Geoscience Canada

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Volume 12, Number 2, June 1985

URI: https://id.erudit.org/iderudit/geocan12_2art02

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

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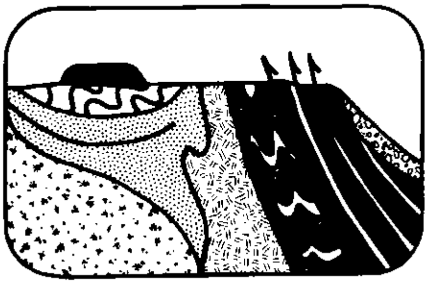
Cite this article

Kumarapeli, P. S. (1985). Vestiges of lapetan Rifting in the Craton West of the Northern Appalachians. *Geoscience Canada*, *12*(2), 54–59.



Vestiges of Iapetan Rifting in the Craton West of the Northern Appalachians

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Summary

Plate tectonic models for the evolution of the Appalachians involve a Wilson Cycle of a late Precambrian-early Paleozoic ocean basin – the Iapetus. On one side of the Iapetus lay the continent of Laurentia, which included the ancient North American landmass. Continental rifting, which initiated the formation of the Iapetus in late Hadrynian/early Cambrian times, left its mark on the continental margin of Laurentia in the form of structural damage and rift-related magmatic/volcanic products, and some of these are recognizable from the southeastern parts of Canadian Shield and the adjacent platform. These include two well-defined aulacogens, zones of step faults parallel to the ancient continental margin and possible fracture zones transverse to the ancient margin. Carbonatite complexes yielding K-Ar ages of approximately 565 Ma occur in both aulacogens. Closely associated with one of them is a prominent dike swarm of probable Hadrynian age.

Introduction

Plate tectonic models for the evolution of the Appalachian orogen involve a Wilson Cycle (Wilson, 1966; Dewey, 1969) of a late Precambrian-early Proterozoic ocean basin — the Iapetus. The cycle began in the late Precambrian (Hadrynian) by fragmentation of a supercontinent (Scotese *et al.*, 1979). The Iapetus came into existence between two of the fragments: Laurentia, which included the ancient North American landmass, and Baltica (Fig. 1). The ocean expanded through the Cambrian to the Ordovician, then began to contract in the Ordovician, and finally closed in the early Devonian.

The breaking up of the supercontinent may have taken place in the manner outlined by Dewey and Burke (1974). Mantle plumes produced the initial ruptures in the form of three-pronged rifts which, by rift propagation, integrated into multibranched rift systems. Expansion of the more active rifts of these systems led to continental fragmentation. Regardless of the actual mechanisms, the breakup of a continent is bound to leave its mark on the lithospheric plates of the fragments in the form of structural damage and rift-related magmatic/volcanic products. It appears that Laurentia was no exception, for in the southeastern parts of the Canadian Shield (Shield Area) are several structural and magmatic/volcanic features which are probably by-products of this rifting episode. This event will be referred to as the Iapetan rifting, although in previous works (Kumarapeli, 1976, 1978) this same event has been referred to as eo-Appalachian rifting.

The Shield Area on which the Iapetan structural and magmatic/volcanic features are superimposed belongs to the Grenville structural province (Wynne-Edwards, 1972) whose last major thermal-structural event, the Grenville orogeny, peaked approximately 1100 Ma ago (Doig, 1977). A characteristic feature of this part of the Shield is the presence of numerous lineaments in the form of narrow rectilinear or zig-zag valleys (Kumarapeli, 1976, 1978). They range in length from a few kilometres to several tens of kilometres. Only a small portion of these lineaments can be considered as reflecting bedding or foliation directions, for many of them cut across these trends, and therefore seem to be fracture controlled. These lineaments produce a remarkably persistent pattern. They prevalently fall into two sets, one that trends approximately northeast and the other approximately northwest. In some areas a north-south trend also has been recognized (Forsyth, 1981). That they reflect a regional fracture pattern (RFP) is also indicated by the fact that their directions coincide with the dominant directions of diabase dikes in the Canadian Shield. The RFP is a very old feature of the crust in this region, for in some areas it controls the localization of Archean mineral deposits (Kutina and Fabri, 1972). It had a dominating influence in controlling the directions of Iapetan faults (Kumarapeli, 1976, 1978).

Aulacogens

A model for the breakup of the supercontinent, with initial ruptures forming as three-pronged rifts, has already been briefly outlined. Usually, only two of the three arms open to form oceanic crust; the third arm remains as a failed arm, and eventually becomes an aulacogen. Thus, aulacogens come to be superimposed on the continental fragments. They commonly radiate into the continental interiors from reentrants of continental margins, or in the case where a continental margin has become involved in collisional orogeny, from salients of the resulting foldbelt. In the latter case, the deeper parts of the aulacogens may become buried under the nappes of the foldbelt or

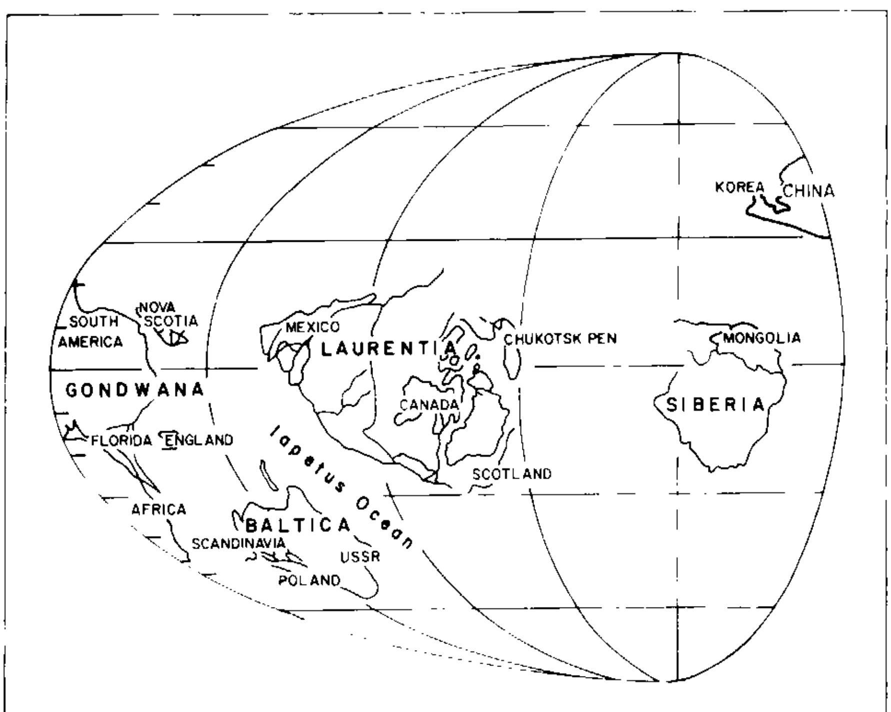

Figure 1 *Cambrian continental reconstruction showing the relation of the Iapetus to Laurentia and Baltica (after Scotese et al. 1979)*

otherwise become obscured by orogeny. Two grabens, the Ottawa graben and the Saguenay graben, have characteristics which suggest that they are Iapetan aulacogens.

The Ottawa Graben. The Ottawa graben (Fig. 2) is a deeply eroded feature, and yet displays unmistakable rift valley morphology along a 200 km segment west of Ottawa. This segment was the first to be recognized as a graben, the Ottawa-Bonnechere graben of Kay (1942). Since then, the graben has been traced northwestward to Lake Nipissing and Lake Timiskaming areas where the graben bifurcates and its main faults split into divergent smaller faults. Eastward, the graben has been traced into the Montreal area (see section JK, Fig. 2), and further east its presence beneath the thrust sheets of the Appalachian foldbelt can be inferred from the fact that intrusions (Monteregian), presumably localized along graben faults, continue well into the foldbelt. Thus, the length of the graben is about 700 km.

The graben is discordantly superimposed on Grenville structural trends. However, the directions of graben faults appear to be controlled by the RFP (see Ramberg and Smithson, 1975). Where the internal structure of the graben is known in sufficient detail, it is usually a complex graben, consisting of combinations of longitudinal, tilted blocks and/or small grabens and horsts. Cross sections are typically asymmetrical, and in the Lake Timiskaming area a major fault is present only on one side. Results of the 1982 COCRUST long-range seismic experiment across the graben show that it has expression at Moho depth (Mereu *et al.*, 1984).

The Ottawa graben extends into the continental interior from a prominent salient of the Appalachian foldbelt – the Sutton Mountains salient (Rankin, 1976). The apical segment of this salient is characterized by prominent, nearly coincident, gravity and magnetic anomalies whose axes follow a narrow (<10 km) discontinuous belt of greenschists of volcanic derivation – the Tibbit Hill Volcanics (Fig. 2) – which in the Waterloo area of Quebec contain minor rhyolitic bands. Modelling of the anomalies shows that this seemingly minor belt is the surface expression of a much larger mass of dominantly mafic metavolcanic rocks (Kumarapeli *et al.*, 1981). The bimodal character of the volcanic parent, coupled with its alkalic or transitional character as indicated by trace element geochemistry (Pintson *et al.*, 1985), supports the hypothesis that these rocks are rift-related. The gravity-magnetic model of the Tibbit Hill Volcanics is triangular-shaped (Fig. 2), with its apex pointing approximately in the direction of the graben. Even allowing for some northwestward thrusting of the Tibbit Hill Volcanics (and the underlying basement) during the Taconic orogeny (Ando *et al.*, 1983), their initial space relations with the graben were probably not substantially different from what they are today. A magmatic event which is more obviously related to the rifting is the emplacement of a diabase dike swarm – the Grenville dike swarm – along the length of the graben. It is quite conceivable that this dike swarm radiates into the continental interior from the apex of the mass of Tibbit Hill Volcanics and that dike emplacement and the volcanism were coeval. This episode of volcanism/magmatism was accompanied or, more likely, followed by the emplacement of

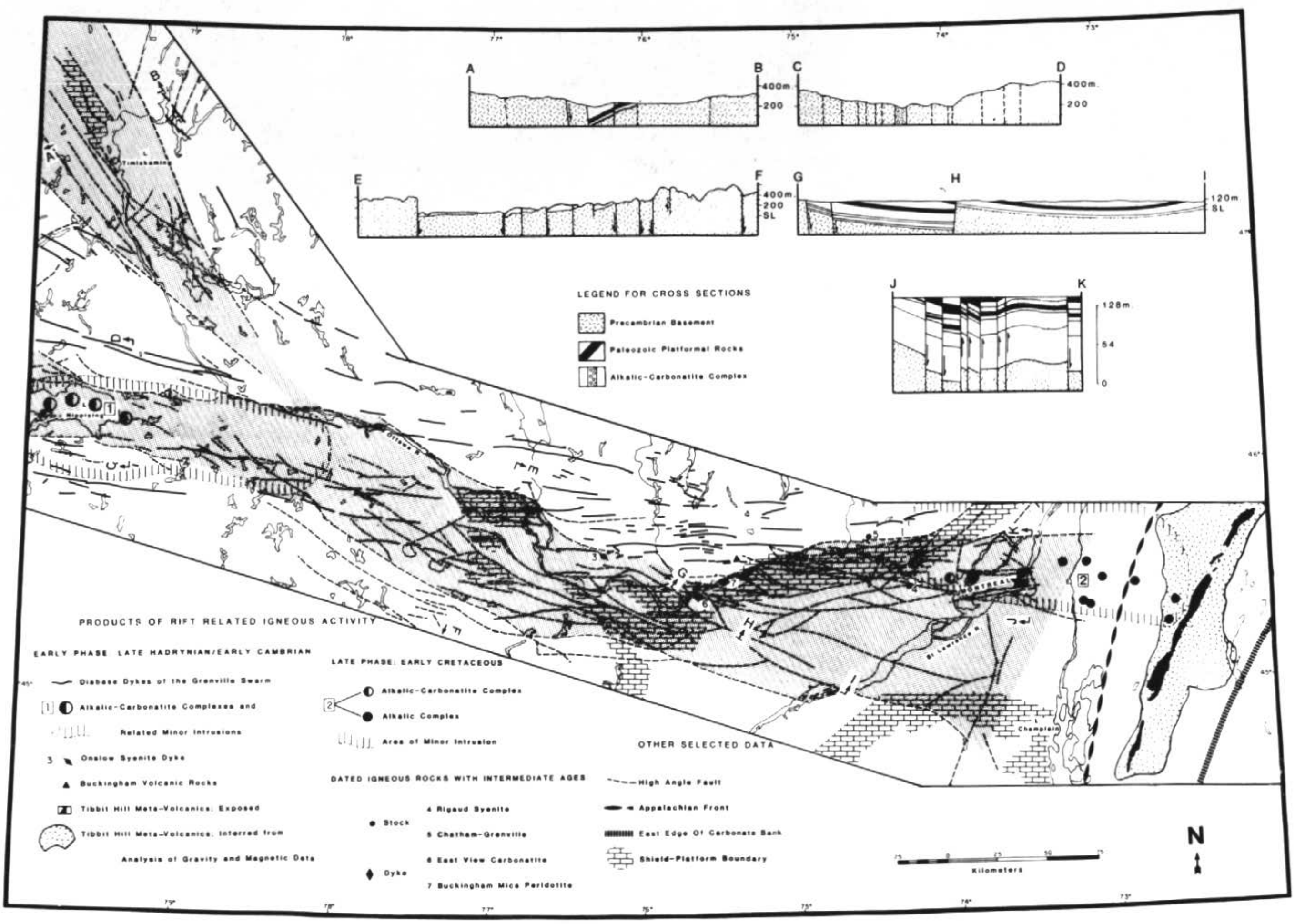

Figure 2 *Structural and magmatic features of the Ottawa graben. Section EF after Kay 1942, JK after Clark 1972*

alkalic complexes, including several carbonatite complexes which yield K-Ar ages of about 565 Ma (Doig, 1970). These complexes are concentrated mostly in the Lake Nipissing area (Currie, 1971; Fig. 2). A second and much younger episode of alkalic magmatism occurred along the eastern part of the graben in the early Cretaceous. The products of this event are the Monteregian intrusions (Fig. 2), which also include two carbonatite complexes.

The eastern part of the graben is floored by Cambro-Ordovician platformal rocks which formed on the shelf bordering the Iapetus. In the western part, these rocks have a patchy distribution, having been partly removed by erosion. The original rift fill of the graben, if preserved, should occur between the platformal rocks and the Grenville basement. Rocks representing such material are not present in most areas, indicating that deep erosion of the graben had taken place when the Early Paleozoic marine transgression occurred in Late Cambrian – Early Ordovician time. However, in the Montreal area and further to the east, lithologies derived from coarse clastics form the basal unit (Covey Hill Formation of the Potsdam Group) of the platformal sequence. The clastics may be Hadrynian in age (Hofmann, 1972) and may represent reworked rift fill of the Ottawa graben.

The timing of the initial rifting is not known precisely, but a late Precambrian (Hadrynian) age is most probable. The only reliably dated event that sheds light on the question is the emplacement of alkalic and carbonatite complexes along the graben about 565 Ma ago. Paleomagnetic studies of the Grenville dike swarm have indicated that the dikes were emplaced about 700 Ma ago (Murthy, 1971). A solution to the problem will have to wait until rocks from the Grenville dike swarm and Tibbit Hill Volcanics are age dated.

Any model incorporating the origin of the Ottawa graben must provide a coherent rationale for the following aspects of the graben: (1) the Ottawa graben represents the trace of a tension crack of the lithosphere which propagated westward from the apex of a prominent salient of the Iapetus margin which is now represented by a salient of the Appalachian foldbelt; (2) rocks in the apical area of the salient include a large mass of schistose rocks of volcanic derivation, the Tibbit Hill Volcanics, whose pristine petrological and geochemical characteristics indicate that they are products of continental rifting; (3) the metavolcanic mass is triangular-shaped in plan, the apex of which points in the direction of the Ottawa graben; (4) the Grenville dike swarm which has been emplaced along the length of the graben also seems to radiate from the apex of the metavolcanic mass; (5) the initial rifting and the beginning of the Appalachian stratigraphic sequences are nearly contemporaneous (note that the Tibbit Hill Volcanics occur at the base of the Appalachian stratigraphic sequences). A model which is consistent with the above aspects is one in which the Ottawa graben is an aulacogen (first recognized as such by Shatsky, 1946) related to an Iapetan triple junction – the Sutton Mountains triple junction – located in the region where the eastward projection of the graben intersects the ancient continental margin (Figs. 2, 3). During the early stages of the evolution of the Iapetus, the paleogeography and the tectonic setting of this area may have resembled those of the Afar triple junction, the relationship of the Ottawa graben to the early Iapetus being similar to that of the East African rift system to the Red Sea and the Gulf of Aden.

The Saguenay Graben. The Saguenay graben is another structure of tensional origin that radiates into the continental interior from the Appalachian-Shield boundary. Like the Ottawa graben, the Saguenay graben also may extend eastward beneath the Appalachian nappes, but such an extension is not discernible from surface geology or the geophysical signature. Where the graben meets the foldbelt, the latter displays a slight bend but one much less prominent than the bend displayed in the area of the Sutton Mountain salient. There are also no volcanic rocks analogous to Tibbit Hill Volcanics. Westward, the graben faults diverge and progressively curve to assume a northwest direction (probably due to the assertion of the RFP), and seems to die out in splays. Excluding the possible extension beneath the Appalachian nappes, the graben can be traced for a distance of about 300 km.

The time of the initial rifting is not known precisely. The graben contains two down-faulted Ordovician outliers which are the remnants of a once extensive Paleozoic platform. Two carbonatite complexes, St. Honoré (Vallee and Dubuc, 1970; Thivierge *et al.*, 1983) and Crevier (Woussen *et al.*, 1979) occur in the graben. St. Honoré complex has yielded a K-Ar age of 564 Ma (Doig and Barton, 1968) which is almost identical to the ages of carbonatite complexes in the Lake Nipissing area (Ottawa graben). The fact that carbonatite magmatism broke through these two widely separated rifts at about the same time supports the view that they formed as parts of a single event.

Iapetan Faults And Fracture Zones

Faults Parallel to the Iapetus Margin. Block faulting appears to be a characteristic feature of rifted continental margins (Scrutton, 1982). It seems that listric faults, dipping toward the edge of the continent and paralleling the rifted margin, are the most common type (de Charpel *et al.*, 1978; Morton and Black, 1975). Relatively wide (100-200 km) zones are affected in some areas (see Montadert *et al.*, 1979). The faulting appears to be a byproduct of rifting and stretching of the crust during the early stages of the evolution of rifted margins (McKenzie, 1978).

What was initially a rifted margin may eventually become involved in collisional orogeny. As a result, the faults proximal to the collisional boundary may become interlocked and sealed by processes related to orogeny, but those that are distal may persist in the craton, susceptible to later reactivation. The fault zones described below appear to be Iapetan structures of this type.

The margin of the craton adjoining the Northern Appalachians is, in places, severely block-faulted. This type of faulting is probably present along the entire margin of the craton, but is best known from the St. Lawrence and Champlain Valleys (Fig. 3). The majority of these faults show varying degrees of parallelism to the orogen and dip toward it, their cumulative effect being to step down the Grenville crystalline basement (also the overlying platformal rocks) toward the orogen (Fig. 3, inset A). Seismic reflection studies show that the step-faulting of the crystalline basement continues even beyond the Appalachian front (SOQUIP, 1979; St.-Julien *et al.*, 1983).

There is evidence that the faults in the St. Lawrence and Champlain Valleys were already in existence when the Late Precambrian and/or Early Cambrian basal units of the platformal sequence began to form (Lewis, 1971). Thus, the relations of space and time and the geometry of the fault zones suggest that they are Iapetan faults produced by rifting and stretching of the crust in late Hadrynian/Early Cambrian times. These processes led to the formation of the passive margin of Laurentia. The dominant northeasterly trend of the faults was probably controlled by the northeast component of RFP. These faults were active during the buildup of the early Paleozoic platform and controlled the character of the platformal sedimentation (Zen, 1972; St.-Julien and Hubert, 1975). They underwent further reactivation in the Early Cretaceous and triggered minor magmatic activity (Kumarapeli, 1976, 1978).

Deep Drainage Lines and Their Possible Significance. Pleistocene glaciation has modified the drainage system of the Canadian Shield, mainly by filling the drainage lines, in varying degrees, by glacial debris. A typical drainage line consists of a succession of lakes connected by stretches of fast water. The lakes are merely expanses of quiet water, impounded in valleys, by dams of glacial debris. A distinctive feature of the drainage system of the Shield Area is that it also contains a few deeply incised drainage lines which persist for long distances (Fig. 3). Some of their valleys attain depths of 300 m or more, and yet even the deepest of them is partially filled with glacial debris. They commonly have zig-zag trends, the linear segments being parallel to the components of the RFP, and hence appear to be fault and/or joint controlled.

Ambrose (1964) has pointed out that the physiographic elements of the Shield Area, including the deep drainage lines, are pre-Ordovician features and have remained buried under a protective blanket of platformal rocks, and that this pre-Ordovician surface has undergone little modification and lowering since its exhumation. His arguments were based on the fact that the surface of the Shield Area contains numerous outliers of Early Paleozoic (Ordovician and younger) platformal rocks which are probably remnants of a once continuous platform cover. The wide distribution of these outliers suggests that no great lowering of the Precambrian surface has taken place since its exhumation. Some of the outliers are preserved in downfaulted

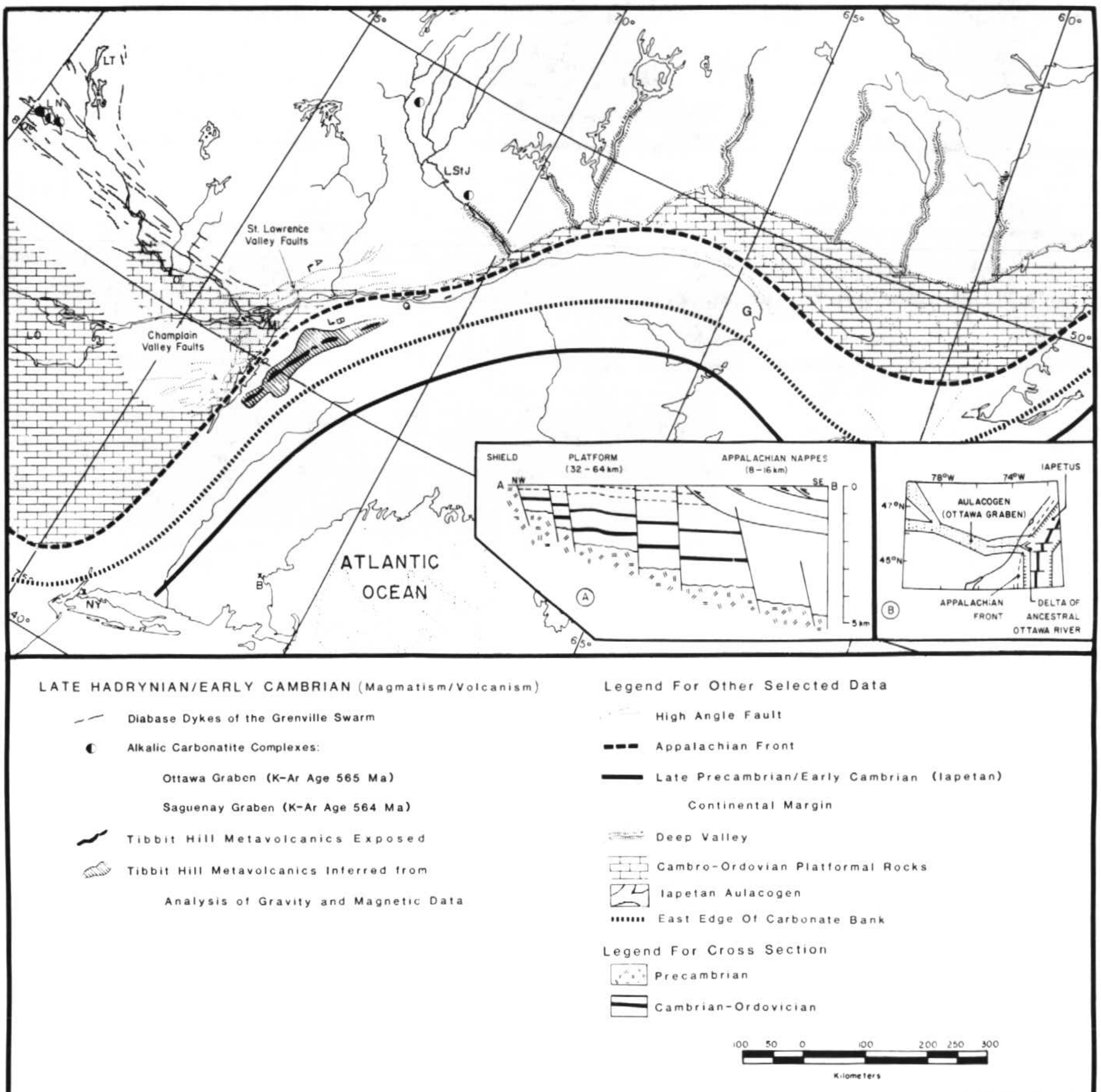

Figure 3 *Map showing features related to the Iapetan rifting: Appalachian front and the late Precambrian/early Cambrian continental margin. Inset A, schematic structural section across the boundary between the craton and the Appalachian foldbelt. Inset B, interpretive sketch of the postulated Sutton Mountains rrr triple junction*

depressions, but many simply lie on the bottoms or cling to the sides of valleys on Precambrian rocks.

The physiographic evolution of this part of the Canadian Shield, and in particular the origin of the deep valleys, attracted the attention of early workers (e.g., Wilson, 1903). It is conceivable that during the Iapetan rifting some of the rivers which drained into the rift basins became entrenched into the uplifted shoulders of the rifts along fracture zones which radiated into the continent at a large angle from the rift margins. Such lateral fracture zones could develop, especially in areas where doming preceded rifting. Later, subsidence of the rifted margin allowed the establishment of a continental shelf and the entire landscape, including the valleys, became buried under a platformal cover.

The deep drainage lines, Iapetan aulacogens and faults discussed in this paper are shown in Figure 3, together with the Appalachian front and the probable outline of the North American continental margin in Cambrian and Early Ordovician times (see Zen, 1983; Rodgers, 1968). The trends of the aulacogens and of the presumably fracture-controlled deep drainage lines, if extended, will intersect the ancient continental margin at large angles. Together, they form a distinctive pattern, whose space relations are consistent with the idea that they formed as lateral dislocations radiating from the principal Iapetan rifts. That these structural lines continue as basement features beneath the Appalachian nappes is indicated by the presence of prominent lineaments disposed transversely to the Appalachian trends.

Closing Remarks

In the foregoing sections, several structural and magmatic features in the southeastern parts of the Canadian Shield and the adjacent platform have been interpreted as by-products of continental rifting in late Precambrian times, as a prelude to opening of the Iapetus. It is perhaps pertinent to mention here that these features are also parts of the St. Lawrence Rift System (Kumarapeli and Saull, 1966). This Rift System appears to have developed, essentially in its present form, in the mid-Mesozoic but superimposed on older fault zones, also of tensional origin. Kumarapeli (1976) identified these older fault zones as by-products of eo-Appalachian rifting, which in this paper is referred to as Iapetan rifting. Thus, a major part of the St. Lawrence Rift System has formed by reactivation and integration of Iapetan fault zones and aulacogens and the similarities of features of this rift system with those of the classical continental rift systems (Kumarapeli, 1978), such as the East African Rift System, do not imply unity of origin.

Acknowledgements

Paul Hoffman of the Geological Survey of Canada and Reinhard Hesse of McGill University, critically read the manuscript and offered many useful suggestions. I also would like to extend my appreciation to Andrew D. Miall, the editor of this journal, for his suggestions. I thank Lori Bertrand, Hillar Pintson and Joel Scodnick for help in the preparation of the manuscript.

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Ms received as revised December 24, 1984