Eocambrian granite clasts in southern British Columbia shed light on Cordilleran hinterland crust[1]

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Abstract: The Spa Creek assemblage is a distinctive thin pericratonic succession that crosses the Okanagan Valley in the hinterland of the southern Cordilleran Orogen in Canada. The succession was ductilely deformed and metamorphosed before deposition of overlying Triassic dark metaclastic strata. A metaconglomerate within the succession, locally composed of more than 90% biotite granite clasts, yielded five fractions of euhedral zircon that define a precise U–Pb upper intercept of 555.6 ± 2.5 Ma, inferred to be the age of a nearby pluton. Other clasts in the metaconglomerate are generally more abundant, consisting of quartzite, amphibole schist, chlorite schist, sericite schist, biotite schist, and quartz–feldspar porphyry. They are likely host rocks of the pluton and, if so, are Late Proterozoic or older. The granite is interpreted as a terminal product of the Eocambrian rifting that preceded Paleozoic miogeoclinal sedimentation farther inboard. The continuity of pericratonic rocks west of the miogeocline and the occurrence of Proterozoic cratonic rocks at the surface west of the Okanagan Valley show that the ancient continental margin extends into a region where most of the crustal lithosphere was until now thought to consist of accreted Phanerozoic arc and accretionary complexes.

Résumé : L’assemblage de Spa Creek constitue une séquence distincte, mince et péri-cratonique qui recoupe la vallée de l’Okanagan dans l’arrière pays de l’orogène de la Cordillère sud, au Canada. La séquence a subi une déformation ductile et du métamorphisme avant d’être recouverte par les strates métaclastiques foncées du Trias. Un métaconglomérat à l’intérieur de la séquence, composé localement de plus de 90 % de fragments de granite à biotite, a donné cinq fractions de zircon automorphe qui définissent un paramètre cristallographique U–Pb supérieur précis de 555,6 ± 2,5 Ma, que l’on croit être l’âge d’un pluton avoisinant. D’autres fragments dans le métaconglomérat sont généralement plus abondants et comprennent du quartzite, du schiste à amphibole, du schiste à chlorite, du schiste à séricite, du schiste à biotite et des porphyres de quartz–feldspath. Ils sont probablement des roches encaissantes du pluton et, si c’est le cas, datent du Protérozoïque tardif ou sont plus anciens. Le granite serait un produit terminal d’une distension à l’Écambrien qui a précédé la sédimentation miogéoclinale plus à l’intérieur. La continuité des roches péricratoniques à l’ouest du miogéocline et l’occurrence de roches cratoniques datant du Protérozoïque en surface, à ouest de la vallée de l’Okanagan, montrent que l’ancienne marge continentale s’étendait à l’intérieur d’une région où, jusqu’à présent, on croyait que la plus grande partie de la lithosphère crustale consistait de l’accrétion de complexes d’accrétion et de complexes d’arcs datant du Phanérozoïque.

[Traduit par la Rédaction]

Introduction

The eastern 250 km width of the Cordilleran Orogen in southern Canada consists of a miogeoclinal succession of Paleozoic and lower Mesozoic shelf-carbonate, shallow-water siliciclastic and off-shelf clastic strata that onlapped the ancient continental margin (e.g., Porter et al. 1982). The remaining 600 km width of the orogen, at surface, has been interpreted as a collage of magmatic arcs and oceanic accretionary complexes tectonically accreted by plate convergence starting in mid-Jurassic time (e.g., Monger et al. 1982). The transition zone (Fig. 1), a hinterland area of higher metamorphic grade termed the Omineca Belt that presumably underwent the most intense horizontal compression,

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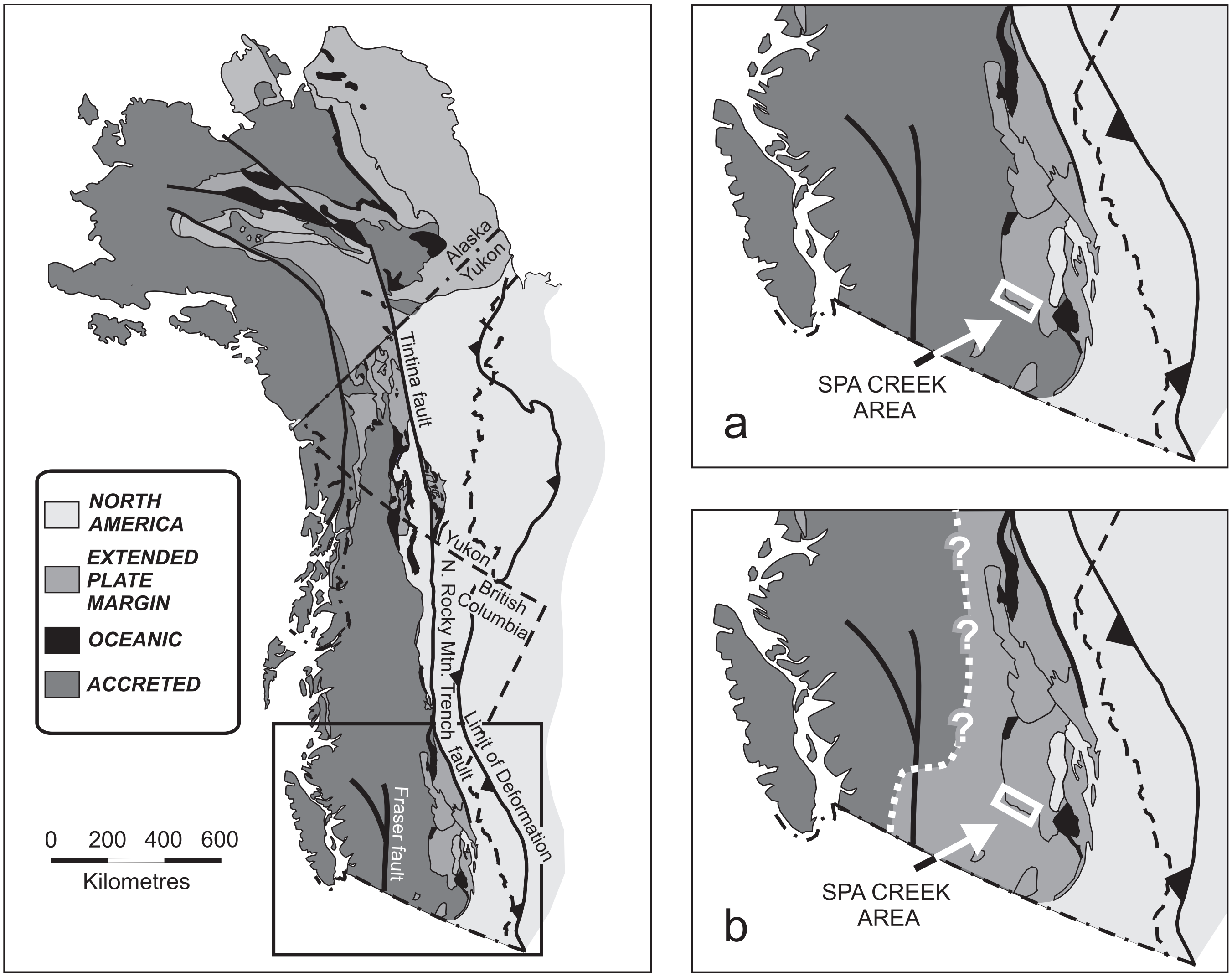
Fig. 1. Autochthonous and accreted parts of the Canadian Cordillera. Insets show (*a*) previously proposed extent of ancient plate margin rocks in southern British Columbia, and (*b*) potential extent of ancient plate margin rocks on the basis of evidence presented here that rock units assigned to the Quesnellia terrane are a thin succession overlying mainly cratonic crust west of the Okanagan Valley. Most of the area of the Quesnellia terrane could be underlain by heterogeneously stretched Proterozoic continental crust (see text). The existence of similar crust to the west of the Fraser fault is implied in any restoration of strike-slip displacement on that structure, although its extent is speculative. The Spa Creek area is enlarged in Fig. 2.

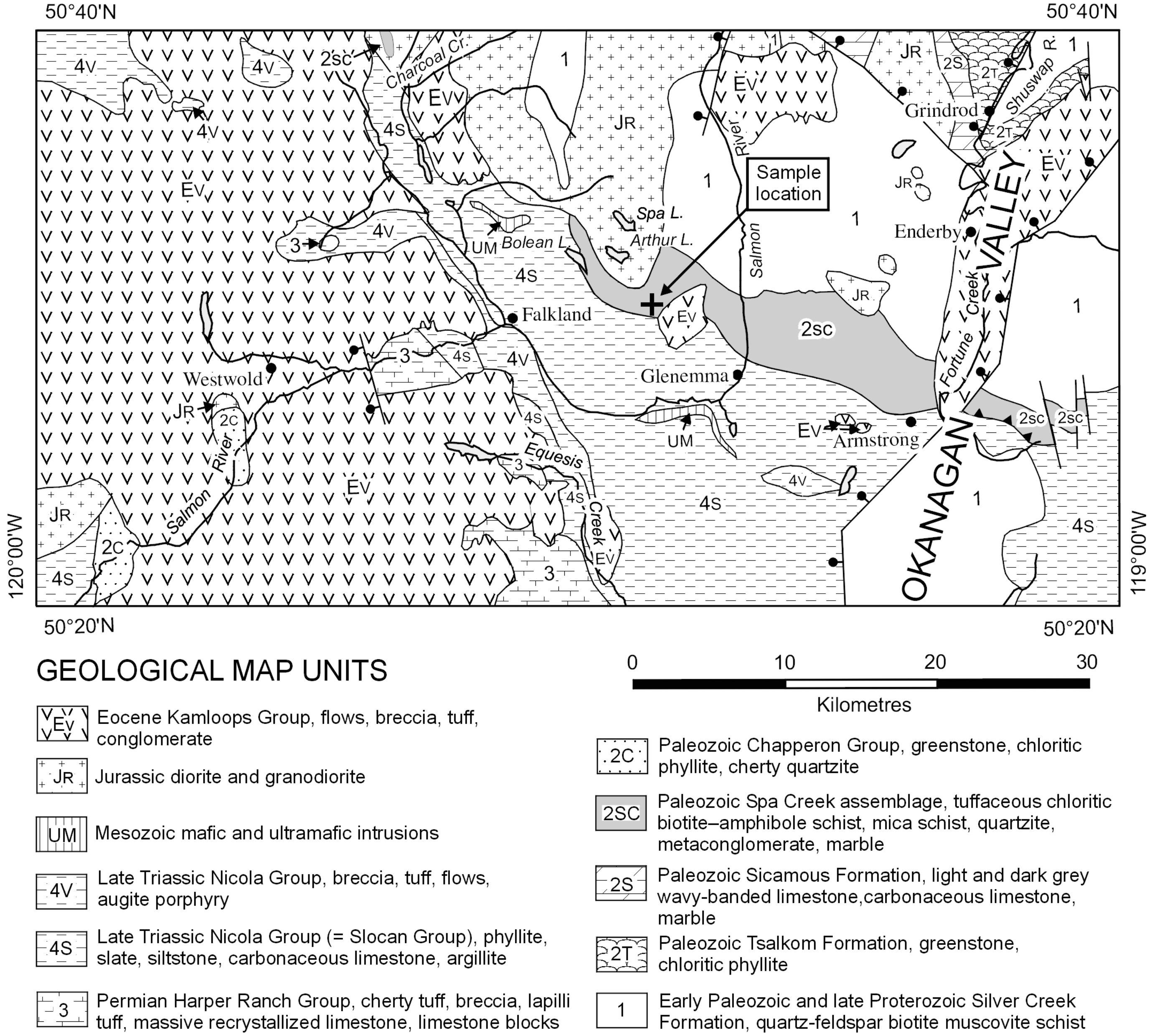


has been interpreted as crust in which the bounding edges of the accretionary collage and the passive margin overlap and are tectonically thickened.

By applying a "back stripping" technique to the lower part of the carbonate shelf succession in the Rocky Mountains, Bond and Kominz (1984) hypothesized that the transition from continental rifting to sea-floor spreading and continental drift, which is marked by the initiation of passive margin subsidence, occurred in latest Proterozoic or earliest Cambrian time. Devlin and Bond (1988) presented stratigraphic evidence of the existence of a latest Proterozoic or earliest Cambrian unconformity that overlaps synrift deposits of the Lower Cambrian Gog Group in the Rocky Mountains and the Hamill Group in the Selkirk Mountains, which they interpreted to record the rift to drift transition. Lickorish and Simony (1995) identified a half-graben structure in the Western Ranges of the Rocky Mountains, which is overlapped by the unconformity and interpreted it to be related to margin extension immediately prior to the onset of shelf-carbonate deposition.

We report the existence of a granite pluton contemporaneous with the hypothesized timing of the Cordilleran rift to drift transition. Of itself, this is an important finding that adds to emerging evidence of magmatism during plate edge definition. However, it is equally significant, because the pluton and its host rocks occur to the west of the Okanagan Valley, the proposed surface boundary of thick accreted crust in existing terrane interpretations and lithospheric profiles of the orogen. Although North American lower crust and upper mantle have been projected as far west as the Fraser fault (Cook et al. 1992), accreted Phanerozoic oceanic crust and magmatic arc rocks were predicted to be more than 20 km

Fig. 2. Geological map of the Salmon River – Armstrong area, southern British Columbia. Dot-and-tick ornament on the straight line indicates hanging-wall block of steep normal fault.



thick in that part of the hinterland (e.g., Clowes et al. 1998). The occurrence of Precambrian crust at the surface precludes any significant thickness of Phanerozoic crust at least locally.

The granite pluton also sheds new light on the extent of the ancient plate margin and has important ramifications for its paleogeographic character. The existence of one or more outer highs beyond the miogeocline had been previously suspected. For example, Struik (1987, 1988) postulated the presence of an outboard block approximately 300 km northwest of the Okanagan Valley, consisting of cratonic basement and (or) Proterozoic and lower Paleozoic North American sedimentary successions, onto which a thin (2–3 km), late Paleozoic and Triassic volcanic and sedimentary succession was deposited. Such a block may have extended to the Okanagan Valley and include the rocks described here. We present new data from the Okanagan region in this paper, discuss their implications, and suggest that the complexity of the southern Canadian Cordillera results partly from rifted margin heterogeneity rather than the accretion of exotic elements.

Regional setting

The evidence of latest Precambrian plutonism derives from granite clasts in metaconglomerate 30 km northwest of Vernon, British Columbia. The metaconglomerate is part of a belt of ductilely deformed and metamorphosed pericratonic strata of Paleozoic age, which we informally name the Spa Creek assemblage. The belt can be been traced without offset from the eastern side of the Okanagan Valley for more than 30 km westward (Fig. 2). Farther east in the orogen, contact

Table 1. Nd-isotope analyses, Spa Creek and surrounding Vernon map area, British Columbia.

Sample No.	Rock type	Sm (ppm)	Nd (ppm)	$\frac{^{147}\mathrm{Sm}}{^{144}\mathrm{Nd}}$	$\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}$	±2 SD	$\varepsilon_{\mathrm{Nd}}(0)$	T (Ma)	$\varepsilon_{\mathrm{Nd}}(T)$	T_{DM} (Ga)	Stratigraphic unit; location; UTM coordinates in NAD 1983
RC-98-07	Mica schist	4.94	26.91	0.1109	0.511363	0.000006	–24.9	600	–18.3	2.65	Silver Creek Formation; Hwy. 1, east of Chase, B.C.; 5633750N, 311613E
RC-98-08	Mica schist	5.96	32.54	0.1108	0.511275	0.000010	–26.6	600	–20.0	2.78	Silver Creek Formation; east of Scotch Creek, B.C.; 5642463N, 321314E
PE99-24	Grey phyllite	6.24	30.87	0.1221	0.512111	0.000012	–10.3	210	–8.3	1.75	Triassic phyllite (Slocan Formation); Spa Creek; 5597980N, 327785E
PE98-33C	Granite	4.15	23.65	0.1061	0.511869	0.000008	–15.0	360	–10.9	1.83	Devonian biotite granite; Spa Creek; 5601374N, 328474E
PE98-33A	Mica schist	3.23	17.96	0.1088	0.511369	0.000009	–24.8	600	–18.1	2.59	Silver Creek Formation, contact with Devonian biotite granite; Spa Creek; 5601374N, 328474E
97TW-173A	Granite clasts	3.15	14.02	0.1357	0.512639	0.000009	0.0	550	+4.3	1.02	Granite clasts from metaconglomerate; Spa Creek; 5597257N, 326746E
97TW-173B	Whole rock	4.16	19.52	0.1287	0.512614	0.000005	–0.5	550	+4.3	0.99	Dated metaconglomerate; Spa Creek; 5597257N, 326746E

Note: Sm–Nd isotopic analyses were conducted at the Radiogenic Isotope Facility at the University of Alberta using isotope dilution mass spectrometry (see method described by Creaser et al. 1997). SD, standard deviation.

relationships between Eocambrian – lower Paleozoic units of the miogeocline, middle Paleozoic units, and late Paleozoic pericratonic units are mapped as stratigraphic (Klepacki and Wheeler 1985; Colpron and Price 1995; Read and Wheeler 1976; Reesor 1996; Høy and Dunne 1997). In the Spa Creek assemblage, quartzite, amphibole and biotite schist, heterolithic metavolcanic rocks, pelite, and marble occur together with metaconglomerate, having an estimated aggregate thickness of 200–400 m. Internal stratigraphic relationships are poorly exposed and internal structure may be laterally complex.

The Spa Creek assemblage consistently overlies quartz- and feldspar-rich mica schist of the Silver Creek Formation (Jones 1959) of presumed latest Proterozoic to Eocambrian age. The contact is not exposed; its location is constrained by the change in rock types, with no repetition or exposed strain zone. The Silver Creek Formation has been interpreted at least in part as metaclastic strata deposited on the ancient North American continental margin (e.g., Johnson 1990; Thompson and Daughtry 1997). Two samples of the Silver Creek Formation we collected ~50 km to the north as part of regional reconnaissance have yielded $\varepsilon_{\mathrm{Nd}}(T)$ values of –18.3 and –20.0, with respective model ages of 2.65 and 2.78 Ga (Table 1). A sample of the Silver Creek Formation in the Spa Creek area yielded an $\varepsilon_{\mathrm{Nd}}(T)$ value of –18.1 and a model age of 2.59 Ga. These values are similar to those of samples of the Horsethief Creek, Miette, and Hyland groups, which are Neoproterozoic strata of the miogeocline exposed in the Cordilleran foreland belt that yielded $\varepsilon_{\mathrm{Nd}}(T)$ values ranging from –15 to –22 and depleted mantle model ages (T_{DM}) from 2.1 to 2.85 Ga (Boghossian et al. 1996; Garzione et al. 1997). The results from the Silver Creek Formation are thus consistent with derivation from the North American craton. In the Spa Creek area, the Silver Creek Formation is cut by granodiorite of Late Devonian – Early Mississippian age (see U–Pb zircon geochronology).

The Spa Creek assemblage is overlain regionally, in a veneer locally no more than a few hundred metres thick, by weakly metamorphosed dark siltstone, argillite, and platy phyllite marking the “Triassic unconformity” of south-central British Columbia (cf. Read and Okulitch 1977). In the Glenemma–Armstrong area (which includes Spa Creek; see location in Fig. 2), these dark metaclastic rocks have been interpreted by Read and Okulitch (1977) as an eastern facies of the Upper Triassic Nicola Group. However, because physical continuity with classic Nicola rocks to the west cannot be demonstrated, the dark clastic strata at Spa Creek may instead be part of the Triassic Slocan Group exposed to the east between Arrow Lake and the Okanagan Valley. As the Slocan Group has been correlated with the Nicola Group on the basis of lithologic similarity and stratigraphic position (Read and Okulitch 1977), the distinction is moot in the present context.

The Mississippian to Permian Harper Ranch Group and the Upper Triassic Nicola and Slocan groups have been interpreted as a volcanic arc complex and adjacent clastic basin, called the Quesnel (or Quesnellia) terrane, thought to have been accreted to the continental margin in Jurassic time (e.g., Monger et al. 1991), with up to 190 km of proposed tectonic overlap relative to the underlying outboard part of the miogeocline (e.g., Ghosh 1995). However, approximately 40 km to the west of Spa Creek, the basal contact of Triassic (Nicola) strata above rocks whose metamorphic grade is similar to the Spa Creek assemblage, comprising chloritic phyllite, greenstone, metachert, quartzite, and marble of the Chapperon Group, is a well-exposed angular unconformity of regional extent (cf. Read and Okulitch 1977).

Regional constraints on the timing of deposition of the Spa Creek assemblage are difficult to establish. Because Permian volcanic and carbonate rocks constitute erosional outliers that lie disconformably beneath more extensive Upper Triassic siltstone and argillite, and can be considered on the basis of their lack of strong deformation and their low grade of metamorphism to have had a similar history, we infer that the Spa Creek assemblage is older than Permian.

Geology of the Spa Creek section

We focused our study on part of the Spa Creek assemblage exposed near the headwaters of Spa Creek, approximately 10 km west-northwest of Glenemma and south of an undeformed granitic intrusion several tens of kilometres across, which is likely of Jurassic age because there are plutons nearby with similar lithology that are dated (Fig. 2). The succession of amphibolitic and other mafic schist, marble, and metaconglomerate is underlain to the northeast by mica schist, quartz-rich schist, and quartzite of the Silver Creek Formation.

The Spa Creek succession is overlain on the southeast by lower grade carbonaceous dark grey phyllite, metasiltstone, and argillite of the basal part of the Nicola (or Slocan) Group (Fig. 3). A sample of phyllite located a few tens of metres above the contact yielded an $\varepsilon_{\mathrm{Nd}}(T)$ value of –8.3 and a model age of 1.75 Ga (Table 1). The evolved crustal $\varepsilon_{\mathrm{Nd}}(T)$ value is similar to values obtained from Triassic strata in the Cordilleran miogeocline; Ross et al. (1997) reported $\varepsilon_{\mathrm{Nd}}(T)$ values of –6.7 to –10.5 for samples of the Toad, Sulphur Mountain, and Whitehorse formations exposed in the foreland belt. The provenance of Triassic strata near Spa Creek is thus similar to that of Triassic Cordilleran miogeoclinal strata.

Because of poor exposure, the contact between the Triassic strata and the Spa Creek assemblage was not found, but the gap in exposure is only a few tens of metres in places, and no strain zone or repetition of rock types is evident. At both the map and outcrop scale, there is angular discordance between variably steeply dipping lithologic layering in the Spa Creek assemblage and generally shallowly dipping lithologic layering in the overlying Triassic rocks. Coarse-grained ductile fabrics in the Spa Creek assemblage record deformation and metamorphism at depths well below the brittle–ductile transition. In contrast, the overlying fine-grained Triassic slate and phyllite preserve bedding, laminations, and other primary sedimentary structure and regular lithologic layering and slaty cleavage across entire outcrops.

Within the Spa Creek assemblage, the mafic schist unit is up to several hundred metres thick; contacts are parallel to schistosity. The unit includes fine- to medium-grained hornblende–albite schist, fine-grained amphibolite, hornblende–biotite schist, and minor biotite–muscovite phyllite. On the basis of its commonly heterolithic character, it was likely derived from a mafic to intermediate tuff or tuffaceous pyroclastic

Fig. 3. Schematic stratigraphic column of the Spa Creek section.

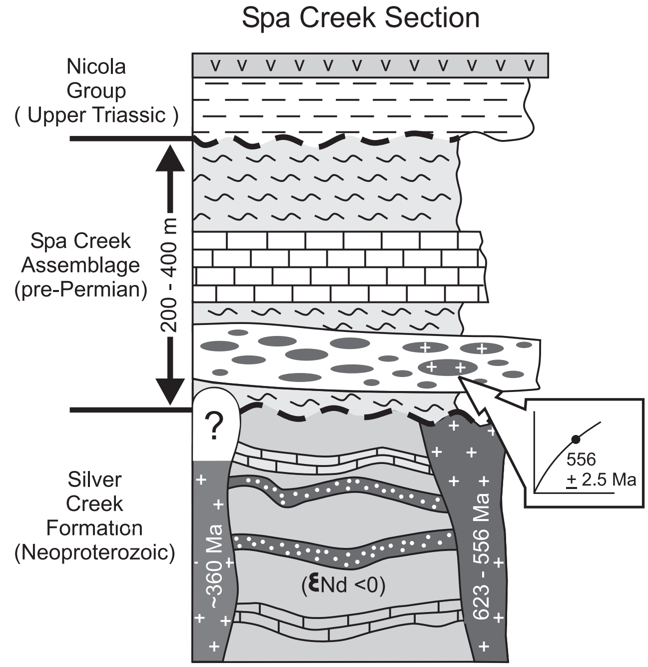


Fig. 4. Photograph of a natural weathered surface of the sample of granite-cobble metaconglomerate that was used for U–Pb analysis. One clast in the centre of the photograph is biotite schist; all other clasts are biotite granite with a primary igneous crystallization texture. The coin used for scale is ~2 cm across.

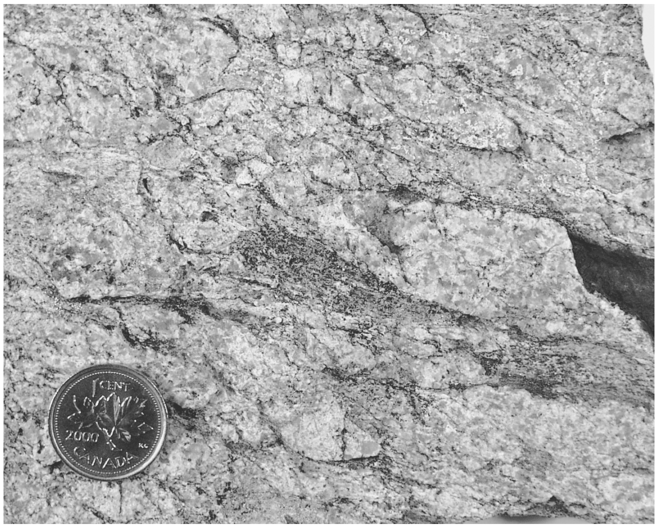
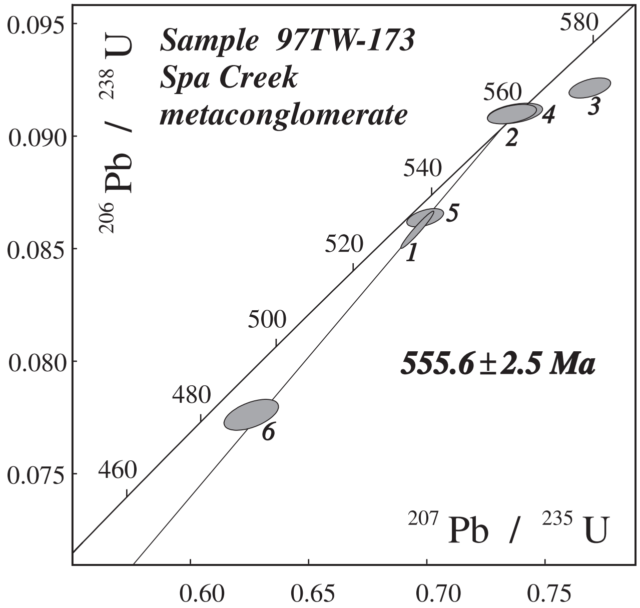


Fig. 5. Concordia diagram showing U–Pb results for six fractions of zircon from metaconglomerate in the Spa Creek assemblage. Error ellipses are represented at the 2σ level. Five of these fractions plot along a single discordia line that intersects the concordia curve at 555.6 ± 2.5 Ma. Analytical data are given in Table 2.



protolith. Schistosity is overgrown statically by variably oriented porphyroblasts and clots of amphibole or biotite. The marble is at least 10 m thick; its contact with amphibolite schist is not exposed but is assumed to be parallel to schistosity.

There are several layers of metaconglomerate. The metaconglomerate we studied is at least 25 m thick. Its upper contact is not exposed. It grades downward into heterogeneous amphibolitic schist. It is a clast-supported rock with a schistose matrix of biotite and muscovite in wispy folia locally less than 0.5 mm thick between clasts. Clasts range in size from more than 30 cm to less than 1 cm in their shortest dimension, averaging 2–5 cm, with a flattened prolate ellipsoid shape. Clast shape and orientation define an external foliation and lineation resulting from ductile flattening and stretching. Similar strain is characteristic of other exposures of metaconglomerate at the same stratigraphic position along regional strike (see Erdmer et al. 1999). The metaconglomerate is polymictic and includes mainly clasts of grey to sugary white quartzite (more than 80% abundance is typical), with minor amphibole schist, chlorite schist, sericite schist, biotite schist, quartz–feldspar porphyry, and fine-grained unidentified granitoid rock types. Foliation in the metamorphic clasts is discordant with respect to the matrix foliation and variably oriented.

Across several metres of layering in one rock face, the relative distribution of clast types is remarkably skewed: nearly all clasts are medium-grained, pale pink to buff, locally submegacrystic K-feldspar biotite granite. The nearly monomictic clast composition indicates derivation as a gravel or a wash from a local source. Because the matrix constitutes only a few percent of the rock, the granite clasts and the penetrative deformation locally impart the superficial appearance of a sheared plutonic rock at the outcrop scale (Fig. 4). Granite in individual clasts is massive when examined in hand specimen. This is also the case at the thin-section scale, where quartz is not dynamically recrystallized and does not display undulose extinction. Biotite flakes in the granite are strain free, variably oriented, characteristically green, and strongly pleochroic and locally host rutile needles aligned with the crystallographic planes of the mica. Feldspars are not sericitized. Primary igneous crystallization texture is characteristic. Thin sections of a range of granite clasts confirm that they are from a similar protolith.

Similar to the rest of the Spa Creek succession and the Silver Creek schist, the metaconglomerate is polymetamorphic.

Table 2. U–Pb zircon results for sample 97TW-173 metaconglomerate, Spa Creek, British Columbia.

											Model ages (Ma)			
Description[a]	Wt. (mg)	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	TC Pb (pg)[b]	^{206}Pb/^{204}Pb	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	% Disc.[c]
1. z, col, nabr (100)	50	150	117	15	0.78	4	9159	0.0858±3	0.696±3	0.0588±0	531±2	536±2	560±2	5.4
2. z, col, abr (1)	10	221	159	23	0.72	10	1230	0.0910±2	0.736±2	0.0586±1	561±1	560±1	554±5	–1.3
3. z, col, nabr (9)	6	171	140	20	0.82	13	460	0.0921±2	0.769±4	0.0605±3	568±1	579±2	623±9	9.2
4. z, col, abr (1)	1	410	337	42	0.82	2	1274	0.0911±2	0.738±5	0.0588±4	562±1	561±3	558±13	–0.7
5. z, col, abr (1)	1	606	453	60	0.75	4	1082	0.0864±2	0.699±3	0.0587±2	534±1	538±2	557±9	4.3
6. z, col, abr (1)	2	240	170	21	0.71	2	1152	0.0776±3	0.626±5	0.0585±4	482±2	493±3	547±14	12.4

Notes: Uncertainties reported in the table are listed at one sigma. Th concentration is estimated from the amount of ^{208}Pb and ^{207}Pb/^{206}Pb age.

[a] Number of grains analyzed is given in parentheses. abr, abraded; col, colourless; nabr, not abraded; z, zircon.

[b] Total amount of common lead in the analysis.

Garnet porphyroblasts averaging 0.5 cm across occur in the mica-rich matrix, where they statically overprint schistosity that is locally crenulated. The overlying Triassic strata at Spa Creek also host small garnet porphyroblasts that grew statically across slaty to phyllitic cleavage and across bedding. The age of the static metamorphism is undetermined; we assume that it is Jurassic and is related to the nearby pluton.

U–Pb zircon geochronology

We investigated the granite-clast phase of the metaconglomerate using U–Pb analysis in zircon in an attempt to identify the age and nature of the crustal basement that the pericratonic succession and the Triassic strata overlie. A ~25 kg rock slab was crushed whole to separate zircon (sample location: universal transverse Mercator (UTM) coordinates 5597257N, 326746E, North American datum (NAD) of 1983). The rock consisted of more than 90% clasts, averaging 2 cm across in their shortest dimension; more than 90% of the clasts were biotite granite (Fig. 4). The zircon population consisted dominantly of small (40–60 µm), euhedral, short prismatic (ratio of length to width = 2:1), colourless grains. Colourless and slightly resorbed fragments occurred in addition, but there was no indication that grains were rounded by sedimentary transport or that there was subsequent zircon growth during metamorphism (i.e., no visible core–overgrowth relationships). Because the zircon grains are relatively homogeneous, they do not record the sampling of a distant terrain or of a lithologically varied source, and they are likely derived principally from the granite clasts.

All zircon fractions showed moderate uranium content (150–600 ppm), similar Th/U (0.71–0.82), and a low content of common Pb (2–13 pg), attesting to a relatively simple zircon geochemistry. Two zircon analyses included unabraded multigrain fractions (1 and 3, Fig. 4), and four consisted of single, abraded, colourless, 1–2 µg prisms (4, 5, 6) and a 10 µg blocky fragment (2). The ^{207}Pb/^{206}Pb dates obtained for five of the six fractions are between 560 and 547 Ma; most analyses were less than 5% discordant. Remarkably, the majority of the zircon grains analyzed (approx. 100) yielded similar ^{207}Pb/^{206}Pb dates within the narrow range 560–554 Ma. A best-fit discordia line constructed to pass through five of the analyses (1, 2, 4, 5, 6) yielded a precise upper intercept of 555.6 ± 2.5 Ma (2σ; mean square of weighted deviates (MSWD) = 1.4), which we consider as the age of the main zircon source in this sample. The presence of some older detrital grains and (or) clasts (minimum age of 623 Ma) is indicated by multigrain analysis 3. A maximum age for this older detritus is given by an upper intercept age of 2.60 ± 0.23 Ga, using analyses 2, 3, and 4. The U–Pb results from the six zircon analyses are presented in Fig. 5. Analytical data are given in Table 2.

There is no evidence of a zircon population younger than Eocambrian in the metaconglomerate. Because younger rocks are exposed nearby, we consider this fact significant. We have identified two deformed granitic bodies cutting the Silver Creek Formation less than 5 km to the north of the metaconglomerate sample site. One intrusion, which is at least 1.5 km in its longest horizontal dimension, is of latest Devonian age from our preliminary U–Pb zircon analysis; it has yielded an $\varepsilon_{Nd}(T)$ value of –10.9 and a model age of 1.83 Ga (Table 1). However, despite their proximity, neither these plutons nor the Silver Creek Formation appear to have had detrital input into the Spa Creek metaconglomerate. Thus, unroofing of the 556 Ma pluton and conglomerate deposition may have occurred before latest Devonian time. We hypothesize that deposition occurred shortly after granite intrusion and that active rifting in the latest Neoproterozoic or early Paleozoic provided the required geomorphic setting. However, the evidence allows that erosional exhumation could instead have taken place at another time, for example in a geographically isolated normal-fault basin as young as Late Devonian.

A portion of the dated whole-rock sample of granite-clast metaconglomerate yielded an $\varepsilon_{Nd}(T)$ value of +4.3 and a model age of 0.99 Ga (Table 1). A second sample consisting of selected granite clast fragments from the same slab yielded an $\varepsilon_{Nd}(T)$ value of +4.3 and a model age of 1.02 Ga (Table 1). In contrast to the Spa Creek metasedimentary rocks, these values are inconsistent with derivation from evolved cratonic crust and indicate derivation mainly from a mantle source. A rift origin is compatible with these data.

Discussion and implications

The exact depositional age of the Spa Creek assemblage is poorly constrained; it is younger than 556 Ma and older than Permian (the latter, because nearby little-strained and low-grade Permian strata lie disconformably beneath and are stratigraphically continuous with regionally more extensive Upper Triassic strata; see earlier in the paper). Although we think from the zircon characteristics that the Spa Creek assemblage is only slightly younger than the granite clasts, we are intrigued by the close lithological similarities, including metaconglomerate with granite clasts, with parts of the Mississippian Milford Group. The Milford Group is exposed more than 100 km to the east (Read and Wheeler 1976; Roback et al. 1994), where it overlies lower Paleozoic rocks of the outer miogeocline with angular unconformity and is therefore stratigraphically part of the North American continental margin. Two granite clasts from metaconglomerate within the Milford Group have yielded upper intercept zircon dates of 418 ± 5 and 431 ± 12 Ma (Roback et al. 1994).

The granite clasts in the metaconglomerate at Spa Creek lack tectonic fabric, and other clasts display predeposition tectonic fabrics. Although some of the other clasts may be younger than the granite, some were likely derived from the host rocks of the granite pluton. These foliated metamorphic rocks are therefore Proterozoic and preserve an orogenic record older than 556 Ma.

The presence of only a thin (less than 1 km) Paleozoic succession on, or close to the source of the Eocambrian granite clasts implies (*i*) severe stratigraphic thinning of Paleozoic strata atop a continental block that was high relative to the adjacent and inboard miogeocline, (*ii*) one or more periods of uplift and removal of Paleozoic strata prior to Triassic deposition, or (*iii*) severe structural attenuation of an originally thicker succession (which we consider least likely, as no evidence exists). In all of these cases, a significant present-day thickness of cratonic crust is required to account for the exposure of Proterozoic metamorphic rocks and the lack of Paleozoic section thickness. Because the Triassic section at Spa Creek is also thin, in the order of a few hundred metres, we conclude that the estimated present-day 32 km thickness of lithospheric crust at Spa Creek (see Clowes et al. 1995) does not consist mainly of accreted Phanerozoic arc rocks but cratonic or continental margin rocks of Late Proterozoic age or older.

The rocks that underlie the Spa Creek assemblage and the Silver Creek Formation could, for example, be equivalent to the Late Proterozoic Windermere Group in the upper crust and correlate with the mid-Proterozoic Belt–Purcell Group at mid-crustal depths. Alternatively, if deposition of Windermere and Belt–Purcell strata did not extend this far west, the rocks could be Early Proterozoic crust such as in the core of the Shuswap Metamorphic Complex. Irrespective of their exact stratigraphic affinity, they are Precambrian, which leads us to propose that Permian and Triassic volcanic rocks in this part of the Cordillera are thin because they were deposited stratigraphically on cratonic or continentally derived rocks of the ancient continental margin (see Fig. 1, inset *b*). The existence of a regional unconformity can be further tested through field mapping. The interpretation of a depositional contact does not preclude the development of locally thick arc rock successions or incipient oceanic rifts containing older strata, expected in the general setting of a heterogeneously stretched and evidently wide continental "margin."

Whether the Spa Creek assemblage is lower or upper Paleozoic, and whether or not it is physically continuous with units farther inboard, the implications for the composition of the local crust and the thinness of the Paleozoic succession remain the same. We have considered and rejected the possibility that the granite clasts were derived via long-distance transport from a source located elsewhere on the North American continent. The Spa Creek metaconglomerate clasts are too large and too numerous and the spectrum of zircon ages too limited to support the possibility of a distal, interior cratonic source. For example, Gehrels and Dickinson (1995) reported a dominant population of 500–525 Ma detrital zircon grains in quartz sandstone of the Late Triassic Chinle Formation in Nevada, together with other populations in the ranges 220–235 Ma, 1.41–1.44 Ga, and 1.68–1.74 Ga. They interpreted the Cambrian grains to be derived from plutons in Oklahoma, Texas, New Mexico, and Colorado, which have yielded a variety of ages from ~500 to 570 Ma. The distances from these locales to Spa Creek are too great for them to be plausible source regions of the clasts described here.

Part of the evidence used by Devlin and Bond (1988) to constrain the time of Cordilleran rift to drift transition is a succession of mafic flows, tuff, and breccia up to several hundred metres thick interlayered with shale and arkosic sandstone within the Hamill Group, an Eocambrian transgressive, shallow-water quartzite succession that underlies the Lower Cambrian shelf-carbonate "drift" sequence farther inboard relative to the Spa Creek area. Approximately 150 km northeast of Spa Creek, the Hamill Group contains a minor volcanic component that includes trachyandesite flows (Logan et al. 1996; Logan and Rees

1997), for which preliminary zircon analysis has yielded an age range overlapping the 555.6 ± 2.5 Ma result obtained in this study (J.K. Mortensen, personal communication, 1999). Other evidence of Eocambrian magmatic activity is provided by detrital zircon in quartzite near Grand Forks, British Columbia. Ross and Parrish (1991) obtained detrital zircon grains, whose age they inferred from $^{207}Pb/^{206}Pb$ dates to be 570–674 Ma. Although the grains were markedly discordant and had experienced sillimanite-grade metamorphism leading to significant lead loss, Ross and Parrish concluded that the quartzite correlated with the Hamill Group, an assertion first proposed by Preto (1970) on the basis of lithological similarity.

A rift origin of the Spa Creek granite is compatible with the primitive $\varepsilon_{Nd}(T)$ values obtained. The mafic magmatism within the Hamill Group is also compatible with rifting. On the basis of available evidence, we propose that the rift to drift transition postulated by Bond and Kominz (1984) was preceded by a magmatic event within a crustal block outboard of the eastward-tapering wedge of shelf sediment that onlapped the craton. Alternative explanations of the magmatism can be considered, such as crustal thickening due to collision. For example, the upper intercept age of the Spa Creek metaconglomerate granite (2.60 ± 0.23 Ga) is similar to the model ages obtained for the Silver Creek Formation (2.59–2.78 Ga), which may indicate that the granite was contaminated by Silver Creek rocks. However, the dissimilarity of model ages for the Silver Creek schist (2.59–2.78 Ga) and the granite (0.99–1.02 Ga) shows that the granite could not be produced exclusively by melting of the Silver Creek Formation, thus making a collision origin unlikely. Other causes of the magmatism remain possible.

Knowledge that the stratigraphic underpinnings near Spa Creek are Proterozoic, together with the lack of a major surface break in the interpreted lithospheric profile for more than 100 km to the west (see Clowes et al. 1995), leads us to the inference that most of the upper crust between the Okanagan Valley and the Fraser fault is cratonic, instead of the root of an accreted arc(s) or oceanic crust (see Fig. 1). On that basis, the hypothesis that a Mesozoic crustal obduction ramp dips west beneath the Okanagan Valley and separates accreted arc – oceanic and parautochtonous parts of the Cordillera at depth (e.g., Cook et al. 1992; Clowes et al. 1995) needs reevaluation. Other evidence appears inconsistent with a major Mesozoic structure at that location. For example, if the proposed Quesnellia terrane had traveled up such a ramp as an allochthon, the surface geology would show contrasts in depth of exposure across the ramp of more than 20 km, given the throw implicit in the structural geometry. That is not the case, as rocks assigned to the Quesnellia terrane are generally low grade and vary little in metamorphic grade across its 100–200 km width at this latitude.

Struik (1987, 1988) was unable to establish direct stratigraphic links of his proposed outboard continental crust block with proximal portions of the ancient margin succession and therefore left unanswered the question of paleogeographic location of the block. It is possible that the postulated block is part of a single crustal element of regional extent that includes the Spa Creek assemblage and has not undergone significant lateral displacement relative to the ancient continental margin. However, even if there were several disconnected crustal blocks rather than a single large one, the existence of outboard cratonic crust is no longer hypothetical.

We conclude that the ancient plate margin extends farther at surface in the southern Canadian Cordillera than previously recognized. We infer that the present geological complexity results at least in part from rifted margin heterogeneity. We suggest that the accretion of exotic elements as a dominant orogenic process in the Mesozoic may be incorrectly emphasized in previous crustal interpretations.

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