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IMPLICATIONS OF NEW CHRONOSTRATIGRAPHY FOR TECTONIC EVOLUTION OF WOPMAY OROGEN, NORTHWEST CANADIAN SHIELD

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ABSTRACT. New stratigraphic correlations and U-Pb zircon ages on intercalated volcanic ash beds calibrate the temporal evolution of the passive margin sequence exposed in Wopmay orogen, northwest Canadian Shield, and require revision of tectonic models to explain it. Unconformity-bounded depositional sequences in Kilohigok basin, located east of Wopmay orogen, contain several ash beds that can be traced laterally into the autochthon of Wopmay orogen. The age of initial passive margin sedimentation in Wopmay orogen is 1969 Ma, and its destruction during collision and initiation of foreland basin subsidence occurred by 1882 Ma. Therefore, the duration of the passive margin was on the order of 80 to 90 my. This contrasts with an earlier estimate of less than about 10 my, which was based on the interpretation of the Akaitcho Group (1.900 Ga) as an initial rift sequence thought to underlie the passive margin. The new age data require reconsideration of the stratigraphic position and tectonic significance of the Akaitcho Group. Accordingly, a new tectonic model for Wopmay orogen is proposed that involves collision of an extending, arc-bearing microcontinent (Hottah terrane) with a west-facing passive margin developed on the edge of Slave craton. In this model, the portion of the Akaitcho Group dated at 1.900 Ga developed in response to pre- to syn-collisional extension of the Hottah terrane and is allochthonous with respect to the passive margin. Only the isolated, easternmost part of the Akaitcho Group (Melville Group; new name), which remains undated, may represent rift deposits precursory to the overlying passive-margin sequence.

INTRODUCTION

Tectonic interpretations of Phanerozoic orogenic belts often rely on information derived from analysis of the preserved record of subsidence and sedimentation events in marginal sedimentary prisms. However, owing to the lack of biostratigraphic control, it is generally difficult to utilize the Precambrian stratigraphic record to establish the timing of orogenic events. In fact, the timing of events in Precambrian marginal prisms is often indirectly inferred by correlation with dated magmatic events in the interiors of orogenic belts (Ethridge, Rutland, and Wyborn, 1987; Hoffman and Bowring, 1984).

However, through the application of sequence stratigraphic concepts to Precambrian sedimentary basins, the relative time stratigraphy within and between basins can be greatly enhanced (Christie-Blick, Grotzinger, and von der Borch, 1988; Grotzinger and others, 1988; Grotzinger and others, 1989). Where datable volcanic rocks such as air-fall tuffs are present, the sequences can be calibrated in absolute time (Bowring and Grotzinger, 1989). The scarcity and preservation problems associated with tuffs emphasize the need for accurate stratigraphic correlations from areas where ash beds occur to areas where they are absent. In this manner, a useful chronostratigraphy for certain Precambrian sedimentary basins may ultimately be established.

In this paper we report results of a comprehensive stratigraphic and geochronologic investigation of early Proterozoic sedimentary basins related to Wopmay and Thelon orogens, located in the northwest Canadian Shield. These results have important implications for the tectonic evolution of Wopmay orogen. Recent models for the tectonic evolution of Wopmay orogen (Hoffman and Bowring, 1984; Hildebrand, Hoffman, and Bowring, 1987) have been constrained by the apparently short duration (<15 my) of the passive margin inferred from stratigraphic relationships. The main conclusion of this investigation is that the age of the onset of passive margin subsidence in Wopmay orogen, as determined by dating ash beds deposited within well-defined stratigraphic sequences, is substantially older (>60 my) than the rocks previously interpreted to represent the initial rifting beneath the passive margin. Consequently, the new correlations and temporal constraints require revision of current models for the tectonic evolution of Wopmay orogen.

REGIONAL GEOLOGIC SETTING

Wopmay orogen.—Wopmay orogen and Kilohigok basin flank the west and east sides of the Archean Slave craton respectively (fig. 1). The principal tectonic elements of Wopmay orogen from west to east are the Hottah terrane, the Great Bear arc, a metamorphic internal zone, a foreland thrust and fold belt, and an autochthon underlain by basement of the Slave craton (fig. 1). The Hottah terrane is composed of amphibolite facies sedimentary and intermediate volcanic rocks, cut by 1.94° to 1.90 Ga deformed calc-alkaline, biotite-hornblende-bearing plutons of the Hottah arc (Bowring, ms). On the basis of isotopic and detrital zircon data, the calc-alkaline magmatic arc is inferred to be built upon an older (2.0–2.4 Ga) cryptic basement (Bowring and Podosek, 1989; Housh, Bowring, and Villeneuve, 1989). Overlying the deformed rocks of the Hottah terrane are a sequence of about 1.90 Ga arkosic sandstones and intermediate volcanic rocks (Bell Island Group) which in turn are overlain by a thick sequence of pillow basalts and associated gabbroic intrusives (1.9–1.87 Ga; Reichenbach, ms and 1991; R.S. Hildebrand, personal communication). These rocks have been correlated with a putative rift sequence in the metamorphic internal zone to the east (Reichenbach, ms and 1991), which has encouraged a back-arc interpretation of the

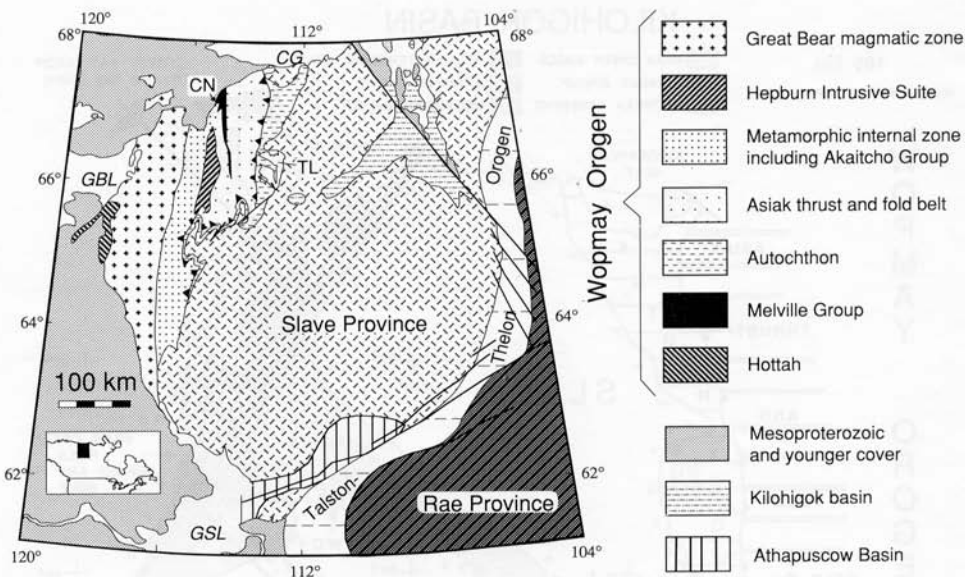


Fig. 1. Simplified geologic map of the northwest Canadian Shield showing the major tectonic elements, with emphasis on Wopmay orogen. CN, Cloos nappe; CG, Coronation Gulf; GBL, Great Bear Lake; GSL, Great Slave Lake; TL, Takuju Lake.

orogen. The Hottah terrane has been interpreted as the remnants of a continental magmatic arc developed on the edge of the Slave craton (Hildebrand, Hoffman, and Bowring, 1987; Hildebrand and Roots, 1985) or, alternatively, as exotic to it (Hildebrand, 1981; Hoffman, 1980).

The Great Bear arc is a continental volcano-plutonic arc which stitches the Hottah terrane to the Slave craton. The arc is a 450 km \times 100 km north-trending belt of calc-alkaline volcanic and plutonic rocks emplaced at 1.878 to 1.843 Ga (Bowring, ms; Hildebrand, Hoffman, and Bowring, 1987). To the east, low-grade sedimentary and volcanic rocks of the Great Bear arc overlie deformed Archean rocks along the western edge of the internal zone of Wopmay orogen, and to the west they overlie deformed Hottah terrane rocks as well as the Bell Island Group and overlying basaltic rocks.

Preserved in a thrust-fold belt and autochthon in easternmost Wopmay orogen is a sedimentary prism composed of a lower succession (Epworth Group) of west-facing shelf and rise clastics (Odjick Formation) and carbonate (Rocknest Formation) overlain by an upper sequence of feldspathic-lithic turbidites and associated black shales and marlstones (Recluse Group), overlain by arkosic fluvial deposits. The lower succession unconformably overlies Archean basement of the Slave Province and has been interpreted as a passive margin sequence; the upper succession

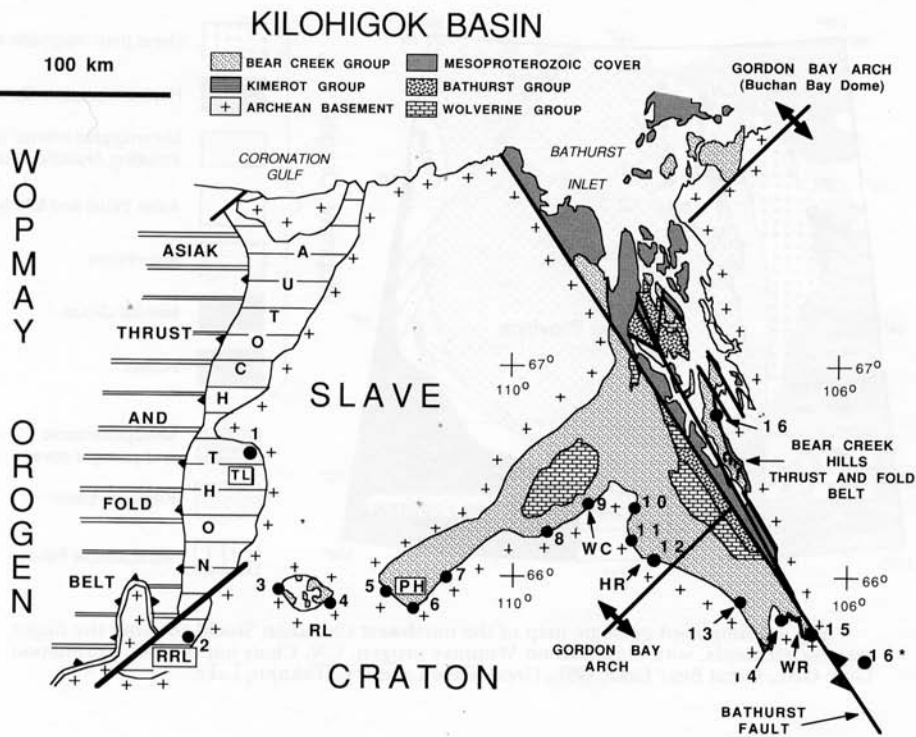


Fig. 2. Location map showing distribution of measured sections illustrated in figure 3. RL—Rockinghorse Lake; PH—Peacock Hills; WC—Wolverine Canyon; HR—Hackett River; WR—Western River. 16* marks the palinspastic location of section 16 after 110 km of sinistral slip is removed along the Bathurst Fault.

has been interpreted as the flysch and molasse of a foredeep sequence (Hoffman, 1973, 1980; Hoffman and Bowring, 1984).

The thin-skinned thrust-fold belt, which incorporates Epworth and Recluse groups, continues westward into an allochthonous metamorphic internal zone, where an additional thick sequence of bimodal volcanic rocks and immature marine clastic sedimentary rocks (Akaitcho Group) is exposed (Hoffman and others, 1978). The Akaitcho Group has been interpreted to underlie stratigraphically the Epworth Group and to represent an initial rift sequence (Hoffman and others, 1978; Easton, 1981; Hildebrand, Hoffman, and Bowring, 1987; Hoffman, 1980; Hoffman and Bowring, 1984). However, as discussed below, new age constraints indicate that the age span of the passive margin overlaps that of the Akaitcho Group, raising the possibility that much of the Akaitcho Group is allochthonous with respect to the passive margin sequence.

The internal zone is intruded by a compositionally diverse suite of plutonic rocks (Hepburn intrusive suite) which range compositionally

from strongly peraluminous granite to gabbro (Hoffman and others, 1980; Lalonde, 1989). The plutons were emplaced at 1.89 to 1.88 Ga (Bowring, ms) into rocks of the Akaitcho, Epworth, and Recluse groups during deformation, and both the plutons and their high-grade metamorphic envelope were transported onto the Slave craton during thrusting. Inverted metamorphic isograds that cut obliquely across the basal décollement resulted as hot plutons tectonically emplaced over the colder autochthon (St-Onge, King, and Lalonde, 1984; St-Onge, 1987). No plutons of the Hepburn intrusive suite are observed to intrude the Slave craton or its autochthonous cover. The intrusions obscure the relationship between the Akaitcho Group, located in the metamorphic internal zone, and an eastern belt that exposes mainly rocks of the Epworth and Recluse groups (fig. 1). Certain rocks within this eastern belt originally believed to be correlative with the western Akaitcho Group are exposed in the core of an anticlinorium (Cloos Nappe; see fig. 1). These rocks have been re-named the Melville Group (P.F. Hoffman, personal communication). Rocks of the Akaitcho Group have an age of 1.900 Ga, but the Melville Group has not been dated. The two have been correlated on the basis of broadly similar lithologies, but the stratigraphic relations of each to the passive margin sequence are equivocal. Semipelite of the Epworth Group face stratigraphically away from the Akaitcho Group in a small septum between plutons of the Hepburn intrusive suite, but the contact is not exposed (Hoffman and others, 1980). The Melville Group anticlinorium is fault bounded on the west, and its eastern margin is not exposed. Thus although the Akaitcho Group has formerly been considered to underlie the passive margin sequence stratigraphically (Hoffman and others, 1978; 1980; Easton, 1981; Hoffman and Pelletier, 1982), we believe this inference and the supposed correlation of the Melville and Akaitcho groups are suspect. It is possible, for example, that the undated Melville Group indeed represents a rift assemblage predating the passive margin sequence, but that the Akaitcho Group is an unrelated assemblage entirely allochthonous with respect to the passive margin. This possibility is a critical component of our model described below.

Kilohigok basin.—The Kilohigok basin (Campbell and Cecile, 1981) is largely a foredeep related to collision in the Thelon orogen, located to the east (Grotzinger and McCormick, 1988; Tirrul and Grotzinger, 1990). A northwest-vergent thrust and fold belt (fig. 2) in the southeastern corner of the basin is related to the Thelon orogen. The orogen is a collisional belt (Gibb and Thomas, 1977; Hoffman, 1987) consisting of granulite facies metamorphic rocks and granitic to dioritic plutons (1.99–1.91 Ga), cut by dextral and dip-parallel shear zones continuous along strike for hundreds of kilometers (James, 1989; Thompson and others, 1986; van Breemen and others, 1987).

The lower strata of the Kilohigok basin contain a basal shallow-water siliciclastic/carbonate platform (Kimerot Group), which is overlain by deep-water flysch, and in turn by shallow-marine and fluvial molasse (Bear Creek Group; Grotzinger and McCormick, 1988). The Kimerot

Group represents a passive margin that foundered during flexural subsidence (Grotzinger and Royden, 1990). During subsequent thrusting, a flexural arch developed and trends subparallel to the Thelon orogen and perpendicular to thrust-related transport indicators (Tirrul and Grotzinger, 1990). Following drowning, the platform was buried by deep-water flysch (up to 2 km thick) and then by shallowing and progradation of molasse (> 3.5 km) toward the foreland and over the craton (McCormick and Grotzinger, in press). The west trending outcrop belt that connects Kilohigok basin to Wopmay orogen (fig. 2) provides nearly continuous exposure of the transition from Kilohigok basin stratigraphy to Wopmay stratigraphy.

SEQUENCE STRATIGRAPHY

The concepts of sequence stratigraphy, as developed for Phanerozoic strata (Sloss, 1963; Vail, Mitchum, and Thompson, 1977), have recently been recognized as an important approach in the correlation of Proterozoic strata (Christie-Blick, Grotzinger, and von der Borch, 1988). Because most unconformities have chronostratigraphic significance, their recognition and correlation over broad areas permit the establishment of relative time surfaces in sedimentary basins. Where unconformity-bounded depositional sequences include volcanic rocks (for example, ash beds), the sediments and stratal bounding surfaces may be calibrated in absolute time.

Figure 3 illustrates the major stratigraphic relationships within the lower Bear Creek Group extending from the Kilohigok basin westward across the Slave craton into Wopmay orogen, based on maps and measured stratigraphic sections. It is important to emphasize that the stratigraphic sections (columns) shown in figure 3 are included for control on unit thicknesses and that all sequence boundaries and most facies transitions have been walked out between sections to confirm the stratigraphic relationships. Exceptions to this include the intervals between sections 1 and 2, 2 and 3, and 4 and 5 where outcrop is poor, or the strata have been eroded down to the basement. Additionally, stratal continuity between sections 15 and 16 is interrupted by the Bathurst Fault.

The lower Bear Creek Group (Hackett through Link formations) consists of at least 5 unconformity-bounded depositional sequences. Most consist of regressive depositional systems tracts characterized by upward-shallowing facies including outer shoreface, graded siltstones and mudstones, passing up into hummocky-stratified fine- to medium-grained sandstones, capped by inner shoreface, trough-crossbedded medium- to coarse-grained sandstones. Sequence boundaries are generally marked by abrupt transitions into overlying deeper water facies with minor evidence for erosion. However, most sequences are at least locally incised to depths of up to 50 m and are filled with fluvial sandstones or transgressive marine sandstones and siltstones.

Generally, transgressive systems tracts are thin to absent (Hackett and Beechey formations). In these cases formation boundaries (flooding

surfaces) coincide with sequence boundaries and are easily mapped because of the strong lithologic contrast across the boundaries. Where developed, transgressive facies are often overlain by intervals of condensed sedimentation (for example, lower member of Rifle Formation). However, where transgressive sediments are absent facies representative of condensed sedimentation were deposited directly on top of the sequence boundary (for example, Beechey Formation between sections 13–16). Intervals interpreted as evidence for condensed sedimentation include subtidal carbonates intercalated within mudstones and siltstones. These carbonates are often clastic-textured dolosiltites with wave and current-ripple lamination. Commonly they contain hardground surfaces and may be reworked to form layers of edgewise conglomerate. Marine cement crusts of dolomite-replaced aragonite are also present and may form continuous layers up to 1.5 m thick that are laterally continuous for over 40 km (Grotzinger and Friedman, 1989). Finally, in some cases (for example, Rifle and Beechey formations) deposition of concretionary mudstones may have occurred during times of condensed sedimentation.

All depositional sequences thicken into the southeast corner of the basin (palinspastic), toward the Thelon orogen. This differential subsidence is attributable to flexure of the lithosphere in response to eastward subduction of the Slave craton during convergence along the Thelon orogen (Grotzinger and McCormick, 1988; Grotzinger and Royden, 1990). Westward across the Slave craton, all sequences thin over the Gordon Bay arch, culminating in major downcutting by Burnside Formation fluvial units, and thicken again into the Wolverine Canyon area. Continuing to the west beyond Wolverine Canyon, the lowermost sequence (Hackett Formation) passes laterally into two sequences, the uppermost of which is correlative with the lower part of the Rifle Formation in the Peacock Hills and Rockinghorse Lake areas. Intermediate sequences (Beechey and Link formations) show no significant changes in thickness, and the uppermost sequence (Burnside Formation) thins significantly and cuts down into older units; this area evolved from an area of initially low subsidence to a positive arch area later on. Farther west, toward the Redrock Lake area in the autochthon of Wopmay orogen, correlatives of the Hackett Formation are present. This correlation is essential in establishing the maximum age constraint on the passive margin sequence in Wopmay orogen; ash beds 1, 4, and 5 are interpreted as equivalents, and thus the age of ash bed 1 limits the age of the basal Odjick Formation at section 2 (see fig. 3). Northward in the Wopmay autochthon correlatives of the Hackett Formation were not deposited suggesting that a positive area was present in this area at that time, possibly associated with residual uplift of the passive margin following rifting. The uppermost units of the Bear Creek Group (upper Rifle through Burnside equivalents) onlap and thicken markedly in the Taki-juq Lake area indicating that this initially positive region rapidly subsided

during deposition of the upper Rifle through Burnside formations, coincident with initial passive margin subsidence.

The inset of figure 3, which is drawn at a different scale than the rest of the figure, represents the major stratigraphic units and their thicknesses of the Coronation Supergroup in the autochthon of Wopmay orogen, in the vicinity of Takijug Lake. This stratigraphic column is included principally to illustrate the position of ash bed #7. However, we note that ash bed #7 was discovered north of this area, and its stratigraphic position is projected for reference. In the Takijug Lake area the base of the Odjick Formation is equivalent to the condensed interval of the lower Rifle Formation. The middle Odjick Formation is correlative with the lower Burnside Formation. Other correlations, not shown here, equate the middle Rocknest Formation with the middle Burnside Formation, and the upper Rocknest Formation through basal Recluse Group with the upper Burnside and Mara formations (Grotzinger and others, 1988; 1989; Grotzinger, McCormick, and Pelechaty, 1987; McCormick and Grotzinger, 1988).

Volcanic ash beds occur at several levels within the stratigraphic sequences of Wopmay orogen, Kilohigok basin, and intervening platform cover (fig. 3). Generally, the ash beds are 0.2 to 1.5 m thick, pale to apple green in color, difficult to break, and fracture conchoidally. The ash beds occur at positions just above the contact between the Epworth Group (Rocknest Formation) and Recluse Group (Fontano Formation; ash bed #7), within the middle Odjick Formation north of Takijug Lake (ash bed #6), at the base of the Odjick Formation north of Redrock Lake (ash bed #5), at the base of the Hackett Formation at Rockinghorse Lake (ash bed #4), within the Link Formation of the Peacock Hills area (ash bed #3), along the sequence boundary between the Rifle and Beechey formations near Rifle Lake (ash bed #2), and at the base of the Hackett Formation along the east side of Bathurst Inlet (ash bed #1). Ash beds 1, 4, and 5 are interpreted as equivalents. Datable zircons were recovered from ash beds 1, 2, and 7. Thus, the successfully dated ash beds reported below are derived from three separate stratigraphic levels. All the dates presented here were determined after the stratigraphic framework had been established (Grotzinger, McCormick, and Pelechaty, 1987; 1988), and dating the ash beds has served as an independent test of the stratigraphy (Bowring and Grotzinger, 1988; Grotzinger and others, 1989).

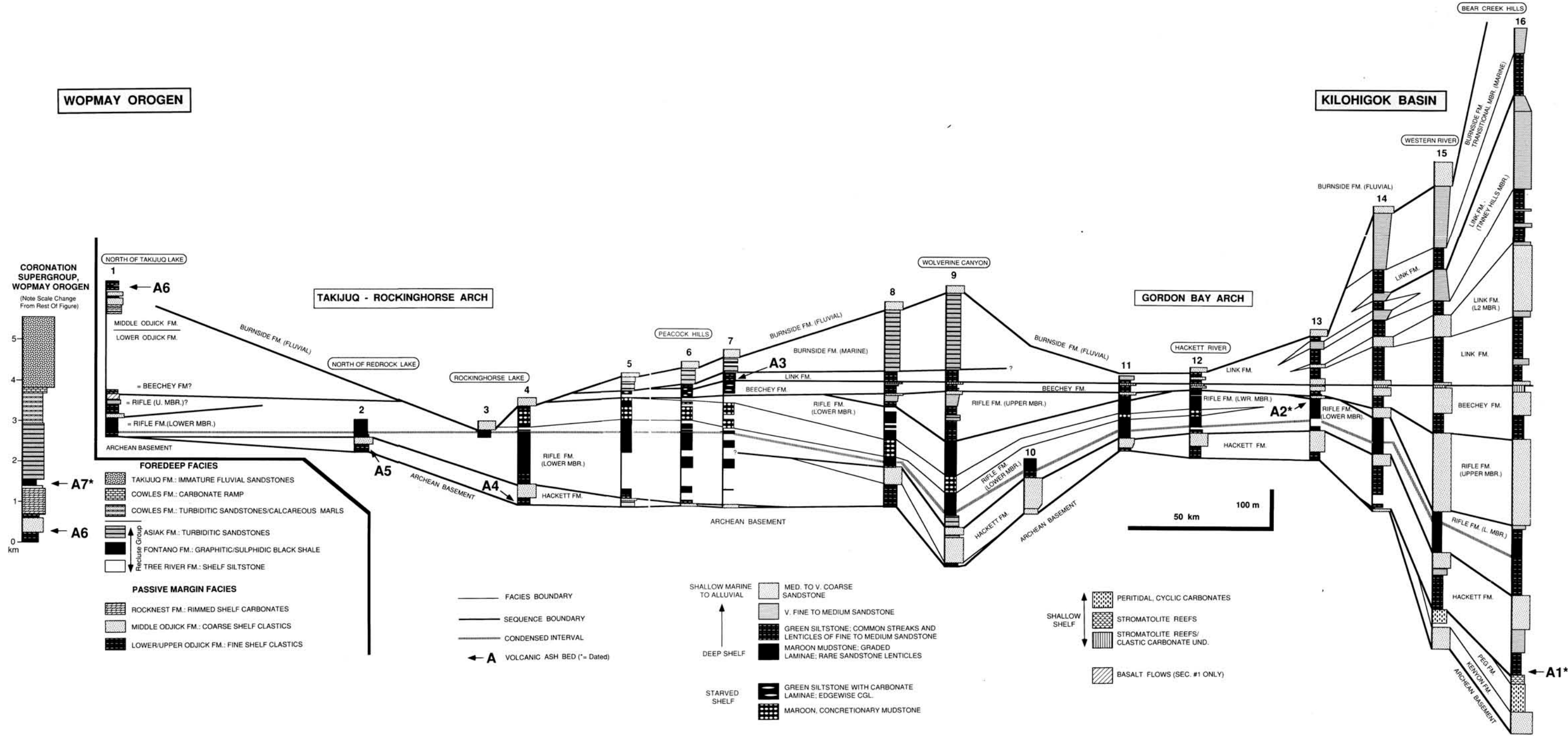
RESULTS OF U-PB DATING OF ZIRCONS IN ASH BEDS

Analytical techniques.—Zircons were separated from crushed ash samples by standard Wilfley table and heavy liquid techniques. Analyzed zircons were individually hand-picked, dissolved in teflon microbombs,

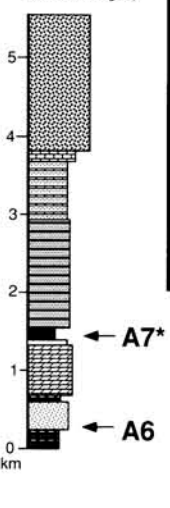
Fig. 3. Stratigraphic correlations between Kilohigok basin (secs. 5–16), Rockinghorse outlier (secs. 3, 4), and autochthon of Wopmay orogen (secs. 1 and 2; lower Odjick Formation). Section 16 is shown in its palinspastic position (16* of fig. 2). Inset illustrates the major stratigraphic units in the autochthon of Wopmay orogen and the position of ash bed #7. Ash beds 1, 2, and 7 were dated in this study.

WOPMAY OROGEN

KILOHIGOK BASIN



CORONATION SUPERGROUP, WOPMAY OROGEN
(Note Scale Change From Rest Of Figure)



- FOREDEEP FACIES**
- TAKIJUQ FM.: IMMATURE FLUVIAL SANDSTONES
 - COWLES FM.: CARBONATE RAMP
 - COWLES FM.: TURBIDITIC SANDSTONES/CALCAREOUS MARLS
- PASSIVE MARGIN FACIES**
- ROCKNEST FM.: RIMMED SHELF CARBONATES
 - MIDDLE ODJICK FM.: COARSE SHELF CLASTICS
 - LOWER/UPPER ODJICK FM.: FINE SHELF CLASTICS

- FACIES BOUNDARY
- SEQUENCE BOUNDARY
- CONDENSED INTERVAL
- ← A VOLCANIC ASH BED (* = Dated)

- SHALLOW MARINE TO ALLUVIAL
- MED. TO V. COARSE SANDSTONE
 - V. FINE TO MEDIUM SANDSTONE
 - GREEN SILTSTONE: COMMON STREAKS AND LENTICLES OF FINE TO MEDIUM SANDSTONE
 - MAROON MUDSTONE: GRADED LAMINAE; RARE SANDSTONE LENTICLES
- DEEP SHELF
- GREEN SILTSTONE WITH CARBONATE LAMINAE; EDGWISE CGL.
 - MAROON, CONCRETIONARY MUDSTONE
- STARVED SHELF

- SHALLOW SHELF
- PERITIDAL, CYCLIC CARBONATES
 - STROMATOLITE REEFS
 - STROMATOLITE REEFS/CLASTIC CARBONATE UND.
- BASALT FLOWS (SEC. #1 ONLY)

← A1*

and spiked with a mixed $^{208}\text{Pb}/^{235}\text{U}$ tracer. Following anion column separation, the Pb was loaded onto rhenium filaments using a standard silica gel-phosphoric acid technique, and the U was loaded on rhenium filaments with graphite. Isotopic measurements were made with a VG-354E mass spectrometer at Washington University in St. Louis. Procedural blanks were between 20 and 30 picograms for Pb and less than 5 picograms for U. Linear regression and calculation of intercepts and uncertainties follow Ludwig (1980; 1988a, b). The error ellipses in figure 4 correspond to two-sigma errors. Uncertainties in calculated upper intercept ages are quoted at the 95 percent confidence interval.

The ash beds all contain generally euhedral zircons which visually appear to be from one population. None contained abraded and/or rounded zircons that could be easily attributed to a detrital component. Typically, the zircons from all the ash beds are magnetic, somewhat cloudy, cracked, have small amounts of matrix adhering to the grains, and contain opaque inclusions. In many cases air abrasion of the zircons following the techniques of Krogh (1982) prior to final selection, eliminated much of the cloudy appearance of the zircons and removed any matrix from the grains. Figure 4 is a concordia diagram for the three ash beds, and the analytical data for the samples is presented in table 1.

The Hackett ash (A1 in fig. 3) yielded abundant, elongate, doubly terminated, cloudy to rarely clear zircons. Eight diamagnetic fractions from the Hackett were analyzed: five were abraded, and three were not. Although many of the zircons contain abundant inclusions, no structurally older cores were identified. The eight points define a chord with an upper intercept of 1968.7 ± 1.1 Ma, a lower intercept of 83 ± 22 Ma, and a MSWD of 1.5 (fig. 4). The five abraded points are the most concordant, but all eight data points are remarkably colinear given the spread in discordance.

Zircons from the Rifle-Beechey ash bed (A2 in fig. 3) are euhedral, elongate, cloudy, and doubly terminated. None of the zircons contained visible cores, and the colinearity of the abraded and unabraded fractions suggests that the zircons do not contain an inherited component. Four fractions were analyzed, including one abraded fraction. These fractions define a chord with an upper intercept of 1963 ± 6 Ma, a lower intercept of 180 ± 33 Ma, and a MSWD of 0.91. Although not as concordant as the Hackett ash bed, the data define a well-constrained chord with an age slightly younger than the Hackett which is consistent with its stratigraphic position.

The basal Recluse Group ash bed (A3 in fig. 3) yielded abundant clear, doubly terminated zircons. None of the grains analyzed contained visible cores, although some of the unanalyzed more magnetic grains appear to have a small amount of core material as well as abundant opaque inclusions. Seven fractions, including five that were abraded, were analyzed. The data define a chord with an upper intercept of 1882 ± 3.5 Ma, a lower intercept of 46 ± 88 Ma, and a MSWD of 2.4 (fig. 4). Two of the more magnetic fractions (m2 aa and m4 aa) have low $^{206}\text{Pb}/^{204}\text{Pb}$ and contained opaque inclusions. The m2 aa fraction also has

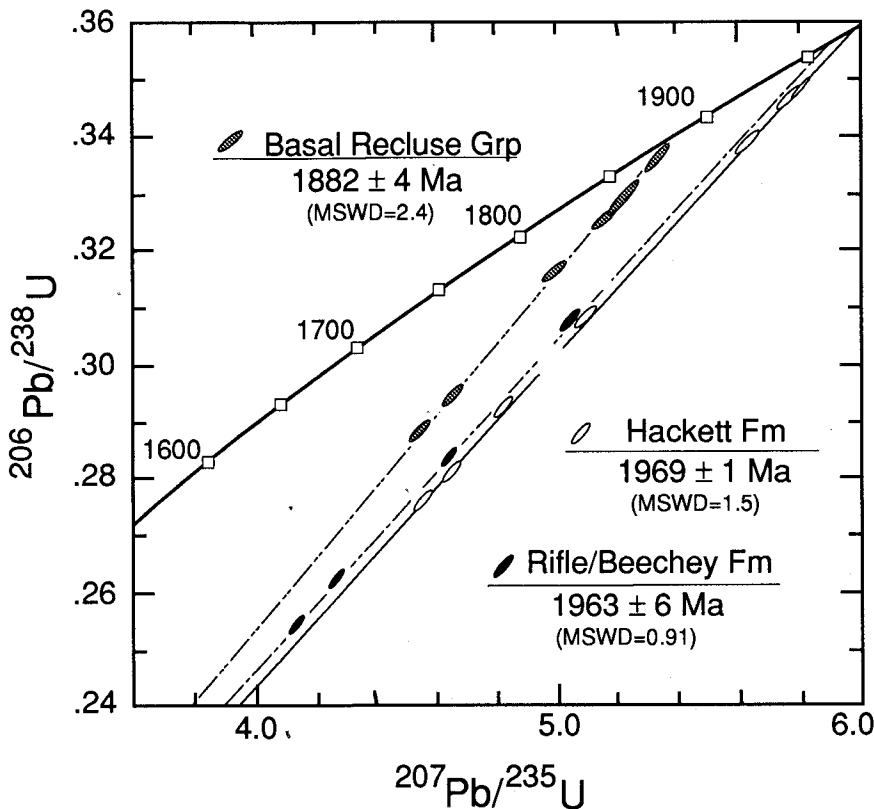


Fig. 4. Concordia plot for the three ash beds dated in this study.

the oldest Pb-Pb age (1885.9Ma) and falls slightly off the chord. It is not possible to ascertain whether this effect is related to the presence of a small amount of core material; in any case, its slight discordance does not greatly affect the upper intercept for the sample. The age of 1882 Ma is 81 my younger than the Rifle-Beechey ash, consistent with its considerably higher stratigraphic position.

To ensure that the ash samples collected did not contain detrital zircons derived from the approximately contemporaneous magmatism and uplift to the east in Thelon orogen, samples of sedimentary rocks stratigraphically above and below the ash beds were also sampled for geochronology. In all these samples, the zircons were of variable morphology and ranged from euhedral and clear to rounded and frosted. All the zircons dated from these samples indicate an Archean provenance at the stratigraphic position of the lowermost two ash beds, and it is not until high in the section of the fluvial molasse phase (Burnside Formation) that

TABLE I

U-Pb analytical data

Fractions	Concentrations		Ratios corrected for blank and common Pb					
	WEIGHT(mg)	U(ppm)	Pb(ppm)	206Pb/204Pb	206Pb/238U	207Pb/235U	207Pb/206Pb	Age (Ma)
RECLUSE ASH								
m2 aa	0.136	254.7	101.1	676	0.33585	5.3432	0.115386	(1885.9)
d-1 aa	1.323	268.4	97.8	7509	0.32904	5.2214	0.115088	(1881.3)
m3 aa	0.490	249.4	90.9	3444	0.32632	5.1752	0.115022	(1880.2)
m4 aa	0.400	262.8	102.9	583	0.32502	5.1588	0.115117	(1881.7)
d-1 aa	0.364	260.2	91.7	3619	0.31517	4.9890	0.114808	(1876.9)
nm 2	0.216	248.0	82.8	1527	0.29321	4.6527	0.115085	(1881.2)
d-1	0.314	261.7	86.8	1274	0.28689	4.5411	0.114803	(1876.8)
HACKETT ASH								
d-4 aa	0.011	244.9	93.7	7773	0.34781	5.7934	0.120808	(1968.2)
d-3 aa	0.151	179.9	72.6	758	0.34649	5.7640	0.120653	(1965.9)
d-2 aa	0.306	639.9	241.6	2806	0.33834	5.6269	0.120619	(1965.4)
d-2 aa	0.394	288.8	99.5	1884	0.30681	5.0956	0.120453	(1962.9)
d-3 aa	0.215	363.0	120.9	3386	0.29984	4.9660	0.120119	(1958.0)
d-2	0.343	303.5	98.4	2837	0.29096	4.8216	0.120619	(1965.4)
d-4	0.413	274.3	86.8	1537	0.27978	4.6429	0.120357	(1961.5)
d-3	0.355	291.6	99.0	419	0.27476	4.5481	0.120052	(1957.0)
RIFLE- BEECHEY-ASH								
m10	0.259	307.5	103.8	1888	0.30619	5.0405	0.119393	(1947.2)
m 6	0.110	268.7	83.0	2938	0.28270	4.6382	0.118994	(1941.2)
nm 1 aa	0.119	336.2	95.2	3567	0.26146	4.2623	0.118236	(1929.7)
m 15	0.101	345.1	94.8	2854	0.25380	4.1279	0.117963	(1925.6)

nm-non magnetic; m-magnetic; d-diamagnetic; numbers following refers to degrees of side tilt on a Franz isodynamic separator; aa-air abraded.

early Proterozoic zircons are detected (McCormick, Bowring, and Grotzinger, 1989).

DISCUSSION

Constraints on the age and duration of Wopmay passive margin.—The sequence stratigraphic correlations established between Kilohigok basin and Wopmay orogen are now dated at three independent stratigraphic levels. The oldest age (1969 Ma; basal Hackett Formation) and the youngest age (1882 Ma; basal Recluse Group) span an interval of 87 my. Because only one of the three dated ash beds occurs in Wopmay orogen (ash bed #7), the interbasinal sequence stratigraphic correlation is critical in extending age constraints from dated ash-bearing sequences.

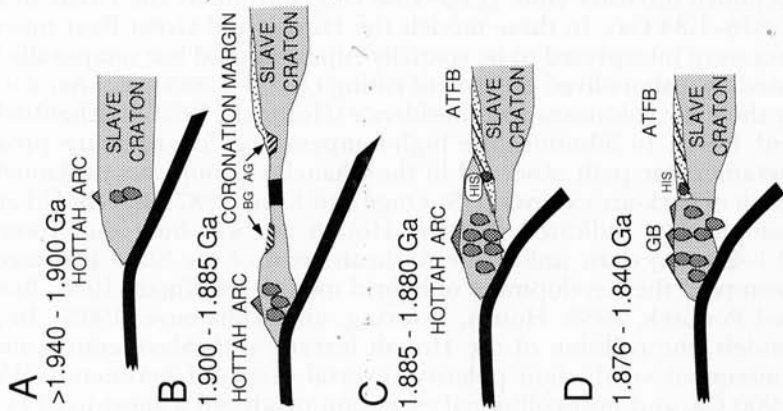
The results presented in this paper provide new temporal constraints on several important events in Wopmay orogen more directly than previously (Hoffman and Bowring, 1984). These include: (1) the onset of passive margin subsidence, (2) the duration of passive margin subsidence, and (3) the onset of foreland basin subsidence. Past models for the tectonic evolution of Wopmay orogen (Hoffman and Bowring, 1984; Hildebrand, Hoffman, and Bowring, 1987; St-Onge and King, 1987; Hoffman, 1988) were constrained by the apparently short duration (<15 my) of passive margin subsidence based on the age difference between the Akaitcho Group (1.900 Ga) and the Hepburn Intrusive Suite (1885 Ma). The new ages on the ash beds in Kilohigok basin, trans-Slave cratonic strata, and Wopmay orogen indicate that the passive margin subsidence phase in Wopmay orogen had begun by 1969 Ma, as shown by the presence of correlatives of the Hackett Formation in the southern part of the autochthon of Wopmay orogen (fig. 3, sec. 2). Foundering of the passive margin is older than 1882 Ma, the age of the basal Recluse Group. Thus, the duration of the passive margin is likely on the order of 80 to 90 my. In addition, the onset of passive margin subsidence in Wopmay orogen is contemporaneous with development of the Kilohigok foreland basin.

A major problem is revealed as a result of the new constraints established above; the inferred age of the Akaitcho Group (1.900 Ga) is approx 70 my younger than the onset of passive margin subsidence. Previously, the Akaitcho Group was assumed to be an initial rift assemblage (Hoffman, 1980) and to represent a maximum age for the passive margin sequence (Hoffman and Bowring, 1984). The age of the Akaitcho Group was obtained from felsic porphyries (Bowring, ms) interpreted in the field as being of both intrusive and extrusive origin (Easton, 1981). Therefore, either the felsic porphyries of the Akaitcho Group are younger intrusives, or the porphyry-bearing Akaitcho Group does not stratigraphically underlie the passive margin. Support for the latter interpretation is provided by Nd and Pb isotopic data (Bowring and Podosek, 1989; Housh, Bowring, and Villeneuve, 1989) which suggest the Akaitcho

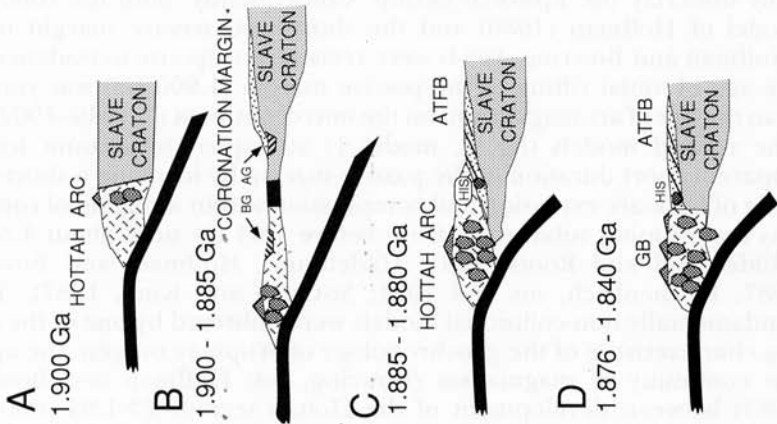
rhyolites and basalts have not interacted with Slave craton, an observation difficult to reconcile with an interpretation involving initial rifting of the Slave craton. In addition, detrital zircon data from the Akaitcho Group indicate a 2.0 to 2.1 Ga source region (Bowring, ms), which is not consistent with a rift sequence developed on Slave craton that would have supplied detritus of Archean age.

Tectonic models for the evolution of Wopmay orogen.—Hoffman (1980) presented the first comprehensive tectonic model for Wopmay orogen in terms of a west-facing passive margin that collided with a microcontinent, followed by a subduction polarity reversal, from west- to east-dipping, and consequent development of the younger Great Bear arc astride the suture. This model was modified in the light of geochronologic data (Hoffman and Bowring, 1984) in terms of a short-lived passive margin (<15 Ma) and its destruction during the 1.885 Ga Calderian orogeny described above. This model assumed that a thick sequence of basalt, rhyolite, and immature clastic sediments (Akaitcho Group) stratigraphically underlay the Epworth Group. Consequently, both the collisional model of Hoffman (1980) and the short-lived passive margin model (Hoffman and Bowring, 1984) were revised in response to evidence that the age of initial rifting of the passive margin (1.900 Ga) was younger than the age of arc magmatism on the microcontinent (>1940–1902 Ma). The revised models (fig. 5, model 1) attempted to account for the apparent short duration of the passive margin by invoking a short-lived cycle of back-arc extension and compression within a regime of continuous east-dipping subduction from before 1.94 Ga until about 1.86 Ga (Hildebrand and Roots, 1985; Hildebrand, Hoffman, and Bowring, 1987; Reichenbach, ms and 1991; St-Onge and King, 1987). These fundamentally non-collisional models were bolstered by one of the striking characteristics of the geochronology of Wopmay orogen: the apparent continuity of magmatism (Bowring, ms; Hoffman and Bowring, 1984) between development of the Hottah terrane (>1.94–1.90 Ga), Akaitcho Group (about 1.900 Ga), Bell Island Group (1.90–1.876 Ga), Hepburn intrusive suite (1.89–1.88 Ga), and finally the Great Bear arc (1.876–1.84 Ga). In these models the Hottah and Great Bear magmatic arcs were interpreted to be spatially superimposed but temporally separated by a short-lived episode of rifting (1.900–1.885 Ga), characterized by tholeiitic volcanism and subsidence (Hoffman, 1988; Reichenbach, ms and 1991). In addition, the high-temperature, low-pressure prograde metamorphic path observed in the Akaitcho Group was explained as a result of back-arc extension (St-Onge and King, 1987). Recent Nd and Pb isotopic data indicated that the Hottah arc was built on Proterozoic (2.1–2.4 Ga) crust unlike the Archean crust of the Slave province and prompted the development of hybrid models (Hoffman, 1988; Bowring and Podosek, 1988; Housh, Bowring, and Villeneuve, 1988). In these models, the collision of the Hottah terrane with Slave craton and the consequent subduction polarity reversal occurred between 1.915 and 1.900 Ga, and post-collisional extension produced a short-lived (1.900–

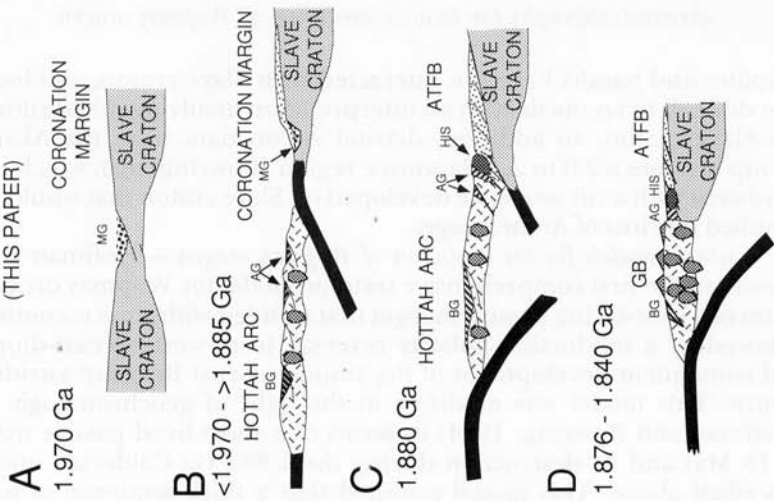
MODEL 1



MODEL 2



MODEL 3 (THIS PAPER)



1.885 Ga) episutural basin in which the Akaitcho and Epworth groups were deposited (Bowring and Podosek, 1989; Hoffman, 1988; see fig. 5, model 2).

The origin of the Akaitcho Group is critical to the distinction between the various models. It may have formed as an intracontinental rift that evolved into an Atlantic-type basin (Hoffman, 1980; 1989), a back-arc rift that evolved into a Japan Sea-type basin (Hildebrand, Hoffman, and Bowring, 1987; Reichenbach, ms and 1991; fig. 5, model 1), or an episutural back-arc basin that evolved into an Okinawa Trough-type basin (Hoffman, 1988; fig. 5, model 2). In all cases, the passive margin deposits (Epworth Group) were assumed to succeed the rifting dated at 1.900 Ga. It is this latter assumption that is challenged by our new chronostratigraphic data. For clarification of the model developed below it is important to recognize that the earlier models for back-arc extension involved development of the arc and back-arc basin on and marginal to the Slave craton (Hildebrand, Hoffman, and Bowring, 1987; Hildebrand and Roots, 1985; Hoffman, 1988; Reichenbach, ms and 1991; St-Onge and King, 1987). In contrast, the data from which our model is developed require both spatial and temporal separation of the Slave craton from the Hottah terrane and Akaitcho Group.

New model for the Evolution of Wopmay orogen

Our results indicate that rifting of the Slave craton prior to the development of the passive margin must predate the basal Odjick Formation at about 1969 Ma. This is compatible with the age of arc magmatism

Fig. 5. Recent plate-tectonic models for the evolution of Wopmay orogen. Model 1: simple arc/back-arc model developed within a continuous regime of east-dipping subduction on the western edge of Slave craton. In this model the Akaitcho Group (AG) underlies the passive margin (Coronation margin): (A) > 1.940 to 1.900 Ga—Hottah arc developed on the western edge of Slave craton; (B) 1.900 to 1.885 Ga—back-arc basin developed with Coronation margin deposited on its east side and Bell Island Group on its west side; (C) 1.885 Ga—back-arc basin closes synchronously with emplacement of Hepburn intrusive suite (HIS) and development of Asiatic thrust/fold belt.; (D) 1.876 to 1.840 Ga—Great Bear arc (GB) developed after closure of the back-arc basin. Model 2: episutural back-arc basin model of Hoffman (1988; Bowring and Podosek, 1989): (A) 1.900 Ga—Hottah terrane and Slave craton were sutured together, and Hottah arc developed as a result of west-dipping subduction; (B) 1.900 to 1.885 Ga—back-arc basin was developed along the suture between the two and above an east-dipping subduction zone. Akaitcho Group and Coronation margin were deposited on the east side, and the Bell Island Group on the west side; (C) 1.885 to 1.880 Ga—back-arc basin closed with emplacement of HIS and development of Asiatic thrust/fold belt; (D) 1.876 to 1.840 Ga—Great Bear arc developed as a result of east-dipping subduction. Model 3: new tectonic model for Wopmay orogen proposed in this paper: (A) 1.970 Ga—western margin of Slave craton was rifted to initiate subsidence of the Coronation margin. Melville Group (MG) deposited as rift fill; (B) < 1.970—> 1.885 Ga—Hottah terrane (2.4–2.0 Ga) approached Slave craton as, in part, a result of west-dipping subduction beneath it. Rocks of the Akaitcho Group (1.900 Ga) were deposited on the actively extending Hottah arc (> 1.94–1.90); (C) 1.880 Ga—Coronation margin collided with Hottah terrane and the Hepburn intrusive suite was emplaced (mean age of 1.885 Ga) as a last manifestation of west-dipping subduction and was buried beneath syn-orogenic flysch (Recluse Group); (D) 1.876 to 1.840 Ga—Great Bear arc developed as a result of the initiation of east-dipping subduction. Magmatism was largely confined to the Hottah Terrane. AG

in Hottah terrane (>1.940 – 1.902 Ga) being related to west-dipping subduction leading to collision with the Slave province (Bowring, ms). However, the Akaitcho Group, dated at 1.900 Ga, cannot be a rift assemblage underlying the passive margin sequence as previously assumed. The as yet undated Melville Group could still represent such a rift assemblage if it is older than about 1969 Ma. What, then, is the origin of the Akaitcho Group? Isotopic data suggest that its igneous components were derived from sources similar to the Hottah terrane rocks (Bowring and Podosek, 1989; Housh, Bowring, and Villeneuve, 1989). In addition, detrital zircon ages in the sediments of the Akaitcho Group are consistent with derivation from the Hottah terrane, in contrast to those of the Melville Group that are more likely derived from the Slave province (Bowring, ms). Accordingly, we propose that the Akaitcho Group was deposited in rift basins developed on Hottah terrane. The depositional age (1.900 Ga) implies, in the context of the arc-continent collision model, that rifting of the Hottah arc occurred just prior to the onset of collision (that is, the foundering of the passive margin about 1882 ± 4 Ma). Additionally, syn-collisional extension of the Hottah Terrane is implied by the age of the Bell Island Group (1.898 – 1.876 Ga). A modern analog of pre- to syn-collisional extension of the overriding plate can be found in the Mediterranean region (Royden and Burchfiel, 1989).

The new stratigraphic and geochronologic constraints allow us to combine positive aspects of both previous models to explain more fully the origin of the principal tectonic elements of Wopmay orogen. In short, a model involving west-dipping subduction leading to a simple arc-continent collision followed by a subduction polarity reversal (Hoffman, 1980) combined with the new idea of pre- to syn-collisional extension of an exotic, overriding plate (arc complex) is more tenable within the constraints established here. The relationships between the various tectonic elements of Wopmay orogen are shown in figure 6, and the proposed tectonic model is shown in figure 5. In this model, oceanic lithosphere attached to the Slave craton is subducted beneath the Hottah terrane until a collision at about 1.883 Ga. As a result of weak coupling between the oceanic lithosphere attached to Slave craton and Hottah terrane, the latter was extended prior to the collision. Passive margin subsidence in Wopmay from about 1.97 to 1.90 Ga was concurrent with development of an arc complex in Hottah terrane over a west-dipping subduction zone. The arc is envisioned to be of low relief and under extension due to the retreat of the subduction zone toward the Slave craton. The Akaitcho Group, formerly thought to underlie the passive margin, must be allochthonous with respect to it and originated on the upper plate of the collisional orogen as a result of within arc extension. At about 1.89 Ga Hottah terrane and Slave craton began to collide synchronous with or slightly pre-dating the initiation of east-dipping subduction along the western edge of Hottah terrane.

The origin of the Hepburn intrusive suite can be explained in at least two ways: (1) during the collision, arc magmas related to east-dipping subduction impinged upon the extended leading edge of Hottah terrane,

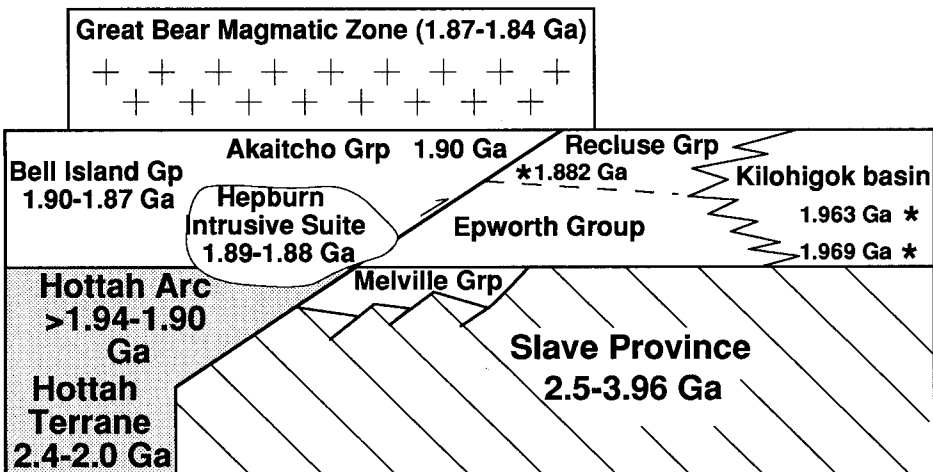


Fig. 6. Schematic representation of inter-relationships between the various tectonic elements of Wopmay orogen and Kilohigok basin. MG-Melville Group; * marks the location and age of ash beds reported in this study.

and the arc geochemical signature of the plutons was modified by late assimilation of pelitic material (Lalonde, 1989), or (2) the Hepburn intrusive suite was the result of the last pulse of magmatism associated with west-dipping subduction, and the compression associated with the collision trapped the plutons in the thick pelitic sediments of the Akaitcho group causing late stage assimilation and attainment of their peraluminous character (see fig. 5). As the collision proceeded, there was uplift in the hinterland and thermal subsidence and limited extension in Hottah terrane. Finally, rocks of the Great Bear arc were intruded into and accumulated on the extended arc. The Great Bear arc is interpreted to be in part synchronous with the last stages of the collision and is superimposed on the highly extended Hottah terrane. The development of the Great Bear arc was subsequent to the end of extension in the overriding plate (Hottah terrane) caused by coupling between Hottah terrane and Slave craton driven by east-dipping subduction along the western margin of Hottah terrane. The accumulation of rocks of the Great Bear arc in a simple basin (Hildebrand and Bowring, 1984) may be in part related to thermal subsidence of the extended Hottah arc. The Great Bear arc was subsequently uplifted and folded due to a terminal collision to the west around 1.84 Ga.

CONCLUSIONS

1. Stratigraphic units containing ash beds are recognized within or can be correlated into autochthonous passive margin and lowermost foredeep strata of Wopmay orogen.

2. U-Pb zircon ages from these ash beds constrain the minimum age of rifting and initial subsidence of the passive margin at about 1.969 Ga and collision and initial foredeep subsidence at about 1.882 Ga. The duration of passive margin subsidence in Wopmay orogen is 80 to 90 Ma, considerably longer than the previous estimate of less than 15 Ma. This is consistent with an Atlantic-type margin as inferred from stratigraphic comparisons with Phanerozoic orogens.

3. The new geochronologic constraints imply that the Akaitcho Group of Wopmay orogen is allochthonous with respect to the Coronation margin and was originally deposited on Hottah terrane.

4. A new model involving collision of the passive margin with an arc undergoing extension best explains the geologic and geochronologic constraints.

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REFERENCES

- Bowring, S. A., ms, 1985, U-Pb zircon geochronology of Early Proterozoic Wopmay orogen, N.W.T., Canada: an example of rapid crustal evolution: Ph.D. thesis, University of Kansas, Lawrence, Kansas.
- Bowring, S. A., and Grotzinger, J. P., 1989, Implications of new U-Pb dating and stratigraphic correlations for current tectonic models for Wopmay orogen and Thelon Tectonic Zone: Geological Association of Canada Programs with Abstracts, v. 14, p. A74.
- Bowring, S. A., and Podosek, F. A., 1989, Nd isotopic evidence for 2.0–2.4 Ga crust in western North America: Earth and Planetary Science Letters, v. 94, p. 217–230.
- Campbell, F. H. A., and Cecile, M. P., 1981, Evolution of the Early Proterozoic Kilohigok Basin, Bathurst Inlet-Victoria Island, Northwest Territories, in Campbell, F. H. A., Proterozoic Basins of Canada: Geological Survey of Canada Paper 81-10, p. 103–131.
- Christie-Blick, N., Grotzinger, J. P., and von der Borch, C. C., 1988, Sequence stratigraphy in Proterozoic successions: Geology, v. 16, p. 100–104.
- Easton, R. M., 1981, Stratigraphy of the Akaitcho Group and the development of an early Proterozoic continental margin, Wopmay orogen, N. W. T., Canada, in Campbell, F. H. A., Proterozoic Basins of Canada: Geological Survey of Canada Paper 81-10, p. 79–95.
- Ethridge, M. A., Rutland, R. W. R., and Wyborn, L. A. I., 1987, Orogenesis and tectonic process in the early to middle Proterozoic of northern Australia, in Kroner, A., Proterozoic Lithospheric Evolution: Washington, D. C., American Geophysical Union, p. 131–148.
- Gibb, R. A., and Thomas, M. D., 1977, The Thelon front: a cryptic suture in the Canadian Shield: Tectonophysics, v. 38, p. 211–222.
- Grotzinger, J. P., Adams, R. D., McCormick, D. S. and Myrow, P., 1989, Sequence stratigraphy, correlations between Wopmay orogen and Kilohigok Basin, and further investigations of the Bear Creek Group (Goulburn Supergroup), District of Mackenzie, in Current Research, Part C: Geological Survey of Canada Paper 89-1C, p. 107–120.

- Grotzinger, J. P., and Friedman, J. S., 1989, Occurrence of thick crust of former botryoidal aragonite, Rifle and Beechey formations (1.97 Ga), Kilohigok Basin, N. W. T.: Geological Association of Canada Programs with Abstracts, v. 14, p. A77.
- Grotzinger, J. P., Gamba, C., Pelechaty, S. M., and McCormick, D. S., 1988, Stratigraphy of a 1.9 Ga foreland basin shelf-to-slope transition: Bear Creek Group, Tinney Hills area of Kilohigok Basin, District of Mackenzie, in *Current Research, Part C: Geological Survey of Canada Paper 88-1C*, p. 313–320.
- Grotzinger, J. P., and McCormick, D. S., 1988, Flexure of the Early Proterozoic lithosphere and the evolution of the Kilohigok Basin (1.9 Ga), northwest Canadian shield, in Kleinspehn, K. and Paola, C., *New Perspectives in Basin Analysis: New York, Springer-Verlag*, p. 405–430.
- Grotzinger, J. P., McCormick, D. S., and Pelechaty, S. M., 1987, Progress report on the stratigraphy, sedimentology, and significance of the Kimerot and Bear Creek groups, Kilohigok Basin, District of Mackenzie, in *Current Research, Part A: Geological Survey of Canada Paper 87-1A*, p. 219–238.
- Grotzinger, J. P., and Royden, L., 1990, Elastic strength of the Slave craton at 1.9 Gyr and implications for the thermal evolution of the continents: *Nature*, v. 347, p. 64–66.
- Hildebrand, R. S., 1981, Early Proterozoic Labine Group of Wopmay orogen: remnant of a continental volcanic arc developed during oblique convergence, in Campbell, F. H. A., *Proterozoic Basins of Canada: Geological Survey of Canada, Paper 81-10*, p. 133–156.
- Hildebrand, R. S., and Bowring, S. A., 1984, Continental intra-arc depressions: a model for their origin with a Proterozoic example from Wopmay orogen: *Geology*, v. 12, p. 73–77.
- Hildebrand, R. S., Hoffman, P. F., and Bowring, S. A., 1987, Tectono-magmatic evolution of the 1.9 Ga Great Bear magmatic zone, Wopmay orogen, northwestern Canada: *Journal of Volcanology and Geothermal Research*, v. 32, p. 99–118.
- Hildebrand, R. S., and Roots, C. F., 1985, Geology of the Riviere Grandin map area (Hottah terrane and western Great Bear Magmatic Zone), District of Mackenzie, in *Current Research, Part A: Geological Survey of Canada Paper 85-1A*, p. 373–383.
- Hoffman, P. F., 1973, Evolution of and early Proterozoic continental margin: the Coronation geosyncline and associated aulocogens of the northwestern Canadian Shield: *Philosophical Transactions of the Royal Society of London, Series A*, v. 273, p. 547–581.
- , 1980, Wopmay orogen: a Wilson Cycle of early Proterozoic age in the northwest of the Canadian Shield, in Strangway, D. W., *The continental crust and its mineral deposits: Geological Association of Canada*, p. 523–549.
- , 1987, Continental transform tectonics: Great Slave Lake shear zone (ca. 1.9 Ga), northwest Canada: *Geology*, v. 15, p. 785–788.
- , 1988, United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia: *Annual Reviews of Earth and Planetary Science*, v. 16, p. 543–603.
- Hoffman, P. F., and Bowring, S. A., 1984, Short-lived 1.9 Ga continental margin and its destruction, Wopmay orogen, northwest Canada: *Geology*, v. 12, p. 68–72.
- Hoffman, P. F., and Pelletier, K. S., 1982, Cloos Nappe in Wopmay orogen: significance for stratigraphy and structure of the Akaitcho Group, and implications for opening and closing of an early Proterozoic continental margin: *Geological Survey of Canada Paper 82-1A*, p. 109–115.
- Hoffman, P. F., St-Onge, M. R., Carmichael, D. M., de Bie, I., 1978, Geology of the Coronation Geosyncline (Aphebian), Hepburn Lake Sheet (86J), Bear Province, District of Mackenzie, in *Current Research, Part A: Geological Survey of Canada Paper 78-1A*, p. 147–151.
- Hoffman, P. F., St-Onge, M. R., Easton, R. M., Grotzinger, J. P., and Schulze, D. L., 1980, Syntectonic plutonism in north-central Wopmay orogen (early Proterozoic), Hepburn Lake Map Area, District of Mackenzie, in *Current Research, Part A: Geological Survey of Canada Paper 80-1A*, p. 171–177.
- Housh, T., Bowring, S. A., and Villeneuve, M., 1989, Lead isotopic study of early Proterozoic Wopmay orogen, northwest Canada: role of continental crust in arc magmatism: *Journal of Geology*, v. 97, p. 735–747.
- James, D. T., 1989, Structural and metamorphic relationships along the Slave and Churchill structural provinces: *Geological Association of Canada, Programs with Abstracts*, v. 14, p. A9.
- Krogh, T. E., 1982, Improved accuracy of U-Pb zircon ages by creation of more concordant systems using an air abrasion technique: *Geochimica et Cosmochimica Acta*, v. 45, p. 637–649.

- Lalonde, A. E., 1989, Hepburn intrusive suite: peraluminous plutonism within a closing back-arc basin, Wopmay orogen, Canada: *Geology*, v. 17, p. 261–264.
- Ludwig, K. R., 1980, Calculations of uncertainties of U-Pb data: *Earth and Planetary Science Letters*, v. 46, p. 212–220.
- 1988a, PBDAT for MS-DOS: a computer program for IBM-PC compatibles for processing raw Pb-U-Th isotope data: United States Geological Survey Open File Report 88-542, 40 p.
- 1988b, ISOPLOT for MS-DOS: a plotting and regression program for radiogenic-isotope data, for IBM-PC compatible computers: United States Geological Survey Open-File Report 88-557, 44 p.
- McCormick, D. S., Bowring, S. A., and Grotzinger, J. P., 1989, Geochronology, provenance evolution, and correlation in foreland basins using volcanic and detrital zircons: The early Proterozoic Goulburn Supergroup, Kilohigok Basin, Canada: *Geological Society of America Abstracts With Programs*, v. 20, p. 373.
- McCormick, D. S. and Grotzinger, J. P., 1988, Aspects of the Burnside Formation, Bear Creek Group, Kilohigok Basin, N.W.T., in *Current Research, Part A: Geological Survey of Canada Paper 88 1-C*, p. 321–339.
- in press, Controls on foreland basin alluvial architecture in early Proterozoic (ca. 1.93 Ga) Burnside Formation, Kilohigok Basin, N.W.T.: *Sedimentology*.
- Reichenbach, I. G. ms, 1986, An ensialic marginal basin in Wopmay orogen, northwestern Canadian Shield: M.S. thesis, Carlton University, Ottawa, Ontario, 120 p.
- 1991, The Bell Island Bay Group, Remnant of an early Proterozoic ensialic marginal basin in Wopmay orogen, District of Mackenzie: *Geological Survey of Canada Paper 88-28*, 43 p.
- Royden, L., and Burchfiel, B. C., 1989, Are systematic variations in thrust belt style related to plate boundary processes? (The western Alps versus the Carpathians): *Tectonics*, v. 8, p. 51–61.
- Sloss, L. L., 1963, Sequences in the cratonic interior of North America: *Geological Society of America Bulletin*, v. 74, p. 93–113.
- St-Onge, M. R., 1987, Zoned poikiloblastic garnets; Documentation of P-T paths and syn-metamorphic uplift through thirty kilometers of structural depth, Wopmay orogen, Canada: *Journal of Petrology*, v. 28, p. 1–28.
- St-Onge, M. R., and King, J. E., 1987, Thermotectonic evolution of a metamorphic internal zone documented by axial projections and petrological P-T paths, Wopmay orogen, northwest Canada: *Geology*, v. 15, p. 155–158.
- St-Onge, M. R., King, J. E., and Lalonde, A. E., 1984, Deformation of the Coronation Supergroup and its basement in the Hepburn metamorphic-plutonic zone of Wopmay orogen: Redrock Lake and the eastern portion of Calder River map areas, District of Mackenzie, in *Current Research, Part A: Geological Survey of Canada Paper 84-1A*, p. 171–180.
- Thompson, P. H., Culshaw, N., Buchanan, J. R., and Manojovic, P., 1986, Geology of the Slave Province and the Thelon tectonic zone in the Tinney Hills-Overby Lake (west half) map area, District of Mackenzie, in *Current Research, Part A: Geological Survey of Canada Paper 86-1A*, p. 275–289.
- Tirrul, R., and Grotzinger, J. P., 1990, Early Proterozoic collisional orogeny along the northern Thelon Tectonic Zone, N.W.T., Canada: Evidence from the foreland.: *Tectonics*, v. 9, p. 1015–1036.
- Vail, P. R., Mitchum, R. M. and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, Part 3: Relative changes of sea level from coastal onlap, in Payton, C., *Seismic Stratigraphy—Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists*, p. 63–81.
- van Breemen, O., Thompson, P. H., Bostock, H. H., and Loveridge, W. D., 1987, Timing of plutonism in the northern Thelon Tectonic Zone and the Taltson Magmatic Zone: *Geological Association of Canada Programs with Abstracts*, v. 12, p. 98.