LA-ICP-MS geochronology of the Greenwood gabbro, Knob Hill complex, southern Okanagan, British Columbia

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Abstract

The Paleozoic basement of Quesnellia in the southern Okanagan region includes rocks of the Knob Hill complex, an ophiolitic suite of gabbros, serpentinites, basaltic rocks, cherts, and argillites. Near the towns of Rock Creek and Greenwood, the Knob Hill complex is exposed in an east-trending belt of inliers within south-vergent thrust panels. These rocks are considered to record intraoceanic arc to back-arc basin environments, but precise U-Pb zircon ages have been lacking. Using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), four samples of pegmatitic gabbro from the Greenwood gabbro unit of the Knob Hill complex yielded U-Pb zircon ages of: 389.3 ±2.5 Ma; 387.3 ±2.5 Ma; 386.9 ±3.0 Ma; and 380.0 ±2.9 Ma (all errors at the 2σ level). Together with tectonostratigraphic and geochemical data, the new ages indicate that intraoceanic subduction processes represented by the Knob Hill complex began as early as 390-380 Ma, entirely outboard of Laurentia. Combined with sparse paleontologic age determinations, these new ages help reveal a protracted history in the Knob Hill complex, spanning the interval from ~390 to 300 Ma, that is now largely masked by younger structures and cover rocks. With the notable exception of the Trail gneiss complex, exposed about 75 km northeast of Greenwood and with a published U-Pb zircon age of ~372 Ma, potentially equivalent rocks elsewhere in the Okanagan subterrane, such as the Anarchist Group west of Osoyoos, the Old Tom Formation southwest of Penticton, and the Palmer Mountain Greenstone in Washington State, remain undated.

Keywords: Quesnellia, Knob Hill complex, Greenwood gabbro, geochronology, Middle Devonian

1. Introduction

In 2005, the British Columbia Geological Survey initiated the Boundary Project to better characterize the lithological and geochemical variations of Paleozoic successions in the southern Okanagan region along the Canada-USA border (Massey 2006, 2007a, 2007b; Massey and Duffy 2008a, 2008b, 2008c). These successions form part of Quesnellia (Fig. 1), which consists mainly of: a Paleozoic basement of mafic and pelitic rocks; unconformably overlying Triassic and Jurassic volcanic and sedimentary rocks; and crosscutting suites of Triassic, Jurassic, and Eocene granitic intrusions. Ongoing tectonic syntheses (e.g., Nelson and Colpron, 2007; Colpron and Nelson, 2009; 2011) emphasize the distinction between Cordilleran terranes with a western Laurentian heritage and those that are entirely exotic to North America. In contrast to farther north, Paleozoic basement in southern Quesnellia (Okanagan subterrane of Monger, 1977; Peatfield, 1978) may not have been built on Laurentian crust (as interpreted by Thompson et al., 2006), but be entirely exotic (e.g., Simony et al., 2006; Colpron and Nelson, 2009). Essential to such evaluations are robust geochronological and geochemical data, hitherto lacking from Paleozoic rocks in the southern Okanagan.

Herein we present laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) data from zircons in gabbroic rocks of the Knob Hill complex (Fig. 2), a structurally disrupted ophiolitic suite of gabbros, serpentinites, basaltic rocks, cherts, and argillites (Little, 1983; Dostal et al., 2001). In a companion paper (Massey and Dostal, this volume) we present geochemical data from the Knob Hill complex and the Anarchist Group, a likely equivalent exposed in structural panels south and west of the complex. Four samples from outcrops of the Greenwood gabbro (Fig. 2) yielded U-Pb zircon ages of 390-380 Ma. These results, together with geochemical data (Massey and Dostal, this volume), and a juvenile εNd value of +7.2 (Ghosh, 1995) suggest that the Knob Hill complex records Middle to Late Devonian intraoceanic subduction processes outboard of North America. However, coupled with a Late Pennsylvanian to earliest Permian (~300 Ma) determination from radiolarians in a single chert sample (Cordey, in Massey,

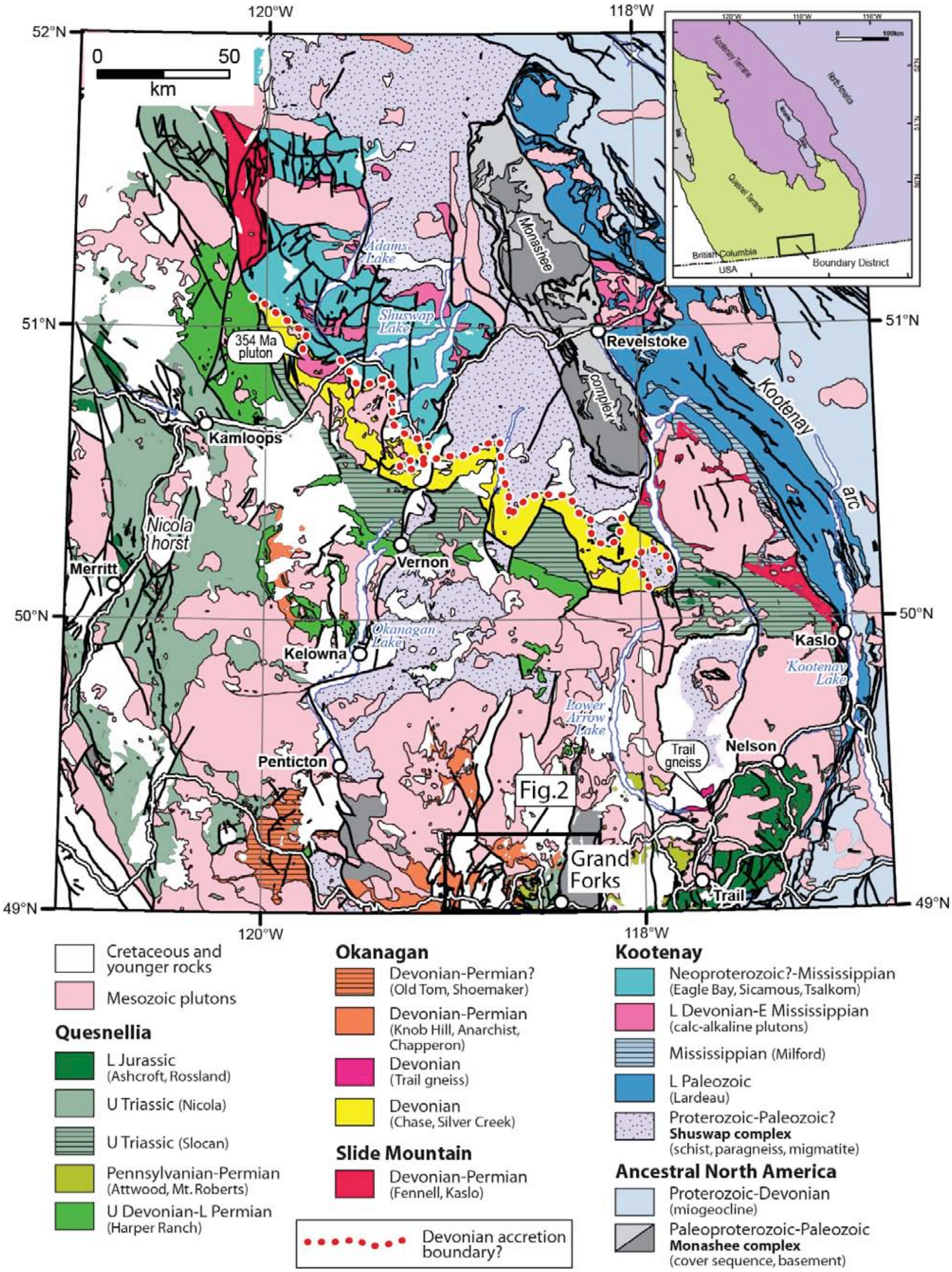

Fig. 1. Regional setting of the Knob Hill complex (after Colpron and Nelson, 2009). Inset, simplified terrane map of southeastern British Columbia (amended from digital geology of Massey et al., 2005).

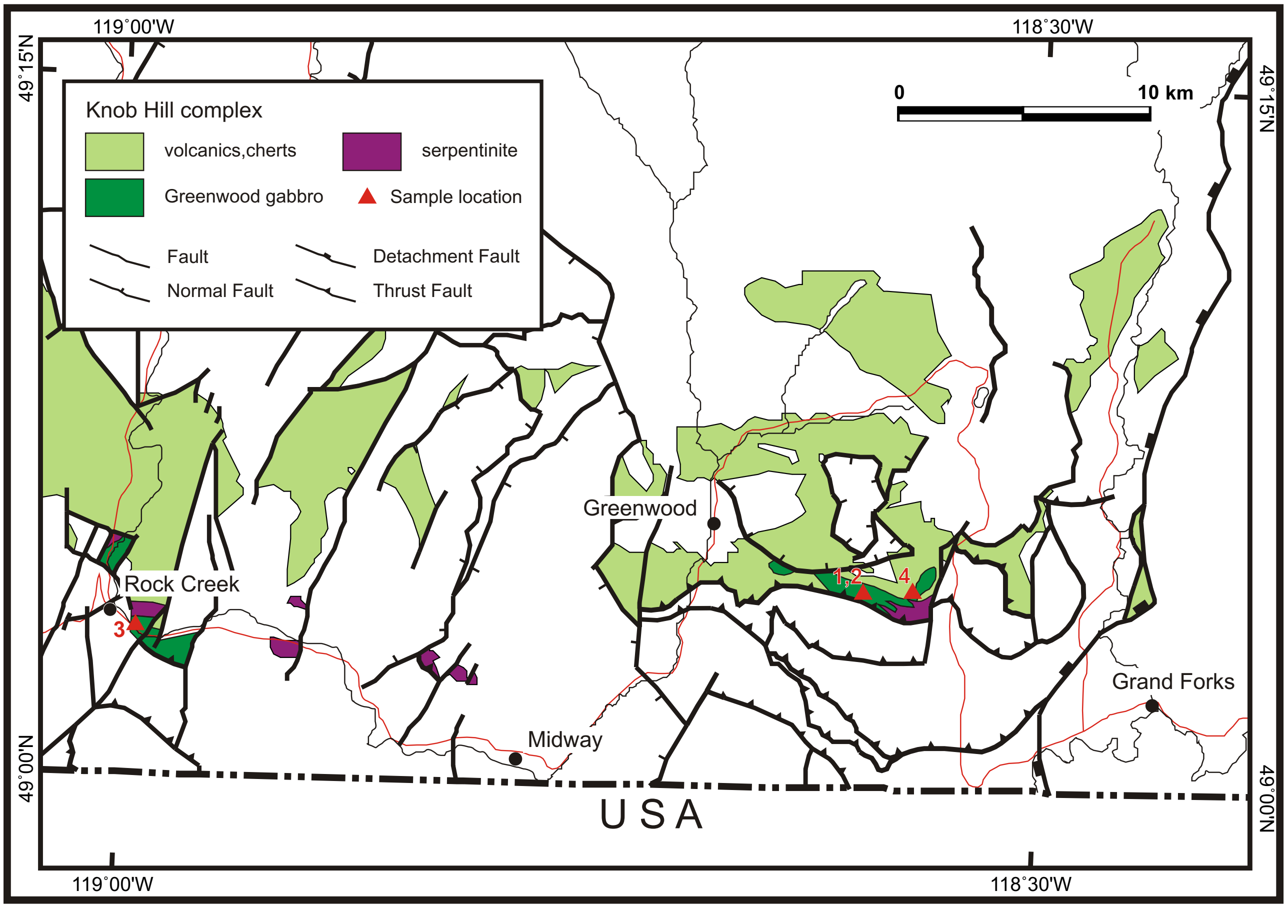

Fig. 2. Distribution of the Knob Hill complex succession; gabbro and serpentinite shown separately. Location of the gabbro sample sites, numbered as in Table 1. Geology amended from the digital geology map of British Columbia (Massey et al., 2005).

2007b), and a Late Devonian (385-375 Ma) determination from conodonts (Orchard, 1993), the U-Pb ages indicate that the geological record of the Knob Hill complex spans 80-90 million years, hinting at multiple, but structurally masked, tectonic environments.

2. Knob Hill complex and Greenwood gabbro

Interpreted stratigraphic arrangement of map units in the Kettle Valley River area north of Rock Creek (Fig. 2) suggests that Knob Hill complex constitutes a disrupted ophiolite (Little, 1983; Fyles, 1990; 1995). Gabbro and serpentinite pass northwards, and probably upwards, into greenstones, mixed greenstones and cherts, and finally into cherts and argillites (Massey, 2007a). Stratigraphic relationships between map units are less clear in the Greenwood area. However, outcrops along the power line adjacent to the Winnipeg Mine, east of Greenwood (location 4, Fig. 2), show well developed chilled margins in medium-grained diabase and microgabbro, suggesting they may be part of a yet to be delineated sheeted dike complex. The stratigraphic thickness of the Knob Hill complex is uncertain and difficult to estimate due to structural disruption. Nonetheless, Little (1983) suggested "a minimum of a few thousands of metres", and Fyles (1990, 1995) gave an estimate of at least 5 km.

The Greenwood gabbro was informally referred to as the "Old Diorite" by previous authors (e.g., Church, 1986) but renamed the "Greenwood gabbro" by Dostal et al. (2001), the term we use herein. The gabbros are composed of white plagioclase and green to black pyroxenes that have been extensively replaced by hornblende. Chlorite is common on fracture surfaces. The gabbros are characteristically variable and patchy in texture (Fig. 3a). Coarse-grained gabbro phases grade into finer microgabbro or even coarser pegmatitic phases (Fig. 3b), and chilled contacts are notably lacking. This suggests that different phases are co-magmatic and were injected over a short time interval. Light-coloured felsic veins (plagiogranite?) crisscross some outcrops (Fig. 3d). Diabase dikes crosscut the gabbro, but local diabase xenoliths in gabbro imply multiple injection episodes of both. Church (1986) reported a K-Ar whole rock age of 258 ±10 Ma (Permian) for uralitized gabbro from the Winnipeg Mine. However it is doubtful that this age records the time of crystallization.

3. Geochronology

Four coarse-grained samples from pegmatitic zones in the Greenwood gabbro were collected at three sites for U-Pb zircon geochronology (Fig. 2; Table 1).

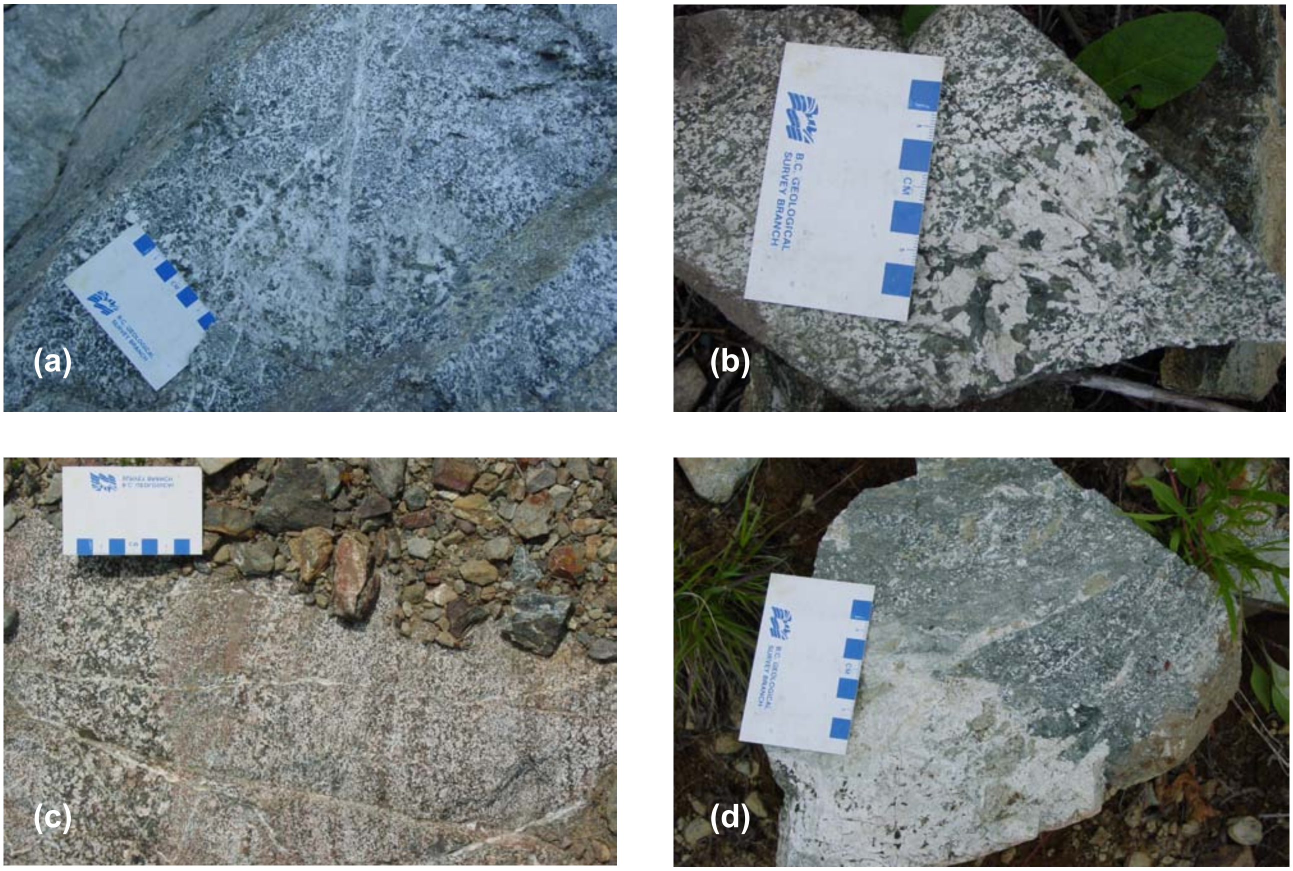

Fig. 3. Greenwood gabbro in outcrop. **a)** Typical varitextured gabbro, with white felsic vein network (05NMA21-02, UTM zone 11, 5436561N, 353922E NAD83). **b)** pegmatitic gabbro (05NMA02-03; UTM zone 11, 5436880N, 385180E NAD83). **c)** compositional and grain size layering (05NMA02-11; UTM zone 11, 5436808N, 385264E NAD83). **d)** plagiogranite dike in varitextured gabbro (05NMA02-11; UTM zone 11, 5436808N, 385264E NAD83).

Table 1. Summary of U-Pb zircon ages from Greenwood pegmatitic gabbro samples, Knob Hill complex. All UTM location data are in zone 11, NAD83. Errors associated with individual ages are listed at the 2σ level (95% confidence interval).

Sample number	Latitude	Longitude	UTM		Area	Age	
	°N	°W	Northing	Easting		Ma	±
05NMAWin	49.071680	118.586500	5436636	384128	Winner Quarry	380.0	2.9
06NMAWinner	49.071680	118.586500	5436636	384128	Winner Quarry	386.9	3.0
06NMAGABB1	49.064603	118.999792	5436564	353924	Rock Creek	389.0	2.9
06NMA04-004	49.074179	118.572028	5436892	385191	Powerline, N of Winnepeg Mine	387.3	2.5

3.1. Analytical methods

Uranium-lead dating of zircons was carried out at the Pacific Centre for Geochemical and Isotopic Research at the University of British Columbia, using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Instrumentation included a New Wave UP-213 laser ablation system and a ThermoFinnigan Element2 single collector, double-focusing, magnetic sector ICP-MS. Data acquisition and reduction protocols detailed by Tafti et al. (2009), are summarized below. Zircons were handpicked from the heavy mineral concentrate and mounted in an epoxy puck along with several grains of the Plešovice zircon standard (Sláma et al., 2007), together with an in-house, 197 Ma standard zircon, and brought to a very high polish. High quality portions of each grain (free of alteration, inclusions, or possible inherited cores) were selected for analysis. The surface of the mount was washed for 10 minutes with dilute nitric acid and rinsed in ultraclean water prior to analysis. Line scans rather than spot analyses were employed in order to minimize elemental fractionation during the analyses. Backgrounds were measured with the laser shutter closed for ten seconds, followed by data collection with the laser firing for approximately 29 seconds. The time-integrated signals were analysed using GLITTER software (Van Achterbergh et al., 2001; Griffin et al., 2008), which automatically subtracts background measurements, propagates all analytical errors, and calculates isotopic ratios and ages. Corrections for mass and elemental fractionation were made by bracketing analyses of unknown grains with replicate analyses of the Plešovice zircon standard. A typical analytical session consisted of four analyses of the standard zircon, followed by four analyses of unknown zircons, two standard analyses, four unknown analyses, etc., and finally four standard analyses. The 197 Ma in-house zircon standard was analysed as an unknown in order to monitor the reproducibility of the age determinations on a run-to-run basis. Final interpretation and plotting of the analytical results used Ludwig's (2003) ISOPLOT software. Interpreted ages are based on a weighted average of the individual calculated $^{206}Pb/^{238}U$ ages.

Although zircons typically contain negligible amounts of initial common Pb, it is important to monitor the amount of ^{204}Pb to evaluate the amount of initial common Pb, and/or blank Pb, in the zircons being analyzed. The argon that is used in an ICP-MS plasma commonly contains at least a small amount of Hg, and approximately 7% of natural Hg has a mass of 204. Measured count rates on mass 204 include ^{204}Hg as wellas any ^{204}Pb that might be present, and direct measurement of ^{204}Pb in a laser ablation analysis is therefore not possible. Instead, mass 202 is monitored; this corresponds exclusively to ^{202}Hg. The expected count rate for ^{204}Hg present in the analysis can then be calculated from the known isotopic composition of natural Hg, and any remaining counts at mass 204 can be attributed to ^{204}Pb. Using this method it is possible to conclude that there was no measurable ^{204}Pb present in any of the analyses in this study.

3.2. Results

Results of the dating studies are summarized in Table 1 and complete analytical data are presented in Table 2. Laser-ablation ICP-MS analyses of the four samples indicate ages that range between 380 and 390 Ma (Middle to Late Devonian; Fig. 4). The two samples from the Winner quarry (1 and 2 in Table 1, Fig. 2) show a spread of 6.9 Ma. Although this spread is only slightly greater than the 2σ error limits of the age determinations (Table 1), it could signify multiple intrusion events.

4. Discussion

Field tectonostratigraphic (e.g., Little, 1983; Fyles, 1990; 1995; Massey et al., 2010), geochemical (Dostal et al., 2001; Massey and Dostal, this volume), and Nd isotopic (Ghosh, 1995) studies indicate that the basement to Quesnellia in the southern Okanagan region represents growth of an intraoceanic subduction complex outboard of North America (Colpron and Nelson, 2009). Geochronologic data presented herein document that subduction processes initiated by at least 390-380 Ma. Previously, Little (1983) assigned a Carboniferous to Permian age to the Knob Hill complex, based on a single macro-fossil locality (his locality F7, page 12), about a kilometre east of the Winnipeg Mine (location 4, Fig. 2). However, this same limestone bed yielded conodonts of Late Devonian (Frasnian; 385-375 Ma) age (Orchard, 1993). Determinable radiolarians are rare in the cherts of the Knob Hill Complex, though one sample from the greenstone-chert sequence has yielded a Late Pennsylvanian to earliest Permian (~300 Ma) age (Cordey, in Massey, 2007b). The geochronologic data in the present paper, together with the sparse paleontologic data in Orchard (1993) and Cordey (in Massey, 2007b), suggest that the Knob Hill complex, as a whole, spans an interval of 80 to 90 million years, seemingly excessive for a single, small subduction-related basin (see Woodcock, 2004). This apparent longevity might imply cryptic tectonic processes and environments now masked by structural complexities and cover rocks.

Potential correlatives to the Knob Hill complex outcrop south and west of the Greenwood area, and include: the Anarchist Group (e.g., Massey et al., this volume); the Old Tom Formation (Bostock 1939, 1940) in the Keremeos area, southwest of Penticton; and the Palmer Mountain greenstone in Washington (Rinehart and Fox, 1972). Isotopic ages are currently unavailable for these units, although studies are ongoing in the Keremeos area (Mortensen et al., 2010). Possibly a tectonostratigraphic equivalent to the Knob Hill complex, the Trail gneiss complex (exposed ~75 km northeast of Greenwood) has yielded a U-Pb zircon age of ~372 Ma and positive initial εNd values (+4.7 - +5.6), and is thought to represent a Late Devonian intraoceanic arc lacking a North American heritage (Simony et al., 2006).

5. Conclusions

Laser-ablation ICP-MS analyses of zircons from four samples of pegmatitic gabbro from the Knob Hill Complex yield late Middle to early Late Devonian crystallization ages that range between 390 and 380 Ma. Together with field tectonostratigraphy, geochemical data, and Nd isotopic data, these ages indicate that the basement to Quesnellia in the southern Okanagan region may represent intraoceanic arc to back-arc environments developed outboard of, and unrelated to, Laurentia.

Acknowledgments

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Table 2. Laser ablation ICP-MS analytical data for zircons from Greenwood gabbro samples, Knob Hill Complex. Isotopic ratios and calculated ages for each zircon grain are listed with their associated errors at the 1σ level. “Rho” refers to the correlation coefficient between the calculated ratios of $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$.

	Isotopic ratios and one sigma errors							Calculated ages and one sigma errors						Background-corrected counts per second on individual masses							
Analysis	$^{207}Pb/^{206}Pb$	error	$^{207}Pb/^{235}U$	error	$^{206}Pb/^{238}U$	error	Rho	$^{207}Pb/^{206}Pb$	error	$^{207}Pb/^{235}U$	error	$^{206}Pb/^{238}U$	error	202	204	206	207	208	232	235	238
05NMA-WIN																					
1	0.04927	0.00391	0.41424	0.03499	0.06144	0.00146	0.28	160.6	175.62	351.9	25.12	384.4	8.85	24	48	1524	71	428	6184	161	16823
2	0.04773	0.00291	0.39467	0.026	0.0601	0.00127	0.32	84.8	139.55	337.8	18.93	376.2	7.71	9	39	7407	405	905	11632	837	84344
3	0.05329	0.00231	0.4566	0.02183	0.06178	0.00106	0.36	341.3	94.81	381.9	15.21	386.4	6.43	30	0	4607	257	147	1424	613	60458
4	0.05348	0.00155	0.44939	0.01415	0.06049	0.00073	0.38	349.2	64.38	376.9	9.92	378.6	4.43	1	0	14235	806	1942	21406	1646	166097
5	0.0554	0.00164	0.46544	0.01498	0.06066	0.00075	0.38	428.2	64.2	388	10.38	379.6	4.56	12	0	5183	279	1006	10974	590	60118
6	0.05282	0.00188	0.45125	0.01755	0.06115	0.00086	0.36	321	79.15	378.2	12.28	382.6	5.23	0	0	12242	720	1195	13547	1395	143764
7	0.0578	0.00182	0.49385	0.01709	0.06052	0.0008	0.38	522	67.92	407.5	11.62	378.8	4.86	0	0	5571	304	154	1798	742	73832
8	0.05229	0.00199	0.44292	0.01847	0.0609	0.00091	0.36	298.3	84.6	372.3	13	381.1	5.54	96	0	3034	166	548	6744	362	36536
9	0.05402	0.00266	0.44189	0.02371	0.05939	0.0011	0.35	371.6	106.65	371.6	16.7	371.9	6.68	21	5	5391	283	989	11831	608	62546
10	0.05199	0.00209	0.45027	0.01981	0.06177	0.00096	0.35	284.9	89.3	377.5	13.87	386.4	5.8	0	0	1720	112	253	3513	236	23520
11	0.06491	0.00476	0.46312	0.03674	0.05254	0.00147	0.35	771.6	147.06	386.4	25.5	330.1	9.02	37	5	6215	335	180	2678	826	82793
12	0.05342	0.00205	0.44495	0.01861	0.0604	0.0009	0.36	346.5	84.27	373.7	13.07	378	5.47	21	26	18	0	0	0	0	0
13	0.05573	0.00209	0.45556	0.01867	0.06082	0.00089	0.36	441.2	81.58	381.2	13.02	380.6	5.41	0	10	2260	126	272	4236	275	26828
14	0.0556	0.00333	0.44891	0.02919	0.06115	0.00131	0.33	436.3	128.51	376.5	20.46	382.6	7.97	36	8	1960	107	63	834	290	29885
15	0.05336	0.00249	0.45567	0.02339	0.06189	0.00111	0.35	344.1	101.81	381.2	16.31	387.1	6.73	26	0	4802	285	1122	15579	543	57999
16	0.05961	0.00252	0.52076	0.02424	0.06047	0.001	0.36	589.5	89.02	425.7	16.19	378.5	6.05	8	32	9	0	0	9	0	0
17	0.05978	0.00307	0.49954	0.02807	0.0588	0.00113	0.34	595.2	108.11	411.4	19.01	368.3	6.88	0	0	4729	240	201	2226	657	64995
18	0.05356	0.00547	0.4475	0.04934	0.0654	0.0022	0.31	352.4	215.65	375.5	34.61	408.4	13.32	0	0	11700	619	2524	31939	1304	131945
19	0.05352	0.00222	0.47778	0.02191	0.06546	0.00105	0.35	350.8	90.83	396.5	15.05	408.7	6.38	0	37	6563	364	1591	19405	710	74865
20	0.05618	0.00253	0.51698	0.02587	0.06486	0.00113	0.35	458.7	97.73	423.1	17.32	405.1	6.81	0	43	19898	1082	3731	46076	2283	228141
21	0.05517	0.00219	0.47962	0.02105	0.06466	0.001	0.35	418.8	85.93	397.8	14.45	403.9	6.05	0	1	5472	280	208	2703	724	76085
06NMA-WINNER																					
1	0.05569	0.00086	0.49537	0.00845	0.06612	0.0004	0.35	439.9	33.41	408.6	5.74	412.7	2.41	72	19	16335	911	2673	50483	1908	241811
2	0.06267	0.00094	0.54343	0.00912	0.06117	0.00038	0.37	697	31.62	440.7	6	382.8	2.31	0	19	22241	1398	3024	53463	2668	356308
3	0.05587	0.00063	0.48125	0.00598	0.06181	0.00029	0.38	446.7	24.35	398.9	4.1	386.6	1.75	0	0	30884	1734	3949	68631	3735	490259
4	0.05488	0.00065	0.46901	0.00609	0.06199	0.0003	0.37	407.1	25.88	390.5	4.21	387.7	1.79	42	59	24359	1345	3651	66858	2973	386019
5	0.06161	0.00135	0.51655	0.01249	0.06203	0.00053	0.35	660.4	46.25	422.8	8.36	387.9	3.24	0	0	7527	469	637	8761	940	119649
6	0.05274	0.00162	0.44867	0.01502	0.06187	0.00068	0.33	317.6	68.15	376.3	10.53	387	4.14	199	0	6493	346	450	7679	800	103584
7	0.05504	0.00089	0.46685	0.00836	0.06319	0.00041	0.36	413.6	35.51	389	5.79	395	2.47	0	3	17566	981	2316	41441	2173	274657
8	0.05454	0.00089	0.47409	0.00859	0.06222	0.00041	0.36	393.2	36.13	394	5.92	389.1	2.47	99	0	15942	883	1346	25049	1926	253443
9	0.05798	0.00367	0.53765	0.03736	0.06553	0.00145	0.32	528.5	133.5	436.9	24.67	409.2	8.8	0	0	1558	92	533	10121	177	23613
10	0.05414	0.0008	0.48442	0.00792	0.06506	0.00038	0.36	376.6	32.97	401.1	5.42	406.3	2.31	45	0	17623	975	3425	66727	2080	269267
11	0.05507	0.00141	0.49707	0.01391	0.06563	0.00061	0.33	415.1	55.43	409.7	9.43	409.8	3.69	8	0	5661	319	636	12695	663	85839
12	0.04985	0.00141	0.43372	0.01342	0.06224	0.00063	0.33	188	64.57	365.8	9.51	389.2	3.83	40	0	9934	508	1178	22839	1210	159258
13	0.05424	0.00068	0.45776	0.00629	0.06105	0.00031	0.37	380.8	27.87	382.7	4.38	382	1.91	0	0	36083	2009	6159	135293	4535	590204

Table 2. Continued.

	Isotopic ratios and one sigma errors							Calculated ages and one sigma errors						Background-corrected counts per second on individual masses							
Analysis	$^{207}Pb/^{206}Pb$	error	$^{207}Pb/^{235}U$	error	$^{206}Pb/^{238}U$	error	Rho	$^{207}Pb/^{206}Pb$	error	$^{207}Pb/^{235}U$	error	$^{206}Pb/^{238}U$	error	202	204	206	207	208	232	235	238
06NMA-04																					
1	0.05237	0.00052	0.48046	0.00529	0.06641	0.00028	0.38	301.6	22.44	398.4	3.63	414.5	1.71	0	11	85890	4693	18192	331607	9979	1304681
2	0.05383	0.00065	0.47561	0.00631	0.06296	0.00031	0.37	363.8	27.06	395.1	4.34	393.6	1.89	0	87	49530	2737	13336	253836	5988	790246
3	0.05451	0.00083	0.46779	0.00783	0.06184	0.00037	0.36	392	33.71	389.7	5.42	386.8	2.26	12	0	41410	2293	9729	212131	5158	670598
4	0.05484	0.00093	0.46821	0.00872	0.0612	0.00041	0.36	405.8	37.26	390	6.03	382.9	2.46	26	24	26780	1489	5564	130841	3353	437967
5	0.05404	0.00086	0.47014	0.00816	0.06283	0.00039	0.36	372.7	35.45	391.3	5.64	392.8	2.35	89	0	59697	3266	17202	310456	7336	950305
6	0.05448	0.00098	0.46678	0.00918	0.06261	0.00043	0.35	391	39.65	389	6.35	391.5	2.62	0	0	68388	3756	16175	327490	8531	1090759
7	0.05583	0.00113	0.48553	0.01075	0.06149	0.00047	0.35	445.5	44.08	401.9	7.35	384.7	2.87	52	5	42643	2395	9630	178415	5239	691880
8	0.054	0.00115	0.46076	0.01068	0.06101	0.00049	0.35	371	47.12	384.8	7.43	381.8	2.97	65	37	40402	2193	8775	179379	5057	660405
9	0.05386	0.00131	0.4726	0.01249	0.06297	0.00057	0.34	365.2	53.78	393	8.61	393.6	3.45	0	36	67645	3652	22985	490258	8222	1069492
10	0.05429	0.00142	0.46334	0.01317	0.06149	0.0006	0.34	382.9	57.42	386.6	9.14	384.7	3.62	79	0	34207	1861	8364	171801	4272	553561
11	0.05488	0.00147	0.45077	0.01316	0.0594	0.00059	0.34	407.1	58.25	377.8	9.21	372	3.6	13	0	39429	2167	10651	211389	5113	660354
12	0.05426	0.00161	0.46775	0.01506	0.06226	0.00068	0.34	381.6	65.13	389.6	10.42	389.4	4.13	93	8	60750	3302	14496	298368	7493	969625
13	0.0546	0.00166	0.47619	0.01569	0.06241	0.0007	0.34	395.9	65.99	395.5	10.79	390.3	4.23	64	0	123410	6753	35051	749211	15037	1964437
14	0.0556	0.0018	0.48058	0.01691	0.06299	0.00075	0.34	436	70.52	398.5	11.6	393.8	4.56	52	10	33239	1852	7309	160494	4083	524058
06NMA-07-GABBRO																					
1	0.05429	0.00069	0.472	0.00664	0.06311	0.00033	0.37	383	28.43	392.6	4.58	394.5	2.02	21	0	52439	2931	4799	87599	6423	832871
2	0.05274	0.00076	0.4547	0.00725	0.06297	0.00037	0.37	317.7	32.41	380.6	5.06	393.7	2.23	0	23	38950	2116	5964	128424	4814	620453
3	0.05316	0.00079	0.45711	0.00747	0.06255	0.00038	0.37	335.8	33.03	382.2	5.2	391.1	2.28	31	0	63662	3488	13504	280186	7896	1021707
4	0.05384	0.00066	0.45419	0.00617	0.06193	0.00032	0.38	364.3	27.61	380.2	4.31	387.4	1.93	57	0	100129	5558	23513	461525	12666	1623941
5	0.05322	0.00067	0.45116	0.00624	0.0615	0.00032	0.38	338	28.01	378.1	4.36	384.8	1.95	65	0	117129	6429	12961	283545	14769	1916427
6	0.05245	0.00075	0.44109	0.00697	0.06109	0.00036	0.37	304.9	32.25	371	4.91	382.3	2.17	49	64	59699	3230	13190	284831	7592	983918
7	0.05257	0.00077	0.43737	0.00703	0.06088	0.00036	0.37	310.5	32.76	368.4	4.97	381	2.2	28	0	81459	4418	14458	292523	10478	1347842
8	0.0521	0.0007	0.45111	0.00668	0.06273	0.00035	0.38	289.8	30.27	378.1	4.67	392.2	2.11	60	0	106479	5723	24087	475388	13167	1710991
9	0.05372	0.00075	0.45086	0.00699	0.06141	0.00036	0.38	359.1	31.4	377.9	4.89	384.2	2.16	39	55	292619	16207	89701	1871480	37376	4809285
10	0.05287	0.00081	0.44831	0.00759	0.06185	0.00039	0.37	323.2	34.31	376.1	5.32	386.8	2.35	3057	709	62066	3382	10937	214644	7850	1013354
11	0.05317	0.00094	0.46823	0.00916	0.06404	0.00045	0.36	336.1	39.37	390	6.33	400.2	2.75	121	402	35022	1918	3328	61189	4267	552418
12	0.0533	0.00104	0.46245	0.00998	0.06195	0.00048	0.36	341.7	43.56	386	6.93	387.5	2.9	0	17	18721	1027	2068	42868	2316	305382
13	0.05335	0.00088	0.45996	0.00843	0.0628	0.00042	0.36	343.6	36.91	384.2	5.86	392.6	2.56	12185	2816	95002	5212	10536	208574	11836	1530123
14	0.05286	0.00087	0.39433	0.0072	0.05393	0.00036	0.37	322.7	36.97	337.5	5.24	338.6	2.21	145	44	298428	16214	136799	3057814	42984	5599116
15	0.0538	0.00094	0.44319	0.00854	0.06025	0.00042	0.36	362.5	38.92	372.5	6.01	377.2	2.58	0	20	85498	4724	7173	145024	11154	1436021
16	0.05251	0.00095	0.4426	0.00885	0.06181	0.00045	0.36	307.6	40.56	372.1	6.23	386.6	2.72	10	0	99791	5378	12001	233858	12726	1634128
17	0.05317	0.00099	0.44229	0.00911	0.06051	0.00045	0.36	336	41.47	371.9	6.42	378.7	2.75	361	91	321351	17491	53671	1193626	41544	5378413
18	0.05306	0.00108	0.45078	0.01015	0.06091	0.00049	0.36	331.4	45.31	377.8	7.1	381.2	3	0	41	52743	2862	9168	173499	6677	877070
19	0.05303	0.00106	0.45832	0.01013	0.06279	0.0005	0.36	330	44.5	383.1	7.06	392.6	3.03	0	2	95620	5180	24007	516676	11900	1542558
20	0.05271	0.00115	0.40977	0.00991	0.05552	0.00048	0.36	316.4	48.89	348.7	7.14	348.3	2.94	926	264	99107	5331	34396	716843	13713	1808201
21	0.05309	0.00117	0.44825	0.01093	0.0618	0.00054	0.36	332.5	49.02	376.1	7.66	386.6	3.26	0	0	92287	4981	12262	265690	11756	1512866
22	0.05406	0.00118	0.46221	0.0112	0.06185	0.00053	0.35	373.2	48.45	385.8	7.78	386.8	3.24	135	24	189771	10416	30422	658526	23871	3108569
23	0.05346	0.0012	0.44281	0.01099	0.06132	0.00054	0.35	348.3	49.93	372.2	7.73	383.6	3.29	324	105	491987	26670	123955	2287381	63884	8127772
24	0.05409	0.00124	0.46443	0.01183	0.06156	0.00056	0.36	374.7	50.87	387.3	8.2	385.1	3.38	209	21	280481	15361	72927	1390259	35130	4615175

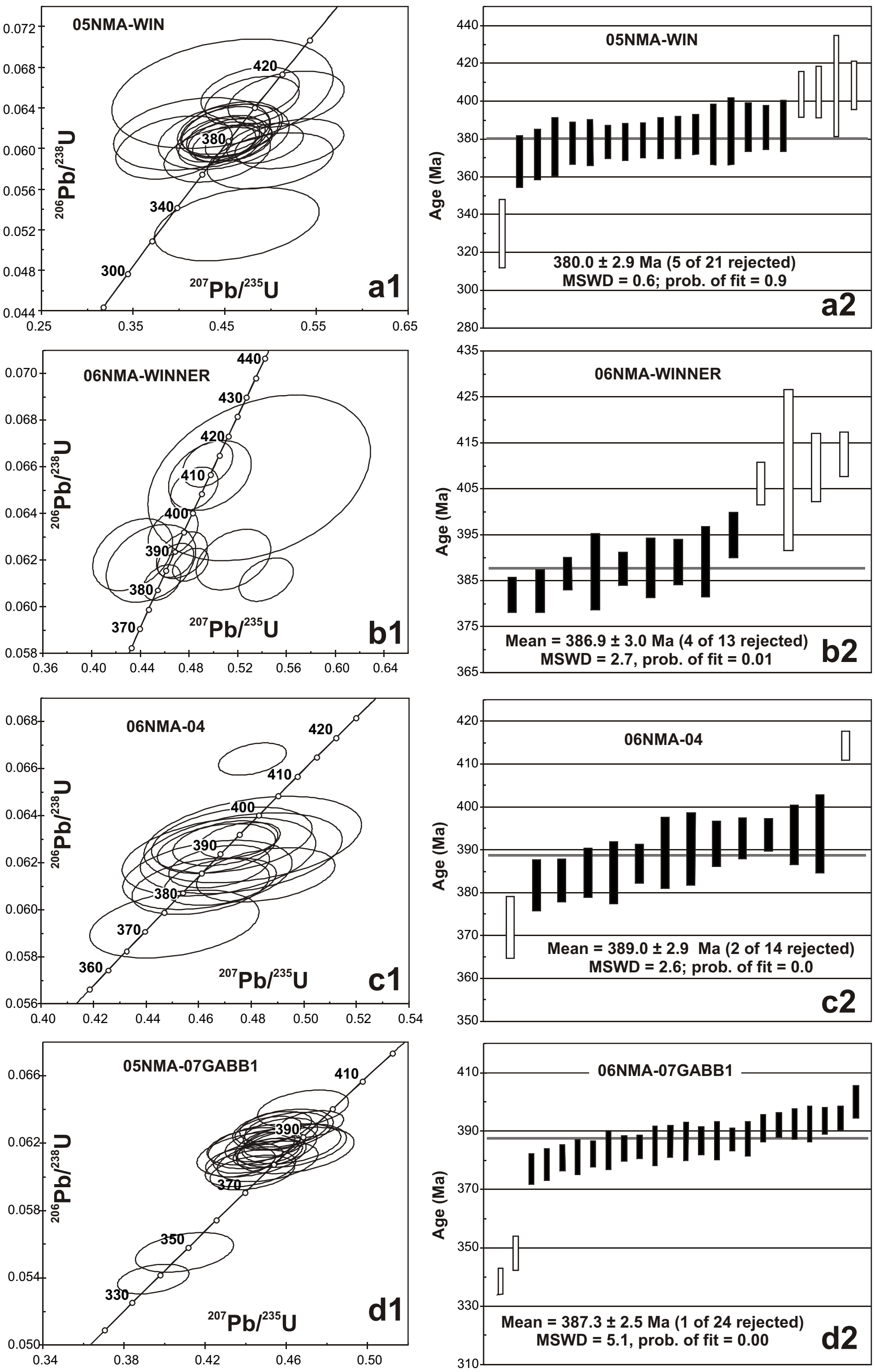

Fig. 4. LA-ICP-MS zircon age determinations for Greenwood gabbro samples, Knob Hill complex. Results are shown as both conventional concordia diagrams and as plots of the weighted average of calculated $^{206}Pb/^{238}U$ ages. **a)** and **b)** separate samples from the Winner Mine, **c)** Rock Creek; **d)** Powerline, north of Winnipeg Mine. See Table 1 and Fig. 2 for locations. Error ellipses and bars for individual analyses, and for the final weighted average ages, are shown at a 2σ level (95% confidence interval). Analyses that were included in the weighted average age are shown as filled bars and those that were rejected are shown as open bars. Rejected analyses are interpreted to represent either older xenocrystic zircon grains, or grains with significant amounts of post-crystallization Pb-loss.

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