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Age and tectonic setting of Early Jurassic episodic volcanism along the northeastern margin of the Hazelton Trough, northern British Columbia

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ABSTRACT

Three temporally distinct Lower Jurassic volcanic successions are exposed in the Spatsizi River area of the Stikine Terrane (Stikinia), northern British Columbia. U-Pb zircon dating reveals that (1) the age of the oldest succession, the Griffith Creek volcanics, is ca. 206 Ma; and (2) the middle unit, the Cold Fish Volcanics, is ca. 194 Ma, consistent with its Early Pliensbachian biostratigraphic (ammonite) age. The age of the youngest unit, the Mount Brock volcanics, is Early to Middle Toarcian, also on the basis of ammonites. The Griffith Creek volcanics were folded along with older strata prior to deposition of the Cold Fish succession.

An inherited component of zircon in some of the analyzed zircon fractions indicates that Precambrian basement or Lower Paleozoic strata of Precambrian provenance was present in the Stikinian subsurface. An evolved basement is also suggested by fluorine-rich compositions of high-silica Cold Fish rhyolites.

The three volcanic successions were deposited in the Early Jurassic along the northeastern margin of the Hazelton Trough, a long-lived marine basin which lay between mainly subaerial volcanic arcs on the eastern and western sides of Stikinia. In Early Pliensbachian to Middle Toarcian time, strata in the Spatsizi River area recorded at least 2.6 km of subsidence, consistent with protracted regional subsidence in and around the trough. Extensional tectonism, and to a lesser degree thermal subsidence and local volcanic foundering, are considered the main causes of subsidence.

INTRODUCTION

Numerous volcanic successions were deposited on the Stikine Terrane (Stikinia) of the Canadian Cordillera in Early to Middle Jurassic time (Fig. 1). These successions, together with related sedimentary sequences, are collectively termed the Hazelton Group (Tipper and Richards, 1976; Marsden and Thorkelson, 1992). The Hazelton Group is exposed throughout much of central and northern Stikinia, extending for approximately 800 km from latitude 51° to latitude 58°30′N, and across the entire width of Stikinia (Wheeler and McFeely, 1987). Restoration of post-Hazelton contractional deformation (Evenchick, 1991) revealed that the width of the volcanic belt at the time of deposition was 450–550 km.

Field and petrologic studies have consistently shown that

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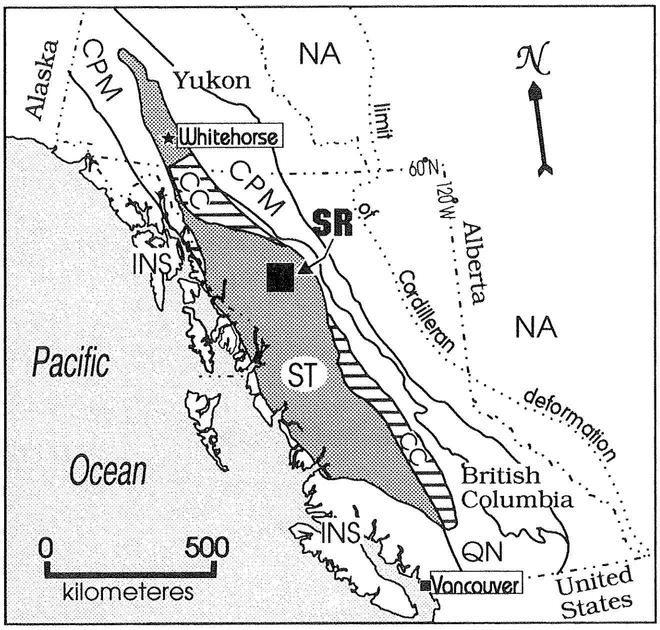

Figure 1. Simplified terrane map of the Canadian Cordillera, showing Stikinia (ST), Cache Creek Terrane (CC), Insular terranes (INS), Quesnellia (QN), continental, pericratonic, and marginal basin terranes (CPM), ancestral North America (NA), and Spatsizi River map area (SR). Nisling Terrane lies within the western part of composite terrane CPM. Modified from Wheeler and McFeely (1987).

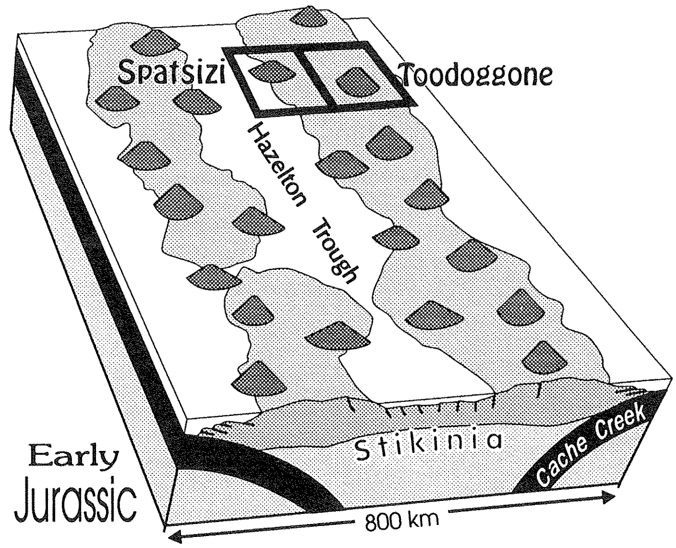

Figure 2. Suggested tectonic environment of Stikinia in Early Jurassic time. Stikinia is bounded on both sides by subducting oceanic plates, the eastern of which is correlative with the Cache Creek Terrane (Fig. 1). Hazelton volcanoes form two largely subaerial volcanic arcs separated by the extending and subsiding Hazelton Trough. Spatsizi River and Toodoggone River map areas are schematically located. Modified from Marsden and Thorkelson (1992).

the Hazelton Group formed in a volcanic arc and back-arc setting (e.g., Tipper and Richards, 1976; Erdman, 1978; Brown, 1987; Diakow et al., 1991), although there has been little consensus on the polarity of subduction and overall tectonic environment. Marsden and Thorkelson (1992) depicted Stikinia as an oceanic microplate beneath which subduction occurred from opposite sides (Fig. 2). In this model, contemporaneous subduction beneath the eastern and western sides of Stikinia produced a pair of coeval volcanic arcs separated by a subsiding marine basin called the Hazelton Trough (Tipper and Richards, 1976). This interarc trough was a shared region of back-arc sedimentation, volcanism, and subsidence. In Middle Jurassic time, the Hazelton Trough became a depocenter for chert-rich detritus shed from the Cache Creek Terrane that was emerging to the north (Souther and Armstrong, 1966). The resultant succession of molasse is called the Bowser Basin.

Two principal stratigraphic packages underlie the Hazelton Group: the Upper Triassic Stuhini Group, and the Devonian to Permian or (?)Middle Triassic Stikine assemblage (Monger, 1977; Read and Psutka, 1990; Brown et al., 1991). Both contain volcanic arc rocks and exhibit juvenile Sr and Nd isotopic signatures (Gabrielse et al., 1980; Armstrong, 1988; Samson et al., 1989). Older rocks that presumably formed the crustal basement to these successions are not exposed in Stikinia. A ca. Middle Proterozoic U-Pb age was obtained for zircon xenocrysts in a Late Triassic syenitic pluton in western Stikinia (Bevier and Anderson, 1991). This finding was the first direct evidence of a possible Precambrian basement to Stikinia. Geochronological data presented in this report support that possibility.

In the Spatsizi River map area (Figs. 1–3), three temporally distinct volcanic successions (Fig. 4) were deposited in Early Jurassic time (Thomson et al., 1986; Read and Psutka, 1990; Thorkelson, 1992). Each of the successions was deposited under mainly subaerial conditions, along the northeastern margin of the Hazelton Trough. A subduction-related setting is clearly evident from major and trace element signatures (Thorkelson, 1992). Trace element profiles from the three formations strongly resemble the average Cascade + Aleutian arc composition from Ewart (1982) (Fig. 5).

The youngest succession, the Mount Brock volcanics, was dated as Early to Middle Toarcian on the basis of ammonites collected from intercalated marine sedimentary layers (Read and Psutka, 1990). The middle succession, the Cold Fish Volcanics, was dated as Early Pliensbachian, also on the basis of hosted ammonites (Thomson et al., 1986; Evenchick, 1986). A Rb-Sr scatterchron from Cold Fish rocks suggested an age of 189 ± 26 Ma (Gabrielse et al., 1980). The oldest volcanic pile is the Griffith Creek volcanics (Thorkelson et al., 1991), whose age was known to be younger than or equivalent to underlying Norian (Late Triassic) strata, and older than the Cold Fish succession (Gabrielse and Tipper, 1984; Thorkelson, 1988). The Griffith Creek strata were folded prior to deposition of the Cold Fish Volcanics; although these two successions are juxtaposed

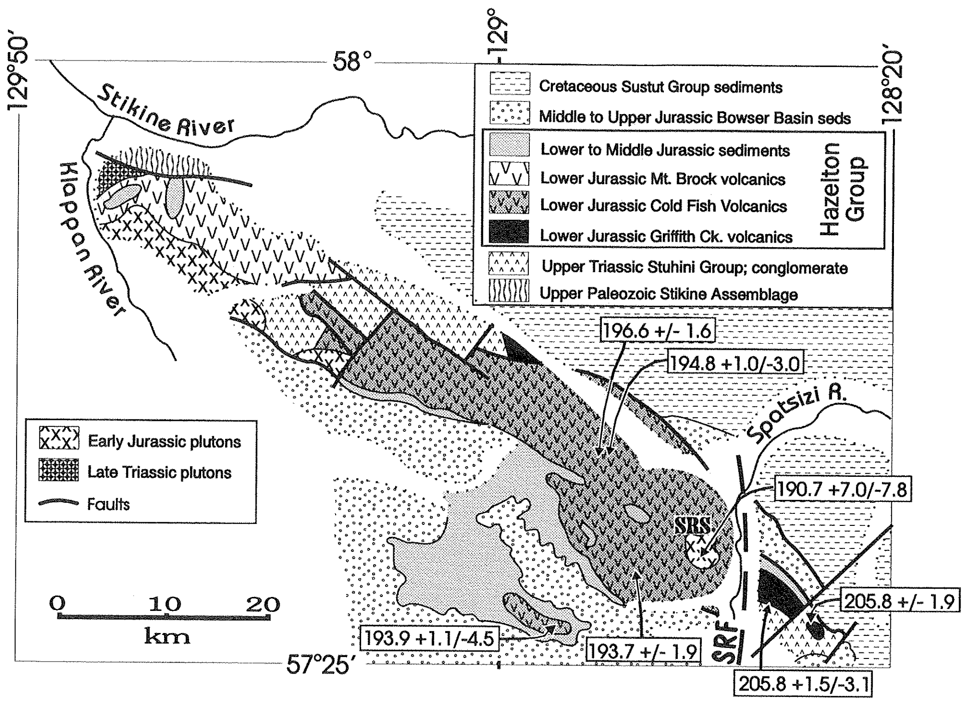

Figure 3. Sketch map of study area, located in the Spatsizi River map area of north-central British Columbia showing distribution of volcanic formations of the Hazelton Group and location of U-Pb zircon age determinations. SRS = Spatsizi River Stock; SRF = Spatsizi River fault. Map modified from Gabrielse and Tipper (1984), Read and Psutka (1990), and Thorkelson (1992).

across faults, the Cold Fish is inferred to overlie the Griffith Creek with angular unconformity.

In this report, U-Pb zircon ages are presented for (1) the Cold Fish Volcanics; (2) the Spatsizi River Stock, a hypabyssal intrusion coeval with the Cold Fish; and (3) the Griffith Creek volcanics. The isotopic ages permit improved correlation between these successions and igneous rocks elsewhere in the Hazelton belt, and constrain the age of post–Griffith Creek, pre–Cold Fish folding. In addition, the isotopic age of the Cold Fish Volcanics may serve to improve calibration of the Pliensbachian stage on the geological time scale.

STRATIGRAPHY AND FIELD RELATIONS

Generalized stratigraphy of Late Triassic to Middle Jurassic rocks in the Spatsizi River map area (Fig. 3) is illustrated in Figures 4 and 6. Detailed field and petrologic descriptions of the Hazelton volcanic rocks were presented by Thorkelson (1992).

The Griffith Creek volcanics comprise an informally defined succession (Thorkelson, 1992) of mafic to intermediate lava flows and intermediate to felsic volcaniclastic rocks that crop out mainly east of Spatsizi River. Predominantly subaerial conditions are indicated by the maroon color of many of the lava flows, dense welding of ignimbrite, and absence of marine indicators such as pillow basalt and intercalated marine sedimentary rock. The succession is disconformably to conformably underlain by conglomerate hosting clasts of Permian and Late Triassic limestone (M. J. Orchard, personal communication, 1988) and undated chert. Interbedded with and underlying the conglomerate are sedimentary and volcanic strata of the (?)Carnian to Norian Stuhini Group. A thick subvolcanic sill correlative with the Griffith Creek volcanics was emplaced into the conglomerate-Stuhini Group sequence. East of Spatsizi River, the Griffith Creek and Stuhini Group successions have been tightly folded about east-trending fold axes. Rocks younger than the Griffith Creek succession have not been observed in stratigraphic contact with the Griffith Creek.

The Cold Fish Volcanics (Thomson et al., 1986), considered a formal unit by Thorkelson (1992), are a silica-bimodal succession of mafic lava, and felsic sills and tuffaceous rocks (Thorkelson, 1992). Many of the felsic rocks have silica contents in excess of 75% and are categorized as high-silica rhyolites. The southeastern exposures of the Cold Fish consist of thick ignimbrite sheets and sills and are interpreted to have been deposited in a resurgent caldera. A small, miarolitic, alkali feldspar granitic intrusion called the Spatsizi River Stock crosscuts some of the caldera-facies strata, and is interpreted as a synvolcanic intrusion. Fluorite, magnetite, and chlorite commonly fill the miarolitic cavities of this stock. The northwestern exposures of the Cold Fish succession comprise about 50%

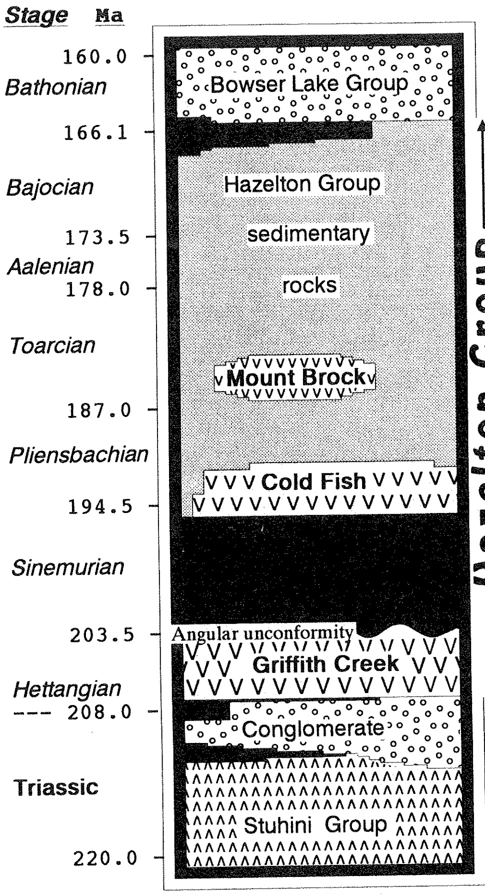

Figure 4. Schematic stratigraphic section of Upper Triassic to lower Middle Jurassic rocks in Spatsizi River area. Solid black regions are unconformities. Numerical time scale is from Harland et al. (1990).

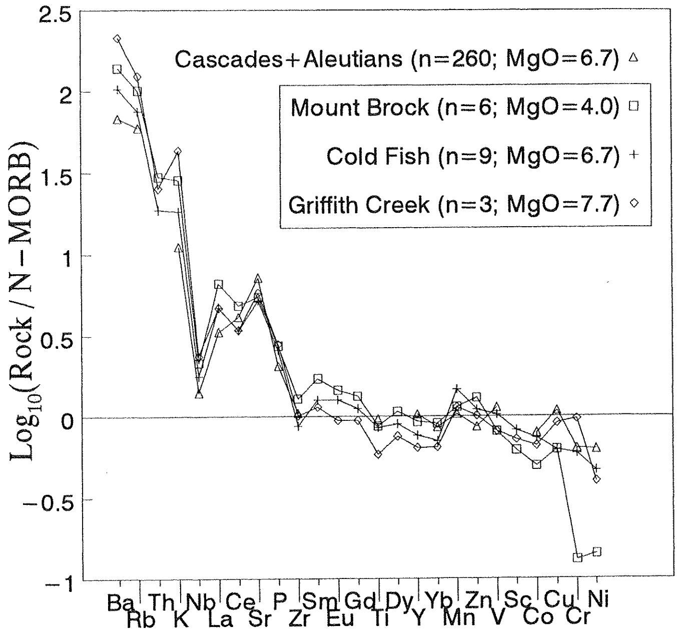

Figure 5. Comparison of trace element profiles of mafic Hazelton Group rocks from each of three formations with average Cascades + Aleutians mafic arc composition of Ewart (1982). All profiles represent compositional averages (n = number of analyses; MgO = average MgO concentration on volatile-free basis), log-normalized to normal mid-ocean ridge basalt (N-MORB). Hazelton Group analyses and compiled N-MORB normalizing values given in Thorkelson (1992).

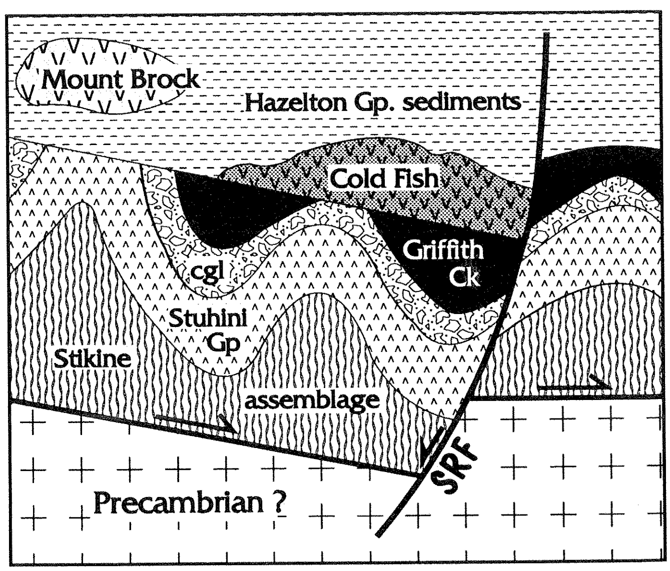

Figure 6. Cross section showing generalized crustal structure of Stikinia in Spatsizi River area in Late Toarcian (latest Early Jurassic) time. Mount Brock and Cold Fish volcanic successions and time-equivalent marine sedimentary strata lie with inferred angular unconformity on folded Griffith Creek volcanics and older rocks. Griffith Creek volcanics lie disconformably on conglomerate (cgl) and Stuhini Group rocks, which are inferred to overlie previously deformed Paleozoic rocks of the Stikine assemblage. Stikine assemblage overlies inferred basement of Early Paleozoic to Precambrian age, perhaps along a formerly active structural detachment. Large extensional faults such as the Spatsizi River fault (SRF), active in Early to Middle Jurassic time, may have involved basement.

mafic lava and 50% rhyolitic rocks that formed a composite volcano or volcanic field. Lahar is a very minor constituent, implying that paleoslopes were gentle. Fluorite veins locally crosscut the succession.

Although the Cold Fish was deposited in a predominantly subaerial environment, as indicated by dense welding in abundant ignimbrite sheets, accretionary lapilli, and reddened (oxidized) margins of mafic flows, some of the strata were deposited under shallow marine conditions. Correlation among stratigraphic sections implies a thickness in excess of 2,000 m (Thorkelson, 1992). In one section within the volcanic pile, thin marine sedimentary and volcanic interbeds of Early Pliensbachian age (Evenchick, 1986) overlie at least 800 m of subaerial lava and tuff. These interbeds indicate that the Cold Fish Volcanics subsided as they were being deposited and suggest that gain in topographic elevation by volcanic aggradation was partly compensated for by synvolcanic subsidence. In addition, approximately 1,000 m of conformable marine sedimentary strata of Early Pliensbachian to Middle Jurassic age cap the volcanic pile (Thomson et al., 1986). These overlying sedimentary strata reveal that subsidence in the region continued for several million years after cessation of Cold Fish volcanism.

The base of the Cold Fish is not exposed, but the succession is inferred to rest with angular unconformity on folded rocks of the Griffith Creek volcanics and older strata (Fig. 6). This inference is based on (1) steeply dipping Griffith Creek and Stuhini Group strata east of the Spatsizi River fault (Fig. 3) that strike toward gently folded Cold Fish rocks west of the fault and (2) a 70° angular unconformity between lava flows of Stuhini Group (which are conformable with the Griffith Creek) and overlying Middle Jurassic strata of the Bowser Basin (which conformably overlie Cold Fish and younger rocks). The deformation affecting the Griffith Creek, which preceded deposition of the Cold Fish Volcanics, may be equivalent to latest Triassic to earliest Jurassic deformation recognized elsewhere in Stikinia (Greig and Brown, 1990; Brown et al., 1992).

The Mount Brock volcanics (Read and Psutka, 1990; Thorkelson, 1992) are an informally defined succession of mafic and intermediate lava and felsic pyroclastic rocks. They crop out toward the northwestern side of the Spatsizi River map area and gradationally overlie marine sedimentary rocks of Late Pliensbachian age (Smith et al., 1984; P. L. Smith, personal communication, 1991). The succession was subaerially deposited except for strata near the base and at a few locations higher in the succession. One marine interbed bearing Middle Toarcian ammonites overlies approximately 2,000 m of mainly subaerial lava and volcaniclastic rocks (Read and Psutka, 1990). This relationship parallels that in the Cold Fish Volcanics and indicates approximately 2 km of synvolcanic subsidence. The top of the 4-km-thick Mount Brock succession is not exposed, but it may be overlain by Early or Middle Jurassic sedimentary strata, a relationship that would indicate subsidence of at least 4 km.

U-PB GEOCHRONOLOGY

Analytical techniques

Zircon concentrates were prepared from 4–6-kg samples of crushed rock using conventional Wilfley table and heavy-liquid techniques. All of the zircon fractions were abraded prior to isotopic analysis to minimize effects of surface-correlated Pb loss (Krogh, 1982). Criteria for selection of grains for analysis and procedures used for dissolution, chemical extraction and purification of U and Pb, and mass spectrometry are described in detail Parrish et al. (1987). Procedural blanks were 5–25 pg for Pb and <1 pg for U. U-Pb analytical data are given in Table 1, and the data are displayed on U-Pb concordia plots in Figure 7. Errors attached to individual analyses were calculated using the numerical error propagation method of Roddick (1987). The decay constants recommended by Steiger and Jäger (1975) and compositions for initial common Pb taken from the model of Stacey and Kramers (1977) were used for age calculations. Concordia intercept ages were calculated using a modified York II model (York, 1969; Parrish et al., 1987) and the algorithm of Ludwig (1980). All errors are given at the 2-sigma (95% confidence) level.

Age determinations

Analytical data are given in Table 1 and shown on conventional concordia plots in Figure 7; the interpreted ages are indicated in Figure 3, tabulated in Table 2, and summarized in Figure 8.

Cold Fish Volcanics. Zircons were dated from four samples of the Cold Fish Volcanics. Sample 1 was collected form a reddish-brown weathering rhyolite sill within a felsic ignimbrite-sill sequence. The zircons of fractions A to E are generally clear and colorless, stubby to slightly elongate euhedral prisms, with scattered tube- and rod-shaped inclusions, and without visible cores. The error envelopes of fractions A, C, D, and E overlap one another and plot on or near concordia (Fig. 7a). This close agreement suggests that no inherited zircon component was present in any of the fractions analyzed. The weighted average $^{207}Pb/^{206}Pb$ of the four analyses is 194.8 ± 1.0 Ma. The crystallization age of the sill cannot be younger than the $^{206}Pb/^{238}U$ age of the most concordant fraction (E) at 192.2 ± 0.4 Ma. We therefore assign an age of 194.8 + 1.0/–3.0 Ma to the sample. Fraction B plots to the right and yields a slightly older $^{207}Pb/^{206}Pb$ age of 206.9 ± 1.8 Ma, indicating that it contains an older, inherited zircon component. Single grain fractions F and G had slightly anhedral "frosted" surfaces and were suspected of being xenocrysts. Although these analyses are considerably less precise than those of the multigrain fractions, they yield somewhat older U/Pb ages, confirming that they are inherited from a slightly older source.

Sample 2 was collected from an altered, pyritic rhyolite dike. The dike belongs to a set of yellowish-white dikes which intrude the felsic sequence of sample 1. The zircon grains in this sample were similar in appearance to those from the sill, except that many of the grains were slightly cloudy and/or yellowish-brown. In Figure 7b, the data define a linear array with calculated upper and lower intercept ages of 194.0 +2.8/–2.3 Ma and –48 ± 25 Ma, respectively. The array appears to mainly reflect recent Pb loss, possibly related to acidic conditions caused by breakdown of pyrite during surface weathering. However, the slightly negative lower intercept age indicates that a minor inherited zircon component was present in at least the more discordant fractions (C, D, and E). The most concordant fractions (A and B) have overlapping $^{207}Pb/^{206}Pb$ ages, with a weighted average age of 196.6 ± 1.6 Ma. We consider this to be the best estimate of the crystallization age of the unit. However, we cannot completely rule out the possibility that a small amount of inherited zircon was present in these fractions as well, in which case the average age can only be considered a maximum crystallization age.

Sample 3 was collected from a densely welded rhyolitic ignimbrite sheet near the top of the Cold Fish succession. Like the zircons from sample 1, those from this sample are clear, colorless (to very pale yellow), euhedral stubby prisms with some inclusions and almost no visible zoning. The three most precise analyses (fractions A, B, and C) have a weighted aver-

TABLE 1. U-Pb ANALYTICAL DATA

	Fraction Size†	Weight (mg)	U (ppm)	Pb† (ppm)	$^{206}Pb^{§}/^{204}Pb$	$^{208}Pb^{†}$ (%)	$^{206}Pb^{**}/^{238}U$	$^{207}Pb^{**}/^{235}U$	$^{207}Pb^{**}/^{206}Pb$	$^{207}Pb/^{206}Pb$ Age‡
	Sample 1. GAT-87-157-2 (Cold Fish Volcanics)									
A	N2,+74	0.103	856	26.2	9,209	10.7	0.03027 (0.10)	0.2087 (0.11)	0.05000 (0.03)	194.9 (1.5)
B	N2,-74	0.105	671	20.5	6,359	10.4	0.03034 (0.11)	0.2102 (0.12)	0.05026 (0.04)	206.9 (1.8)
C	M2,+74-105	0.120	870	26.7	5,948	11.1	0.03024 (0.11)	0.2085 (0.12)	0.05001 (0.04)	195.5 (1.7)
D	M2,+74-105	0.110	920	28.4	2,665	11.5	0.03018 (0.10)	0.2080 (0.13)	0.04998 (0.06)	194.2 (2.7)
E	M2,+74-105	0.029	1,101	34.0	2,422	11.5	0.03017 (0.09)	0.2085 (0.12)	0.04996 (0.06)	193.3 (2.9)
F	N2,+74,s	0.003	1,047	33.1	383	11.0	0.03113 (0.16)	0.2156 (0.86)	0.05025 (0.76)	206.5 (35.4)
G	N2,+74,s	0.005	318	9.4	109	4.5	0.03143 (0.42)	0.2136 (2.43)	0.04930 (2.1)	162.0 (100.5)
	Sample 2. GAT-87-159-2 (Cold Fish Volcanics)									
A	N1,+74-105	0.124	1,195	34.4	6,212	10.3	0.02857 (0.13)	0.1971 (0.14)	0.05004 (0.04)	196.7 (1.9)
B	N2,+74-105	0.251	1,149	33.7	2,474	10.8	0.02900 (0.14)	0.2000 (0.17)	0.05003 (0.07)	196.3 (3.0)
C	N3,-105	0.376	1,561	41.6	12,340	10.7	0.02637 (0.05)	0.1822 (0.50)	0.05012 (0.03)	200.3 (0.14)
D	N3,+105	0.219	1,120	31.7	1,247	10.7	0.02797 (0.13)	0.1934 (0.19)	0.05016 (0.11)	202.4 (5.3)
E	N3,+74-105	0.289	1,528	40.4	9,898	10.3	0.02623 (0.19)	0.1813 (0.20)	0.05014 (0.03)	201.7 (1.5)
	Sample 3. GAT-86-56-3 (Cold Fish Volcanics)									
A	N1,+105,<M	0.076	517	15.6	2,807	10.8	0.02981 (0.09)	0.2054 (0.11)	0.04997 (0.05)	193.4 (2.1)
B	N1,+105,>M	0.259	558	16.9	6.663	10.8	0.02988 (0.11)	0.2058 (0.12)	0.04997 (0.04)	193.6 (1.7)
C	N2,+74,u	0.167	592	17.8	3,426	11.5	0.02943 (0.11)	0.2029 (0.13)	0.05000 (0.05)	195.1 (2.3)
D	N2,+74	0.045	540	16.3	1,683	10.5	0.02986 (0.09)	0.2054 (0.15)	0.04990 (0.10)	190.3 (4.7)
	Sample 4. GAT-87-181-2 (Cold Fish Volcanics)									
A	N2,-105,u	0.057	248	7.9	1,178	16.1	0.02966 (0.10)	0.2045 (0.21)	0.05001 (0.16)	195.4 (7.5)
B	N3,+105	0.019	1,917	67.1	3.745	16.0	0.03243 (0.09)	0.2398 (0.10)	0.05363 (0.04)	355.7 (1.8)
C	M2,-105	0.069	649	21.1	3,143	16.3	0.03017 (0.09)	0.2079 (0.11)	0.04997 (0.04)	193.5 (2.0)
D	N1,-105,u	0.312	278	8.9	2,543	16.3	0.02977 (0.10)	0.2058 (0.12)	0.05013 (0.06)	201.1 (2.7)
E	M2,-74	0.039	302	9.7	788	15.2	0.03006 (0.15)	0.2084 (0.33)	0.05027 (0.29)	207.6 (13.7)
	Sample 5. GAT-86-111-6 (Spatsizi River Stock)									
A	N2,+74	0.040	303	10.1	832	17.8	0.03035)0.10)	0.2099 (0.20)	0.05015 (0.15)	202.1 (7.0)
B	N2,+74-105	0.175	269	8.9	3,665	17.8	0.03016 (0.10)	0.2080 (0.11)	0.05003 (0.05)	196.4 (2.5)
C	N2,+105	0.146	2,539	84.0	3,846	17.6	0.03017 (0.09)	0.2081 (0.11)	0.05001 (0.05)	195.5 (2.2)
D	M2,+74-105	0.134	386	13.0	1,859	19.5	0.03013 (0.09)	0.2077 (0.13)	0.04999 (0.07)	194.4 (3.3)
	Sample 6. GAT-87-219-4 (Griffith Creek Volcanics)									
A	N1,+105,<M	0.575	225	7.1	5,217	8.6	0.03190 (0.11)	0.2210 (0.12)	0.05024 (0.04)	206.1 (1.9)
B	N1,+105,<M	0.180	206	6.5	2,331	8.7	0.03182 (0.10)	0.2206 (0.14)	0.05027 (0.08)	207.5 (3.6)
C	N1,+105	0.569	235	7.4	8.720	8.7	0.03175 (0.11)	0.2199 (0.12)	0.0523 (0.04)	205.7 (1.6)
D	N1,+74-105,<M	0.845	233	7.3	6,310	9.0	0.03166 (0.17)	0.2192 (0.18)	0.05022 (0.04)	205.4 (1.9)
E	N1,+74-105	0.456	230	7.2	7,710	9.0	0.03167 (0.09)	0.2193 (0.11)	0.05022 (0.04)	205.3 (2.0)
	Sample 7. GAT-87-234-3 (Griffith Creek Volcanics)									
A	N1,+105,<M,s	0.720	224	7.1	3,365	8.5	0.03201 (0.10)	0.2216 (0.12)	0.05022 (0.05)	205.0 (2.4)
B	N1,+105,<M,p	0.338	253	8.2	3,750	9.3	0.03241 (0.08)	0.2247 (0.10)	0.05028 (0.05)	207.7 (2.3)
C	N1,+74-105	0.558	315	9.9	9,021	9.6	0.03147 (0.08)	0.2181 (0.10)	0.05025 (0.03)	206.4 (1.6)
D	N1,+105,<M,e	0.116	209	6.6	1,348	8.5	0.03200 (0.09)	0.2213 (0.16)	0.05016 (0.11)	202.4 (4.9)

Note: Decay constants used are those of Steiger and Jäger, 1977. Initial common Pb compositions are from Stacey and Kramers, 1975.

*Sizes (-74+62) refer to length aspect of zircons in microns (i.e., through 74-micron sieve but not the 62-micron sieve); N1,2 = nonmagnetic cut with Frantz at 1° or 2° side slope; M = magnetic; u = unabraded; s = stubby prisms; e = equant; p = elongate prisms.

†Radiogenic Pb.

§Measured ratio, corrected for spike and fractionation.

**Corrected for blank Pb and U and common Pb (errors quoted are 1σ in percent).

‡Corrected for blank and common Pb (errors are 2σ in Ma).

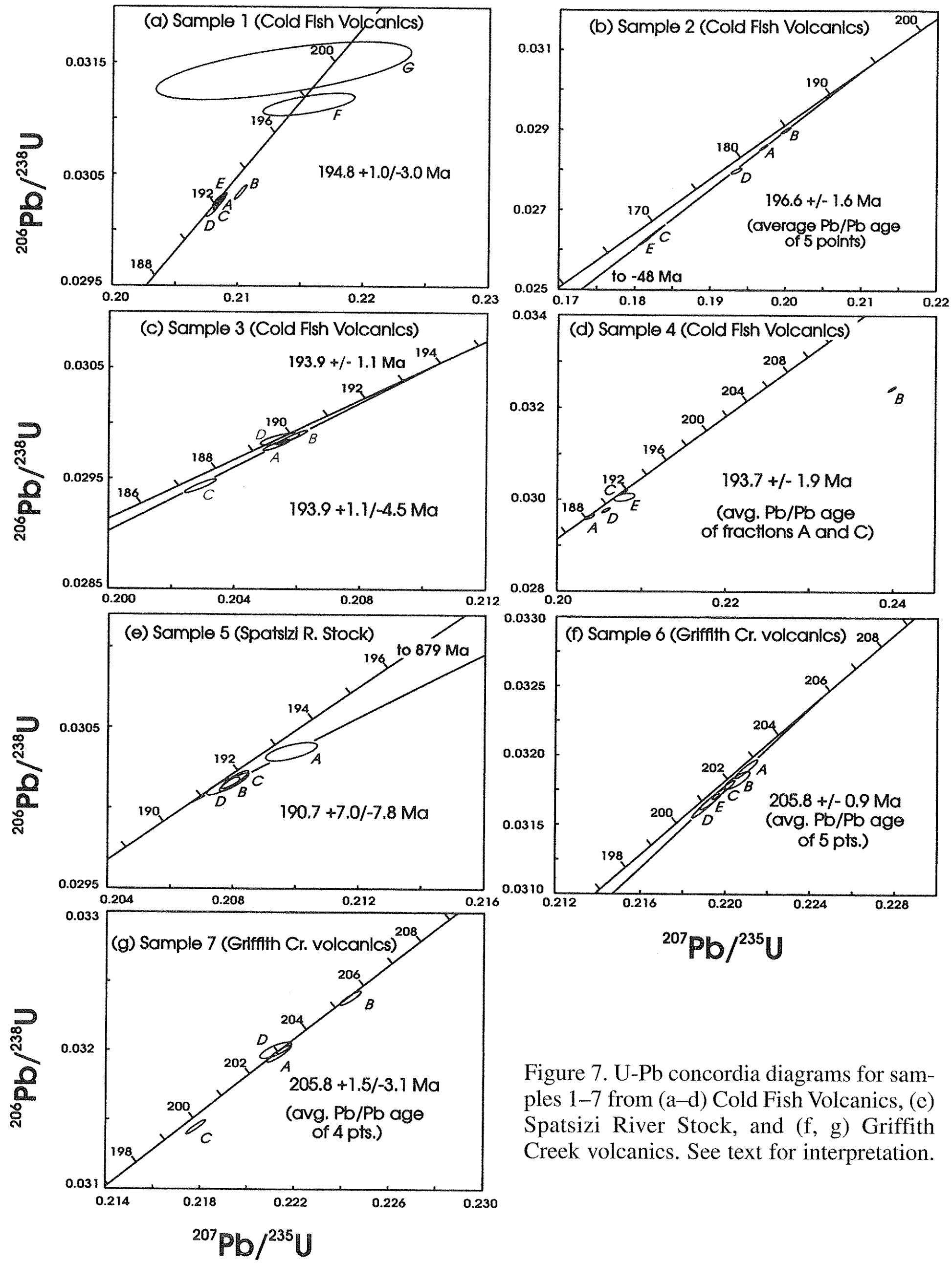

Figure 7. U-Pb concordia diagrams for samples 1–7 from (a–d) Cold Fish Volcanics, (e) Spatsizi River Stock, and (f, g) Griffith Creek volcanics. See text for interpretation.

age $^{207}Pb/^{206}Pb$ age of 193.9 ± 1.1 Ma (Fig. 7c). The analysis of fraction D is concordant but somewhat less precise than the other analyses. The crystallization age cannot be younger than the $^{206}Pb/^{238}U$ age of this fraction at 189.7 ± 0.3 Ma. We therefore assign an age of 193.9 +1.1/–4.5 Ma to this unit.

Sample 4 was collected from a porphyritic rhyolite sill. Its zircons are clear and euhedral, without visible cores, and generally similar to those from sample 3. In Figure 7d, four of the analyses (A, C, D, and E) plot slightly below or marginally overlap the concordia curve. Of these, fractions A and C are least discordant and have $^{207}Pb/^{206}Pb$ ages of 195.4 ± 7.5 Ma and 193.5 ± 2.0 Ma, respectively. The scatter in the data makes is difficult to assign a precise crystallization age to the sample; however, it is unlikely to be significantly older than the $^{207}Pb/^{206}Pb$ age of the most concordant fraction (C). The good agreement between the $^{207}Pb/^{206}Pb$ ages of fractions A and C suggests that they may be free of any inherited component. We interpret the weighted average $^{207}Pb/^{206}Pb$ age of the two fractions (193.7 ± 1.9 Ma) to be the best estimate for the emplacement age of the unit. Fractions D and E have older $^{207}Pb/^{206}Pb$ ages of 201.1 ± 2.7 and 207.6 ± 13.7 Ma, implying a component of zircon inheritance. Point B plots much farther away from the concordia, reflecting significant inheritance from zircon of Precambrian, possibly Middle Proterozoic age.

Spatsizi River Stock. Sample 5 was collected from fine-grained alkali feldspar granite of the Spatsizi River Stock. The

TABLE 2. INTERPRETED AGES AND LOCATIONS OF U/Pb ZIRCON SAMPLES

Sample	Field Number	Rock Type	Location UTM* E	Location UTM N	Age (Ma)	Uncertainty (2σ)
Cold Fish Volcanics						
1	87-157-2	Rhyolite sill	510400	6389600	194.8	+1.0/-3.0
2	87-159-2	Rhyolite dike	509400	6389600	196.6	±1.6
3	86-56-3	Rhyolite ignimbrite	504900	6371700	193.9	+1.1/-4.5
4	87-181-2	Rhyolite sill	515000	6376300	193.7	±1.9
Spatsizi River Stock						
5	86-111-6	Alkali-feldspar granite	520600	6378100	190.7	+7.0/-7.8
Griffith Creek volcanics						
6	87-219-4	Basaltic andesite lava	532300	6370100	205.8	±0.9
7	87-234-3	Dacite sill	528100	6372900	205.8	+1.5/-3.1

Note: UTM = universal transverse Mercator.

stock is chemically indistinguishable from rhyolites of the Cold Fish Volcanics and is crosscut by mafic dikes that have been correlated with the mafic component of the Cold Fish (Thorkelson, 1992). The zircons are clear, colorless, stubby euhedral prisms with abundant clear inclusions, and minor opaque inclusions. Zoning is common, but cores are not visible. The data form a tightly clustered array extending from very near concordia at about 192 Ma toward older model ages. A best-fit line through the array of Figure 7e has a lower intercept age of 190.7 +0.6/–7.8 Ma, and a very imprecise upper intercept age of 879 +748/–600 Ma. Despite its imprecision, the upper intercept supports the interpretation of Precambrian inheritance noted for the previous sample from a rhyolite sill. Allowing for the possibility of Pb loss from some or all of the fractions, the calculated lower intercept is interpreted as a minimum crystallization age for the sample. The stock is unlikely to be significantly older than the $^{207}Pb/^{206}Pb$ age of the most concordant fraction at 194.4 ± 3.3 Ma. We therefore assign an age of 190.7 +7.0/–7.8 Ma to the sample to incorporate errors for both the calculated lower intercept and the $^{207}Pb/^{206}Pb$ age of fraction D. This age overlaps with the interpreted ages of all of the Cold Fish samples.

Griffith Creek volcanics. Sample 6 was collected from a hornblende- and plagioclase-phyric lava flow of basaltic andesite composition east of Spatsizi River. The flow lies above a succession of coarse conglomerate (Thorkelson, 1988) and is the basal flow of the Griffith Creek formation at this location.

The zircons of this sample differ from those of the Cold Fish Volcanics and the Spatsizi River Stock by their slightly pink color and greater relative abundance of multifaceted, equant grains. The grains are clear and euhedral, with faint zoning, and commonly contain small, colorless inclusions. The five analyses have overlapping $^{207}Pb/^{206}Pb$ ages, suggesting that there was no inherited zircon present in any of the fractions analyzed. The data form a short linear array (Fig. 7f) that is too

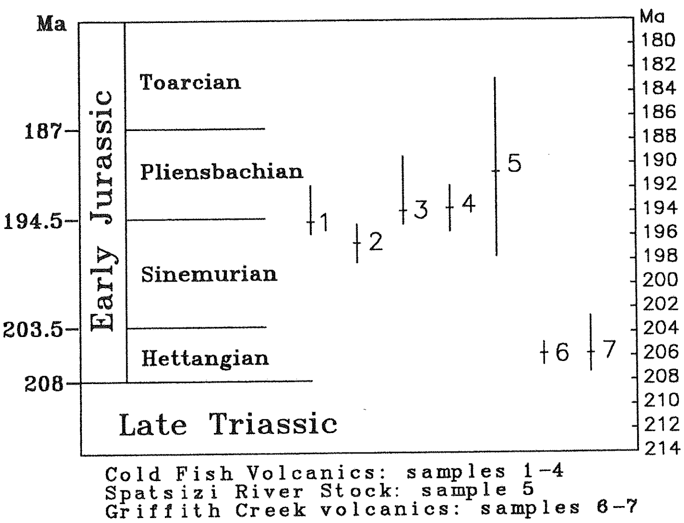

Figure 8. Graph summarizing interpreted U-Pb zircon ages (2-sigma uncertainty) using time scale of Harland et al. (1990).

short to yield meaningful concordia intercept ages. The weighted average $^{207}Pb/^{206}Pb$ age of the five fractions is 205.8 ± 0.9 Ma, which is interpreted as the age of the lava flow.

Sample 7 was obtained from a slightly crosscutting sill of the Griffith Creek volcanics that was emplaced into underlying conglomerate and rocks of the Stuhini Group. The sill is of dacitic composition, with abundant phenocrysts of plagioclase, hornblende, perthite, biotite, and quartz. Three of the four zircon fractions (A, B, and D) fall on or very close to concordia (Fig. 7g), and the $^{207}Pb/^{206}Pb$ ages of all four fractions all overlap at the 2-sigma level, suggesting an absence of inheritance. A weighted average $^{207}Pb/^{206}Pb$ age for the four fractions is 205.8 ± 1.5 Ma. The sample cannot be younger than the $^{206}Pb/^{238}U$ age of fraction D at 203.1 ± 0.4 Ma. Incorporating both of these error constraints gives an age of 205.8 +1.5/–3.1 Ma, which we consider to be the age of the sill.

Zircon inheritance

Zircon fractions in three of the samples (1, 4, and 5) are considered to have inherited some of their isotopic character in the from of cryptic zircon cores. Some of the inherited zircon appears to be slightly older than the Hazelton Group, although some of the inherited zircon is clearly much older and is interpreted to be Precambrian in age. Inheritance of "slightly older" zircon is evident in fractions which plot near concordia, with $^{207}Pb/^{206}Pb$ model ages that are not much older than the interpreted age of the host rock (e.g., sample 1, fractions F and G; Fig. 7a). The age of the inherited component in these samples is probably either Late Triassic, derived from Late Triassic plutonic rocks coeval with the Stuhini Group (Anderson, 1983; Read and Psutka, 1990), or Devonian to Permian, derived from igneous rocks of the Stikine assemblage (Brown et al., 1991). Precambrian inheritance is clearly indicated by the old $^{207}Pb/^{206}Pb$ model ages and relatively high degree of discordance of fraction B of sample 4 (Cold Fish Volcanics; Fig. 7d), and fraction A of sample 5 (Spatsizi River Stock; Fig. 7e). In particular, fraction B of sample 4 contained a significant amount of "old Pb" which was probably Proterozoic in age.

Summary of U-Pb geochronology

The interpreted ages of all the analyzed samples are summarized in Figure 8 and Table 2. The isotopic ages of the four samples from the Cold Fish Volcanics cluster around 194 Ma, with a total range in uncertainty extending from 189.4 Ma to 198.2 Ma, corresponding to latest Sinemurian to late Pliensbachian on the time scale of Harland et al. (1990). This corroborates the Early Pliensbachian biostratigraphic (ammonite) age provided by Thomson et al. (1986). The age we obtained for the Spatsizi River Stock overlaps the Cold Fish ages and is consistent with the field and petrologic evidence indicating that the stock was emplaced as a subvolcanic intrusion during deposition of the Cold Fish Volcanics. Dated at ca. 206 Ma, the Griffith Creek volcanics are older than the Cold Fish succession by approximately 12 million years (Table 2), and correspond to an Hettangian to lower Sinemurian age on the Harland et al. (1990) time scale (Fig. 8).

The crust underlying the study area in the Early Jurassic contributed a component of Precambrian zircon to some of the fractions analyzed. Whether the source of this contaminant was crystalline basement of Precambrian age, or a sedimentary or metasedimentary succession derived from the erosion of a Precambrian terrane, is unknown. However, none of the pre-Jurassic rocks exposed on Stikinia (Devonian to Triassic; Brown et al, 1991) have been recognized as sedimentary derivatives of Precambrian rock, and all have primitive isotopic signatures (Gabrielse et al., 1980; Armstrong, 1988; Samson et al., 1989). Therefore, if the source of the contaminant were sedimentary rock of Precambrian provenance, its depositional age would almost certainly be Early Paleozoic or Precambrian.

Our finding of Precambrian inheritance demonstrates that eastern Stikinia was underlain, at least partly, by rock of Precambrian age or provenance in Early Jurassic time (Fig. 6). It corroborates the recent discovery of Precambrian xenocrystic zircon in the Late Triassic (211 +7/–5 Ma) Zippa Mountain syenite complex in western Stikinia (Bevier and Anderson, 1991; M. L. Bevier, personal communication, 1991). Furthermore, it lends support to the suggestions of Gehrels et al. (1990), Samson et al. (1991), Mortensen (1992), McClelland (1992), and Johnston (1993) that Stikinia may be partly equivalent to the Nisling Terrane (Fig. 1), the basement of which is probably Precambrian.

TECTONIC SYNTHESIS

Episodic volcanism in the Spatsizi River map area resulted in the deposition of three temporally distinct volcanic successions spanning approximately 20 m.y. Each episode was preceded by a hiatus in volcanism. The Griffith Creek volcanics, deposited in Hettangian to early Sinemurian time, were folded along with underlying Stuhini Group strata prior to early Pliensbachian deposition of the Cold Fish Volcanics. This Early Jurassic deformation may be equivalent to Late Triassic to Early Jurassic (Toarcian) deformation documented by Brown et al. (1992) in strata 140 km to the west-southwest and tectonically related to Late Triassic Early Jurassic deformation in the Nisling Terrane (part of terrane unit CPM, west of Whitehorse; Fig. 1) described by Johnston and Erdmer (this volume). Cold Fish volcanism was succeeded by conformable deposition of Lower Pliensbachian to Middle Jurassic sedimentary strata. The Mount Brock volcanics, to the northwest of the Cold Fish, were erupted during deposition of the Early to Middle Toarcian part of the sedimentary succession.

The volcanic successions were deposited as part of a volcanic chain built along the eastern margin of the Hazelton Trough, an interarc basin separating eastern and western volcanic arcs on Stikinia (Fig. 2). Stratigraphic records of marine conditions interspersed with and following subaerial volcanism in the Spatsizi River area corroborate evidence of protracted subsidence elsewhere in the Hazelton Trough (Tipper and Richards, 1976; Marsden and Thorkelson, 1992). The net amount of crustal subsidence can be estimated, for a given period of time, from the sum of (1) the thickness of the subaerial succession, (2) the elevation of the succession at the time of its deposition, (3) the thickness of the overlying marine sedimentary rock, (4) the estimated height of the water column at the end of the period, and (5) the net change in eustatic sea level (subtract this amount if sea level rose). In Early Pliensbachian to Middle Toarcian time, an estimated minimum 2,000 m of subaerial Cold Fish rocks became overlain by approximately 350 m of marine sedimentary strata, under a water column of perhaps 300 m (as suggested by faunal depth zone D of Taylor, 1982; Thomson et al., 1986). Sea level rose eustatically by no more than 50 m during this interval (Hallam, 1981; Vail and Todd, 1981). How far above sea level the Cold Fish strata were deposited is unknown. Crustal subsidence in the region of Cold Fish volcanism, from Early Pliensbachian to Middle Toarcian time, is thereby estimated at more than 2,600 m (Fig. 9). Similar calculations using strata of the Mount Brock volcanics indicate that subsidence in the northwestern part of the study area (Fig. 3), from Early to Middle Toarcian time, was at least 2,000 m.

Regional subsidence in the trough by thousands of meters is likely to be tectonic in origin and probably reflects modest degrees of lithospheric extension concurrent with Early Jurassic subduction and arc volcanism. Extension probably began in the latest Triassic or earliest Jurassic, immediately following a period of regional uplift and widespread conglomerate deposition (Tipper and Richards, 1976; Thorkelson, 1988; Anderson and Thorkelson, 1990; Marsden and Thorkelson, 1992). Processes contributing to the subsidence probably include thermal subsidence following magmatic episodes (cf. Karig and Moore, 1975), caldera formation, and local crustal foundering during rapid evisceration of subvolcanic magma chambers. Subsequent regional marine transgression of Stikinia in the early Middle Jurassic was partly related to flexural depression of Stikinia caused by incipient obduction of the Cache Creek Terrane (Ricketts and Evenchick, 1991) and partly to thermal subsidence coincident with waning and extinction of Hazelton volcanism.

Although Early Jurassic extension and subsidence of Stikinia was concentrated in the Hazelton Trough, peripheral areas were also affected (Marsden and Thorkelson, 1992). In the Toodoggone River area, about 50 km east of the Spatsizi River area (Fig. 2), volcanism was concurrent with block faulting. There, a succession of subaerially deposited volcanic rocks of predominantly intermediate composition known informally as the Toodoggone formation (Carter, 1972; Marsden, 1990; Diakow et al., 1991) was interpreted by Diakow et al. (1991) to have been deposited under extensional conditions in an elongate synvolcanic depression. K-Ar isotopic ages from the Toodoggone span much of the Early Jurassic, but recent $^{40}Ar/^{39}Ar$ determinations (Clark and Williams-Jones, 1991) suggest that most of the Toodoggone volcanism occurred ca. 194 Ma, coincident with eruption of the Cold Fish Volcanics (Fig. 10). However, the partly marine setting, silica bimodality, and tholeiitic to alkaline chemical character of the Cold Fish contrasts with the completely subaerial environment and calc-alkaline composition of the Toodoggone formation. These differences may be explained in terms of tectonic environment, with the Toodoggone formation representing eruption and graben development in a frontal arc setting (Diakow et al., 1991), and the Cold Fish Volcanics representing concurrent back-arc volcanism on the margin of the Hazelton Trough.

Hazelton volcanism was succeeded by clastic deposition of the Middle Jurassic to Lower Cretaceous Bowser Lake Group (Figs. 1, 4). The aerial extent of these deposits define the Bowser Basin, which inherited its basic form from the Hazelton Trough, and not through a separate phase of extensional tectonism. For 60 m.y. prior to the inception of Bowser Lake Group sedimentation, Stikinia hosed episodic, voluminous arc magmatism (Stuhini and Hazelton Groups and related intrusions). Consequently, in the early Middle Jurassic, Stikinia is likely to have been a region of high heat flow (cf. Watanabe et al., 1977),

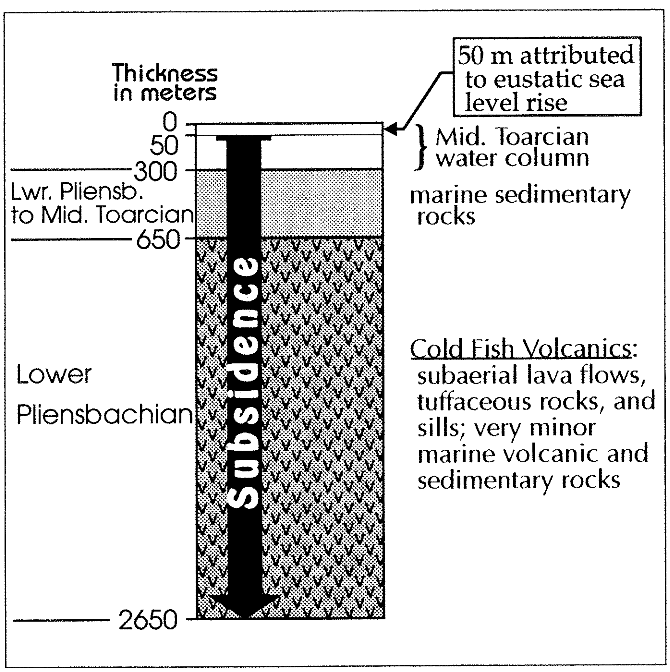

Figure 9. Crustal subsidence of the Cold Fish Volcanics from Early Pliensbachian to Middle Toarcian time. Minimum subsidence of 2,600 m is based on estimated minimum 2,000 m of subaerially deposited volcanic rocks, measured 350-m overlying marine sedimentary rocks, estimated 300-m water depth in Middle Toarcian time, and maximum 50-m eustatic sea level rise. Details and references given in text.

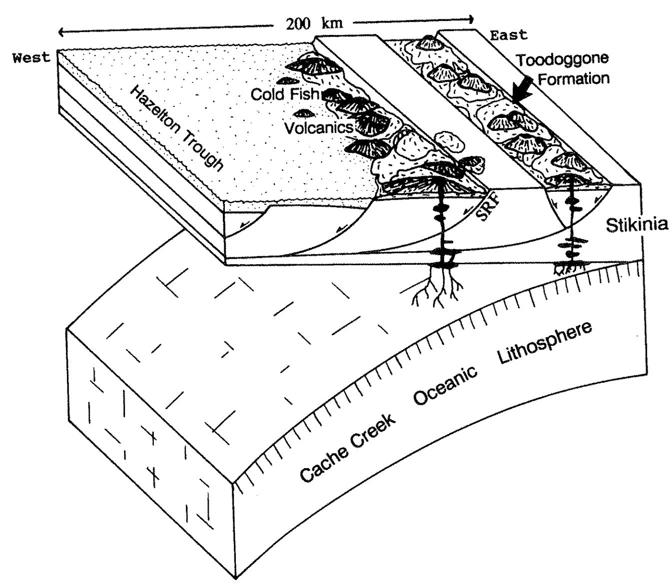

Figure 10. Extensional tectonic conditions in northeastern Stikinia during Pliensbachian time, showing deposition of Toodoggone formation in synvolcanic depression and eruption of Cold Fish Volcanics behind the Toodoggone arc along eastern margin of subsiding Hazelton Trough.

and Stikinian crust is likely to have directly overlain metasomatized asthenosphere (cf. Gill, 1981). Extension of Stikinia during this period would almost certainly have been coupled with alkalic to tholeiitic mafic magmatism, in the manner of Late Cenozoic back arcs and rifted arcs of the western Pacific (Weaver et al., 1979; Lordkipanidze et al., 1979; Taylor and Karner, 1983; Tamaki, 1985; Gill and Whelan, 1989). However, the Stikinian stratigraphic record indicates diminishing Hazelton volcanism toward the end of Early Jurassic time, and no magmatism whatsoever in the proximity of the basin during deposition of the lower Bowser Lake Group. The only igneous rocks of Jurassic age within the Bowser Basin are the Upper Jurassic Netalzul volcanics, a set of minor successions along the eastern and southern margins of the basin (Tipper and Richards, 1976). It is therefore most probable that the amount of extension within the Hazelton Trough lessened during the evolution of the Hazelton Group, becoming virtually nil by the time of earliest Bowser Lake Group sedimentation. The Bowser Lake Group thus infilled an existing marine basin that was centered by the Hazelton Trough and flanked by eroded and subsided remnants of Hazelton volcanoes.

Inheritance of Precambrian zircon in rhyolite of the Cold Fish Volcanics, and in syenite in western Stikinia (Bevier and Anderson, 1991) implies presence of a Lower Paleozoic or Precambrian basement during magmatism (Fig. 6). This possibility is supported by two mineralogical and geochemical aspects of the Cold Fish rhyolites that may indicate magmatic assimilation or crustal anatexis of siliceous basement. Specifically, the rhyolites are characterized by (1) high-silica compositions in conjunction with a "Daly gap" in silica contents between the rhyolites and Cold Fish mafic rocks and (2) high fluorine concentrations. Both of these characteristics are typical features of rhyolites and granites common in felsic and silica-bimodal complexes built above evolved crust (Bacon and Duffield, 1981; Rye et al., 1990; Heinrich, 1990; Creaser et al., 1991), but they are scarce in island arcs built on primitive lithosphere. Further analysis of Cold Fish rhyolites and other siliceous Hazelton Group rocks may provide additional evidence of an "old" crustal basement to Stikinia.

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