contour consists of a single gravity low when traced northeastwards from the Cordillera as far as a point about 125 km southwest of the southern margin of the Athabasca

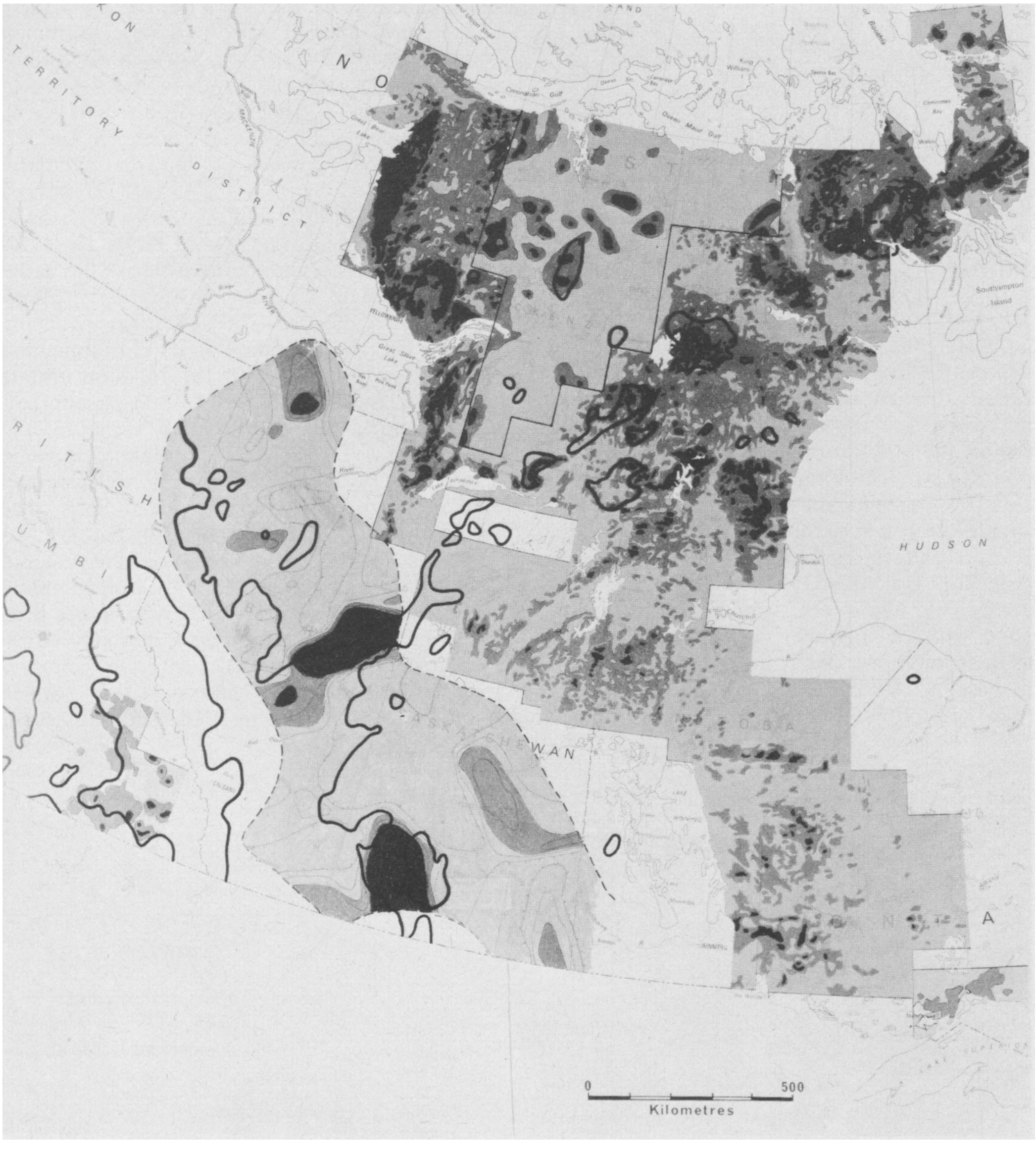


FIG. 5. −80 mGal gravity contour superimposed upon uranium map of west central Canada.

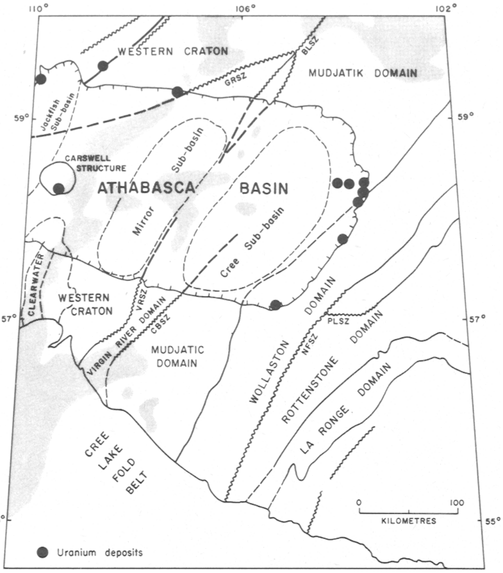
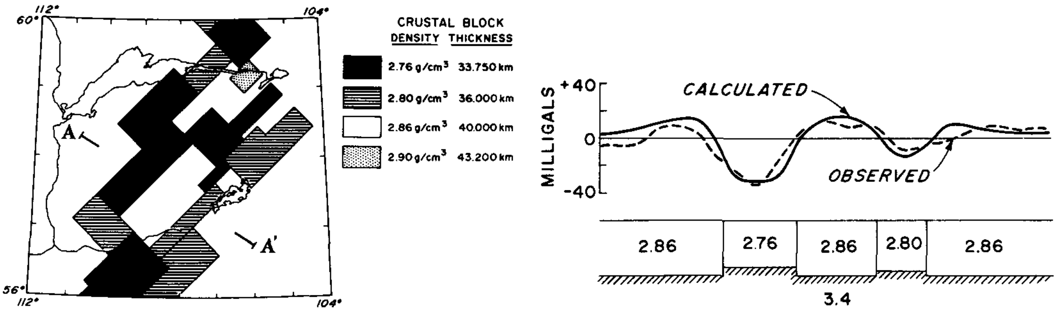


FIG. 6. Athabasca basin showing structure, gravity lows and known uranium deposits.

basin. Here the gravity anomaly branches into two with centre-lines about 150 km apart, the north-westerly branch being stronger and more continuous. A 1:1 million scale magnetic anomaly map of the area (in preparation) shows a corresponding pattern of anomalies. Recent geological work by Lecheminant *et al.* (1979) indicates a complex graben structure on the line of the Athabasca axis which continues under the Baker Lake basin and Walcott's (1968) interpretation of the gravity field across the Athabasca basin is consistent with a twin graben structure (figs. 7 and 8); his interpretation extends the low-density zone to the base of the crust.

The amplitude of the negative Bouguer anomalies (40 mGal maximum) the width of the postulated structures (50 and 30 km respectively) and the distance between their centres resemble the East African twin-rift system at the south of Lake Tanganyika and the Rukwa valley (Bullard, 1936). Many continental rift systems such as those of East Africa and the Rhine graben, are marked by gravity lows and are associated with alkaline volcanism such as that at Baker Lake.

Geological evidence from the vicinity of the Athabasca basin is also compatible with the postulated graben structure and inferred granitic intrusions (Geological Map of Saskatchewan, 1980, Lewry and Sibbald, 1979). Late Hudsonian granites, many of which are anomalously radioactive, occur north and south of the Athabasca basin within the −70 mGal gravity anomaly (fig. 6). They include fluorite-bearing granites in the NE corner of the province, within the Mudjatik domain; granodiorites in the Grease River area north of Fond du Lac; and the Clearwater granite south of the basin. Lewry and Sibbald's (1979) tectonic analysis of the southern side of the basin, to the north of the Y-junction in the gravity pattern is particularly relevant. Their Clearwater domain, with the Clearwater granite on its E. Margin, and Virgin River domain, with the Junction granite (also Late Hudsonian) on its W. margin, approximately coincide with the two branches of the gravity low. The Western Granulite domain between the two branches is mainly Archaean and may therefore represent an uplifted horst. The Virgin River domain is bounded in part by two faults, the Needle Falls shear zone on the west and Cable Bay shear zone on the east, both trending NE. The interior of the Athabasca basin has been subdivided by Ramaekers (1980) into sub-basins, elongated NE–SW illustrated in fig. 6. Comprehensive data and interpretations of this complex area have been prepared by Wallis (1970), Burwash



FIGS. 7 and 8. 7 (*left*). An isostatically compensated model for the central belt anomalies (fig. 5) A–A′ is the line of section for fig. 8. Density and thickness of each block are indicated. Density of mantle assumed at 3.4 g/cm^3. 8 (*right*). Cross section of the model (fig. 7) with observed isostatic and calculated anomalies (from Walcott 1968).

and Culbert (1976), and Lewry and Sibbald (1977).

The graben structure postulated here must post-date the Hudsonian folding that produced the Mudjatik fold belt (fig. 6) because of: the association of late Hudsonian granites such as the Junction granite with late shearing; the sequence of events described in the Baker Lake area; and the observation elsewhere that crustal tension may follow the compression of an orogeny. The presence of late Hudsonian granites with elevated contents of radioelements under the Athabasca basin seems probable in view of the exposed geology elsewhere along the Athabasca axis. The major intrusions are probably centred in the vicinity of the gravity lows.

Athabasca mineralization. The Athabasca basin is potentially one of the world's most valuable mineral-producing areas, as indicated by the number of polymetallic uranium deposits discovered since 1968. It is suggested* that an understanding of the mineralization is provided by the quantitative hydrothermal circulation model developed by Fehn *et al.* (1978). This explains the unusual alteration effects described from the Athabasca basin, and the time interval between sedimentation and the oldest mineralization which was probably between 200 and 300 Ma (Bell and Blenkinsop, 1980; Hoeve *et al.*, 1980). Fehn *et al.* (1978) modelled hydrothermal convection associated with abnormally radioactive plutons using the Conway granite of New Hampshire as an example. This granite averages 4 % K, 15 ppm U and 57 ppm Th with a heat productivity approximately 3.5 times that of average granite. Whereas the heat available from magmatic cooling of an intrusion could maintain hydrothermal convection for a few million years after intrusion, the heat generated by radioactive decay within a radioactive pluton such as the Conway granite is potentially sufficient to drive low-temperature hydrothermal convection over hundreds of millions of years. The SW England granites which were intruded at 290 Ma, at present heat spring water to 52 °C 450 m below the surface (Alderton and Sheppard, 1977). Hydrothermal convection caused by radioactive heat generation is capable of forming low-temperature mineral deposits (about 140 °C above ambient) unrelated to the age of the parent igneous intrusion. In the Middle Proterozoic a given concentration of radioelements would generate 30 % more heat than now. The critical controlling factors are the permeability in and around the pluton, the size of the pluton, and the availability of water. The features delineated by gravity under the Athabasca basin have the dimensions necessary to satisfy the Conway granite model.

The Athabasca basin was (and is still) a natural groundwater reservoir; on the northern and eastern side rocks of above average uranium content are exposed (fig. 4) and most uranium deposits occur (fig. 6) in the eastern portion of the basin. Most of the economic mineralization occurs at or close to the sub-Athabasca unconformity and is structurally controlled, occurring as veins, breccia fillings and associated disseminations. In many cases, reverse faults which offset the unconformity and strike approximately parallel to lithological units in the basement are important controls on mineralization (Hoeve *et al.*, 1980) and there is evidence of repeated fault movements during and after the main stage of mineralization. Uranium is generally associated with other metals including nickel, cobalt, arsenic, and some gold, suggesting a hydrothermal rather than a low-temperature supergene process, which was the preferred hypothesis (although not unanimously accepted, see Little, 1974) following the first discovery in the area (Knipping, 1974). Primary mineralization is considered to have occurred between 1330 to 1050 Ma (Hoeve *et al.*, 1980; Bell and Blenkinsop, 1980) while the age of deposition of the Athabasca sandstone is thought to be approximately 1450 Ma (Bell, this volume). A suite of northwesterly striking basic dykes were emplaced between 1360 and 1000 Ma (Ramaekers, 1980). Pagel (1975) found evidence of hydrothermal alteration at temperatures of about 200 °C at the base of the sandstone involving solution of detrital quartz grains, and subsequent authigenic precipitation of silica and involving regional NaCl brines. Hoeve *et al.* (1980) described pervasive low-temperature hydrothermal alteration especially in the vicinity of mineralized faults which they suggest occurred over a long period time.

Hence the Athabasca uranium mineralization appears to have been precipitated from hot ground waters at intervals over a long period of time associated with fault movements, and basic dyke intrusion. The controls of precipitation have been discussed by Hoeve *et al.* (1980). Several authors (e.g. Hoeve *et al.*, 1980) have suggested that the heat required for hydrothermal circulation could be provided by the periodic basic dyke intrusions contemporaneous with mineralization. Although such heat sources may have been important locally and for short intervals of time their long-term heat contribution would be small compared with the continuous low grade heat output of large radioactive plutons. Nevertheless, basement fracturing

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* A similar suggestion has been made independently by L. A. Clark and G. H. R. Burril of Saskatchewan Mining Development Corporation in a paper (in press, 1981), entitled 'Unconformity-related uranium deposits, Athabasca area, and East Alligator River area N.T. Australia'.

accompanying dyke intrusion was probably an important factor in facilitating hydrothermal circulation. The basic dyke intrusions might also be expected to exert a control on groundwater flow. The polymetallic mineralization in the basin, with associated clay alteration, has compositional similarities to the Hercynian vein mineralization of Western Europe.

Discussion. It has been suggested that the distribution of uranium along the Athabasca axis is related to a major linear structure which developed at the end of the Lower Proterozoic, after the Hudsonian orogeny and before the deposition of the Athabasca sandstone. This zone, identified primarily by its negative gravity anomalies is parallel to the direction of many of the major magnetic linears which are related to compositional or structural discontinuities in the upper crust of the North American continent. It is suggested that the Athabasca axis is a cryptic rift structure which was initiated during a period of tension 100 to 200 Ma after the Hudsonian orogeny. Later deep-rooted uraniferous granites such as the Devonian South Mountain batholith of Nova Scotia also appear to be located along major crustal structures—in this case a megashear more than 1000 km in length (Lefort and Haworth, 1978). Many major geological features in North America have a northeasterly trend (see map of the Americas; Derry, 1980); the main trend of known uranium occurrences in the western USA is northeasterly (Gabelman, 1977), and the mid-continent gravity high in the USA has the same trend (King and Zietz, 1971). The Athabasca axis appears to be one of a family of deep crustal phenomena.

The radioelements provide, and have provided since early in the earth's history the principal source of energy for geological processes (O'Nions *et al.*, 1978). The lithophile nature of radioelements means that not only do they contribute heat but they tend to segregate with the most mobile partial melt fractions including volatiles which will tend to accumulate in the upper mantle or crust. If a model of growth of continental lithosphere during geological time is assumed as a consequence of the expulsion of lithophile material from the mantle

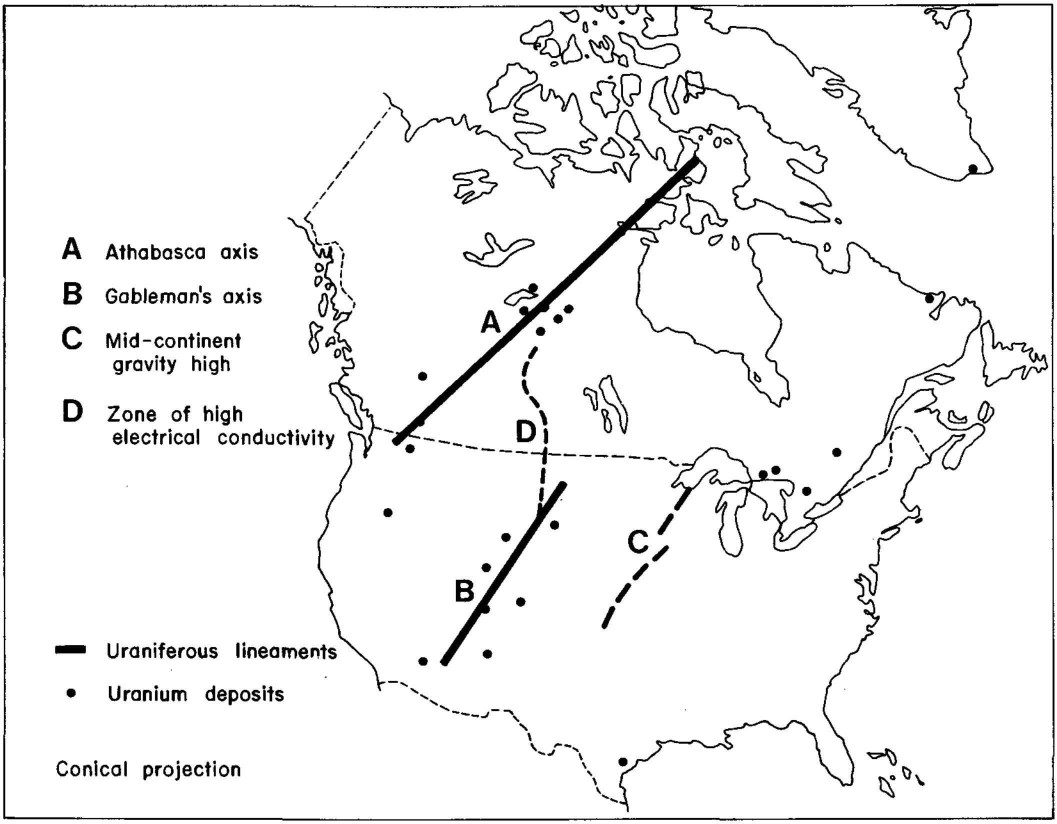

FIG. 9. North American uranium lineaments and uranium deposits.

by convection (O'Nions *et al.*, 1979), radioelements (and other incompatible elements) plus volatiles would be expected to accumulate under continental lithosphere with a distribution pattern related to underlying convection patterns.

Brown and Girdler (1980), in considering possible mechanisms for the evolution of rifting in Africa postulate an initial rise of the asthenosphere into the lithosphere over a broad zone as a result of tension in the African plate, consequent upon mantle convection. The rise of the asthenosphere results in thinning of the lithosphere. Ultimately the asthenospheric material penetrates a narrow zone of the crust, and a Red Sea structure develops. Brown and Girdler (1980) comment that they find it difficult to account for the large region of thinning of the continental lithosphere. The features observed along the Athabasca axis suggest that the rise of the asthenosphere is a consequence of gradual heating caused by the accumulation of radioelements within an elongated zone. It must be assumed that the maximum radioelement concentration achievable in any large volume of differentiate is indicated by the highest concentrations observed in leucogranites or alkali syenites. Earlier differentiates might be more voluminous, but the radioelement concentration would be more dilute. Therefore considerable time is required for radiogenic heating to raise geoisotherms.

If the interpretation of the subsurface structure associated with the East African rift is relevant to the Athabasca axis, it must be assumed that the latter was associated with the differentiation of acid magma, and tensional conditions permitted its ascent from depth. Simpson *et al.* (1979) have argued on isotopic and other evidence that the uranium-enriched granite magmas of the British Isles were derived from subcontinental lithosphere underplated on to pre-existing basement, with magma release triggered by crustal tension after subduction. Evidence from North America, Australia, and Southern Africa suggests that the youngest intrusives within a craton are generally the most radioactive. For example Hudsonian age intrusives in the western Canadian Shield. This phenomenon could result from a large scale transfer of radioelements from mantle to crust, which would have the effect of removing from the underlying mantle the heat sources capable of causing any further disruption of overlying lithosphere. Implicit in this model is the development of a stagnant zone in the sub-craton mantle from which radioelements have been largely depleted. The time required for large-ion lithophile elements to accumulate and generate sufficient heat to initiate an asthenospheric rise, and subsequently become differentiated granite magmas which are emplaced in the crust during tension or shearing could explain their late arrival in tectonic cycles.

In the upper crust 'hot' radioelement-enriched granitic plutons are a long-lived source of heat production. Moreover they tend to be enriched in rare and valuable elements other than the radioactive elements. Once introduced into the crust they become, as described by Simpson *et al.* (1979) and by Plant *et al.* (1980), a focal point for the operation of a near-surface hydro-geochemical cycle. Their economic importance depends on the favourable conjunction of several factors, as in the case of the Athabasca basin.

Hence different types of uranium deposit could be formed in a region over a period of time all related to juvenile acid magmas. Such a model provides an explanation for uranium (or thorium) provinces, and their temporal and spatial characteristics.

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APPENDIX

Availability of GSC publications referred to in this paper

GSC Open Files. All GSC Open Files relating to radiometric and geochemical data are available for reference in Geological Survey of Canada libraries in Ottawa; Bedford, Nova Scotia; Calgary, Alberta; Vancouver, British Colombia.

Radiometric data. The data used to compile the uranium map shown in figs. 4 and 5 consists of both flight line profiles and contour maps showing integral, potassium, uranium, thorium corrected count rates, and U/Th, U/K, Th/K ratios at a scale of 1:250000. The contour maps are intended to provide an over-all view of radioelement distribution, whilst profiles provide detailed information along the flight lines.

All material is available as white prints, from a commercial sales agent, and most of it is available as microfiche from the Publications Office, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8. This office can supply lists relating Open File or Geophysical Series Map No. to specific areas.

Geochemical data. The data incorporated in figs. 4 and 5 is available in National Geochemical Reconnaissance 1:200000 Coloured Compilation Map Series which may be purchased from Campbell Reproductions, 880 Wellington Street, Ottawa, Ontario, K1R 6K7.

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