Micropetrology and mineral geochemistry of the Tombstone and Deadman plutons, Tombstone Plutonic Suite, central Yukon

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ABSTRACT

Micropetrographic observations and mineral geochemistry data, along with previously reported whole-rock geochemistry, defined an A-type granite-affinity for the Tombstone and Deadman plutons of the 120-km-long, mid-Cretaceous Tombstone-Tungsten plutonic belt. This plutonic belt was intruded into the western Selwyn Basin, the western-most edge of the ancestral North American craton, and is situated well inboard of any potential subduction-zone plutonism, which is found in the accreted terranes that were juxtaposed with the North American craton during the Jura-Cretaceous.

Over a dozen mineral specimens were petrographically observed and five were chemically analysed. Similarities found among the two plutons are their alkalic nature, minimal quartz content, presence of igneous andradite garnets and the presence of rare-earth-bearing minerals. Differences between the two plutons include the fact that the Tombstone pluton contains Th, Ce and La with magnetite and titanite, while the Deadman pluton contains Nd with Ce and La, as well as Ba-rich alkali feldspars. These observations are not commonly found in tectonic-related I- or S-type granitoids, and distinguish the Tombstone plutonic suite as being most similar to A-type granites.

RÉSUMÉ

Des observations micropétrographiques et des données sur la géochimie des minéraux, de même que des données déjà publiées sur la géochimie de la roche entière, ont permis de définir une affinité avec le granite de type A pour les plutons de Deadman et de Tombstone de la ceinture de roches plutoniques de Tombstone Tungsten du Crétacé moyen (d'une longueur de 120 km). Cette ceinture de roches plutoniques a pénétré le bassin de Selwyn, le rebord le plus occidental de l'ancestral craton de l'Amérique du Nord; cette ceinture est située bien à l'intérieur de tout éventuel plutonisme de subduction observé dans les terranes accrétés qui se sont juxtaposés au craton nord-américain du Jurassique-Crétacé.

Plus d'une douzaine d'échantillons de minéraux ont fait l'objet d'une analyse chimique. Les similarités observées entre les deux plutons comprennent leur nature alcaline, leur teneur minimale en quartz, la présence de grenats andradites ignés et de minéraux contenant des éléments des terres rares. Les deux plutons diffèrent sur le plan de la composition : le pluton de Tombstone contient du Th, du Ce et du La, de même que de la magnétite et de la titanite, tandis que le pluton de Deadman contient du Nd avec du Ce et du La, ainsi que du Ba dans les feldspaths alcalins. Ces compositions ne sont pas courantes pour les granitoïdes d'origine tectonique des types S ou I.

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INTRODUCTION

During the mid-Cretaceous, an extensive magmatic episode occurred throughout western North America from the Alaskan and Canadian Cordillera to as far south as Mexico. A number of plutonic belts have been identified based on their geographical distributions; in some cases, plutonic suites, which are defined by similar petrological, mineralogical, geochemical and age characteristics have also been identified (Armstrong, 1998). Some of the least-studied plutonic belts exist in the northern Canadian Cordillera and Alaska, where they have only recently been divided into smaller plutonic suites (Hart *et al.,* 2004a).

The most eastern, or inboard, of these plutonic belts in Yukon is the 800-km-long Tombstone-Tungsten Belt (TTB) which comprises the Tombstone, Mayo and Tungsten suites (Fig. 1). The distribution of the numerous plutons that make up this belt is largely within the northern margin of the Neoproterozoic and Paleozoic Selwyn Basin, a site of episodic clastic deposition within the otherwise carbonate-dominant platforms of the ancient North American miogeoclinal margin. This plutonic belt comprises more than 100 plutons and associated east-trending dyke swarms, and is directly associated with the formation of hundreds of mineral occurrences, the most significant being intrusion-related gold deposits (e.g., Dublin Gulch) and tungsten skarns (e.g., Mactung; Hart *et al.,* 2002, 2004a).

The nature of the associated plutonic rocks has been considered to represent a distinct post-collisional tectonic setting (Mair *et al.,* 2006), and this greatly influenced the nature of the associated mineralization. Although all three plutonic suites have associated gold mineralization, the metallogeny, lithology and geochemistry of the Tombstone suite is particularly anomalous as it is characterized by large lithologically variable, highly alkalic, silica-saturated and undersaturated, variably zoned mafic and felsic granitoids with unusual U-Th-F and Cu-Au-Bi metallogenic associations (Anderson 1987; Hart *et al.* 2004a). These diverse features are characteristic of A-type granitoids (Loiselle and Wones, 1979; Eby, 1990; Martin, 2006). This paper focuses on the micropetrology and mineral chemistry of two critical plutons that define this suite, the Tombstone and Deadman plutons.

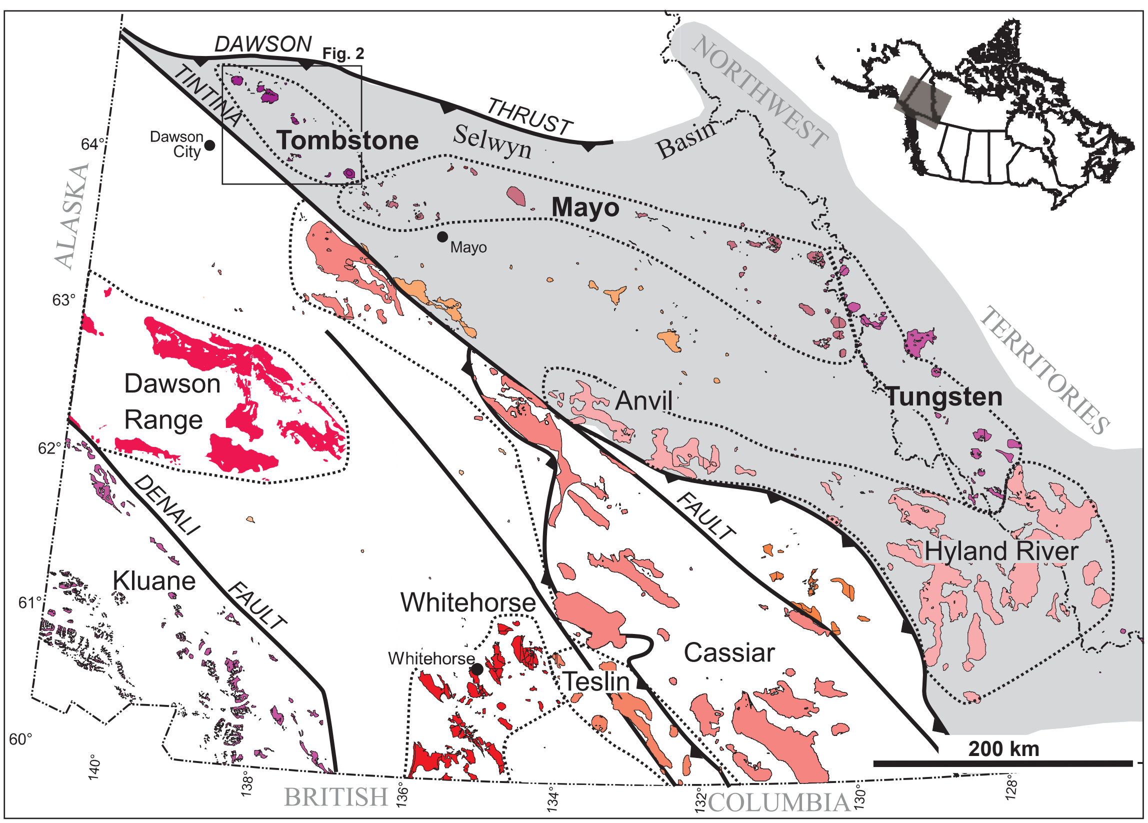

Figure 1. *Regional tectonic elements of the Yukon, and the distribution of mid-Cretaceous plutonic suites (dotted lines). The Tombstone-Tungsten Belt includes the Tombstone and Deadman plutons (Fig. 2) of this study (modified from Hart et al., 2004b).*

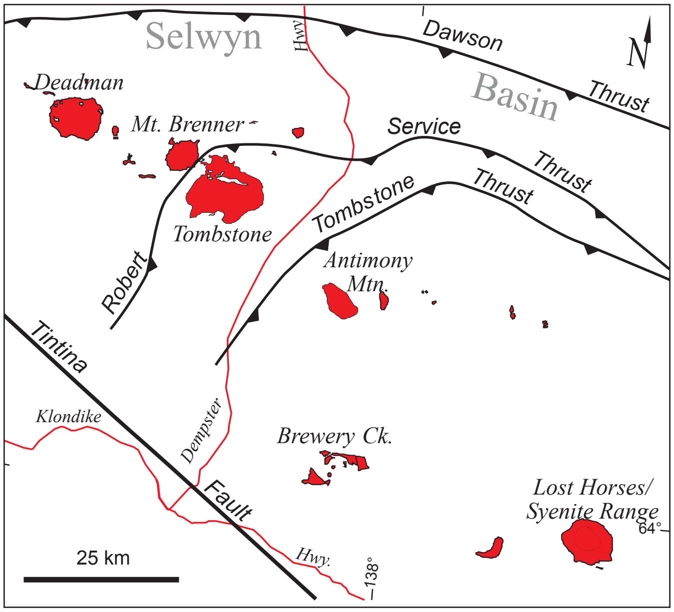

Figure 2. Distribution of the plutons which form the Tombstone Plutonic Suite (modified from Hart et al., 2004b).

REGIONAL

The Tombstone and Deadman plutons are located about 55 km north-northeast of Dawson City, Yukon (Fig. 2). The stocks are among the most northerly members of a 120-km-long northwest-trending string of five large mid-Cretaceous plutons and numerous assorted stocks, dykes and sills that parallel the Tintina Fault (Anderson, 1987; Hart *et al.,* 2004b). They are likely equivalent with the Livengood suite in east-central Alaska. The plutons intrude deformed and weakly metamorphosed strata of the Selwyn Basin, and appear to be entirely post-deformational. However, paleomagnetic studies of the Deadman pluton by Symons *et al.* (2006) indicate notable tilting and likely displacement of the pluton. Selwyn Basin assemblages at this location include Neoproterozoic coarse clastic Hyland Group; lower Paleozoic Road River Group black shales and chert; Mississippian Keno Hill Quartzite; Permian shale and chert; Triassic quartzite, calcareous siltstone, limestone and gabbro; and Jurassic black shale.

The Deadman and Tombstone plutons are both circular, and about 7 and 9 km in diameter, respectively. Both plutons have mostly steep sides, but both plutons host roof pendants and have some irregular contacts indicating shallow-dipping shoulders. Both plutons are variably concentrically zoned, multiphase alkalic plutons composed mostly of medium- to coarse-grained alkali-feldspar syenite and biotite-hornblende monzonite, with lesser amounts of quartz monzonite and pseudoleucite-phyric tinguaite (Anderson, 1987).

Vein, skarn and disseminated mineral occurrences are located within, and adjacent to, the Tombstone suite plutons and have the following metal associations: uranium-thorium-fluorine, antimony-arsenic-gold, tin-silver and gold-copper-bismuth (Hart *et al.,* 2004a). In both the Deadman and Tombstone plutons, uranium-thorium mineralization is associated with the tinguaite, a silica-undersaturated, highly potassic leucite porphyry.

The plutons have several age determinations, but the most accurate is likely the 91 ± 1 Ma determination by the U-Pb SHRIMP[1] (C. Hart, unpublished) on zircons, that are large and mostly unzoned, from the Deadman pluton (Hart *et al.,* 2004a). This date is similar to K-Ar dates from the Tombstone pluton and likely indicates that the plutons cooled rapidly within a few million years (Anderson, 1987; Hart *et al.,* 2004a). Based on petrographic observations and slightly elevated aeromagnetic responses and magnetic susceptibility values, Hart *et al.* (2004a) deemed the Tombstone suite to be magnetite-series granitoids (Ishihara, 1981).

A-TYPE GRANITE CHARACTERISTICS

A-type granites refer to those felsic units that are alkali-rich or have intruded into anorogenic environments, free of any tectonic or deformational events. In both cases, the likely source of magma formation is partial melting of the lower crust due to extreme crustal thickness. A-type granites comprise quartz syenites to peralkaline granites that are characterized by high modal concentrations of orthoclase and sodic plagioclase, and high total modal feldspar concentrations (>60%). Further, the mafic contents include the presence of iron-rich micas, amphiboles and pyroxenes. Geochemically, there are commonly high total concentration of alkali contents and low CaO contents (at SiO_2 = 70%, $Na_2O + K_2O$ = 11%, CaO < 1.8%, high FeO_T/MgO = 8-80), plus elevated halogens such as F contents (F = 1.7%). The Y/Nb ratio has also been used to determine source environments with Y/Nb < 1.2 suggesting sources chemically similar to oceanic island basalts, while those with Y/Nb > 1.2 suggest sources chemically similar to island-continental margin basalts (Eby, 1990; Hess, 1989).

[1]*Sensitive, high-resolution, ion microprobe*

EXPERIMENTAL METHODS

A total of five polished thin sections from both plutons were petrographically analysed. The Scanning Electon Microscope (SEM) and Energy Dispersive Spectrometer (EDS) provided further analyses for mineral content and chemical composition. A 200-point count was used for modal mineral percentages to determine appropriate IUGS igneous rock nomenclature. Element mapping and backscatter imagery on the SEM provided informal mineral identifications and EDS analyses gave oxide chemistry of garnet and other accessory minerals.

ANALYTICAL RESULTS

Recently determined whole-rock analyses are shown in Table 1 for the Deadman pluton (Hart *et al.,* 2004b). They all show peraluminous values, high alkalis versus CaO values (>10% $Na_2O + K_2O$ vs <4% CaO), FeO_T/MgO ratios of 7 to 26, and F between 0.01 and 1.5%. LOI and H_2O+ values are all less than 0.7%. The Y/Nb ratios range from 0.65 to 0.89.

New petrologic observations of the Tombstone and Deadman plutons showed some mineral compositional similarities along with some very distinct differences. Table 2 shows the results of 200-point count analyses, and the resulting IUGS rock calculations and names. Petrologically, both plutons consistently contained > 60% total modal feldspar content. Many of the feldspars showed obvious zoning patterns, albite zoning in the plagioclase and Carlsbad twinning in the orthoclase (Figs. 3 and 4). Further, several isotropic minerals were observed, some with subhedral to euhedral garnet shapes.

Table 1. *Selected whole-rock geochemistry for the Deadman pluton (from Hart et al., 2004b).*

	DM 1	DM 2	DM 3	DM 4
SiO_2	57.8	64.7	58.6	68.3
TiO_2	0.304	0.198	0.303	0.175
Al_2O_3	19.3	17.6	21.1	16.1
FeO_T	2.85	1.92	2.53	1.8
Fe_2O_3	1.65	0.92	0.53	1.0
FeO	1.2	1.0	2.0	0.8
MnO	0.13	0.05	0.06	0.04
MgO	0.11	0.24	0.23	0.26
CaO	3.76	2.34	0.85	1.53
Na_2O	3.59	5.84	2.98	5.38
K_2O	8.6	5.43	12.1	4.9
P_2O_5	0.03	0.02	0.02	0.01
Cr_2O_3	0.005	0.005	0.005	0.005
LOI	0.65	0.6	0.4	0.65
H_2O^+	0.5	0.3	0.7	0.2
Total	**98.8**	**99.4**	**99.4**	**99.4**
Cl	347	30	157	69
F	1050	479	1520	10
B	47	45	29	37
V	38	23	15	21
Co	1	1	2	1
Ga	22	24	32	27
Ge	1.2	1.2	1.5	1.3
Rb	197	178	705	211
Sr	3380	1110	599	637
Y	11.4	17.2	30.4	15.5
Zr	175	414	518	287
Nb	12.8	22.9	40.3	24.0

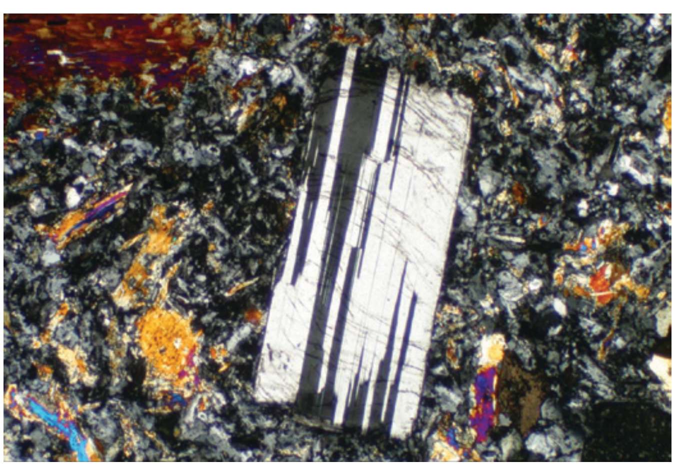

Figure 3. *Polysynthetic twinning of plagioclase shown in thin section (bipolarized light).*

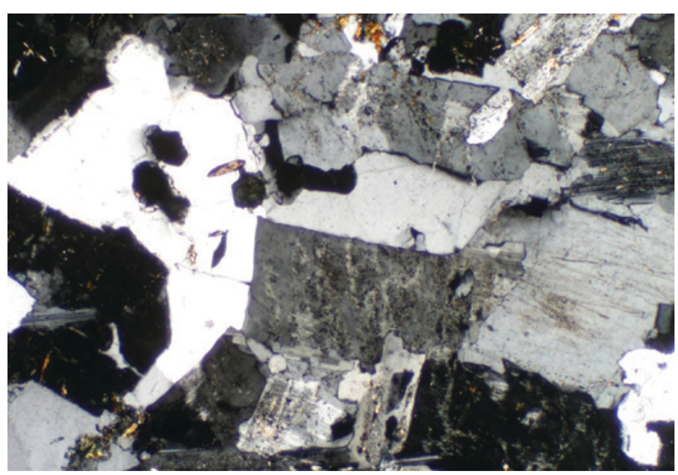

Figure 4. *Orthoclase feldspar and small titanite crystals in thin section (bipolarized light).*

Table 2. Results from 200-point count analyses of the five polished sections. Q = Q/Q+A+P, (F = F/F+A+P), A = A/Q+A+P, M = biotite + amphibole + opaques + titanite.

	DM 1	DM 3	Tomb 6A	Tomb 20	Tomb 22
Quartz	0	2.25	6.74	0	0
K-feldspar	76.9	83.95	48.69	77.42	29.3
Biotite	2.56	13.5	0.75	1.38	1.84
Amphibole	5.13	0.98	39.7	0.46	16.6
Opaques	15.38	0.98	0	20.74	52.3
Titanite	0	0.98	4.12	0	0
Q	0	2.6	12.16	0	0
A	100	97.4	77.84	100	100
P	0	0	0	0	0
M	23.07	16.44	44.57	22.56	70.74
IUGS name	leucocratic alkali-feldspar syenite	leucocratic alkali-feldspar syenite	alkali-feldspar quartz syenite	leucocratic, nepheline-bearing alkali-feldspar syenite	melanocratic alkali-feldspar syenite

EDS analyses confirmed the zoning in the feldspars and the presence of andradite garnets ($Ca_3Fe_2(SiO_4)_3$). As well, both plutons contain minerals with several uncommon rare-earth and radioactive elements that are also uncommon in most granitoids (Tables 3-7).

One of the most enigmatic differences between the two plutons is the presence of up to 2 wt.% Ba in the alkali feldspars of the Deadman pluton, and the absence of the Ba in the Tombstone pluton. Both plutons contain minerals with the REEs, Ce and La. However, Tombstone also contains Th (Fig. 5), which is recordable on a Geiger counter. The Deadman pluton contains Nd rather than Th.

One EDS analysis of a mineral from the Tombstone pluton suggests a possible occurrence of the rare-earth mineral fluoro-carbonate synchesite or parasite. Proper verification would require XRD analysis, which was not possible due to the small sample grain in thin section.

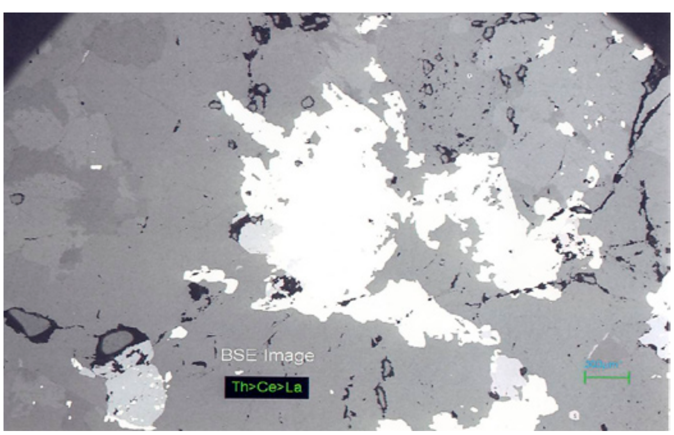

Figure 5. *Backscatter-electron image of a radioactive rare-earth mineral containing greater Th concentration than Ce, La or Nd.*

Table 3. *Mineral chemistry data from Tombstone sample 6A, from EDS analyses (all measured in weight percent, estimated from bar graph). Sample: (1) alkali feldspar; (2) albitic feldspar; (3) andradite garnet; (4) possibly Ca-Mg-Fe clinopyroxene.*

	1	2	3	4
O	66	68	48	22
Si	21	17	22	22
Al	6	6		1
Ca			11	12
Fe			12	12
K	4	1		
Mg			4	5
Mn			1	
Na	3	8	2	1

Table 4. *Mineral chemistry data from Tombstone sample 22, from EDS analyses (all measured in weight percent). Sample: (1-5) zoned garnet from rim to core; (6) a rare-earth element (REE)-bearing mineral.*

	1	2	3	4	5	6
O	45.02	46.76	43.13	45.85	45.16	35.15
Si	15.78	20.98	15.04	14.79	14.93	3.34
Al	1.31	2.12	2.19	1.77	1.87	
C						12.91
Ca	20.94	13.09	21.02	20.35	20.35	3.33
Ce						19.16
F						8.5
Fe	14.73	11.11	14.84	13.26	13.67	
La						14.36
Mg		3.42			0.37	
Mn	0.42	0.39	0.34	0.27	0.38	
Na		1.52				
Ti	1.8	0.6	3.44	3.7	3.26	

Table 5. *Mineral chemistry data from Tombstone sample 20, from EDS analyses (all measured in weight percent). Sample: (1,2) orthoclase; (3-7) different garnet crystals; (8) a REE-bearing mineral; (9,10) nepheline.*

	1	2	3*	4	5	6	7	8	9	10
O	59.37	49.89	45	30.37	48.58	50.16	48.53	41.8	50.04	55.42
Si	24.39	28.07	16	22.34	15.85	15.87	15.62	7.72	17.71	15.07
Al	8.26	8.95	2	2.38	1.51	1.33	2.21		16.4	14.1
C								9.9		
Ca			21	25.7	18.58	18.19	18.75	9.65		
Ce								6.55		
F								2.98		
Fe			14	16.88	13.19	12.38	13.25			
K	6.4	12.66							3.77	2.18
La								2.98		
Mn			1	0.6	0.66	0.69	0.73			
Na	1.61	0.43							12.1	13.2
P								1.77		
Th								16.6		
Ti			1	1.73	1.65	1.38	0.91			

*data estimated from bar graph

Table 6. *Mineral chemistry data from Deadman sample 1, from EDS analyses (all measured in weight percent). Sample: (1-4) mainly perthitic orthoclase; (5) albitic feldspar; (6, 7) same zoned crystal, with (6) the orthoclasic core, and (7) part of the rim of unknown affinity.*

	1	2	3	4	5	6	7
O	66.1	64.16	62.73	51.79	61.42	53.5	54.31
Si	20.24	21.2	21.96	27	20.75	26.4	16.25
Al	8.17	8.02	8.16	9.17	8.54	9.14	7.15
Ba	0.28	0.41	0.3	1.21		0.92	
Ca					0.44	0.25	5.28
Cl							0.2
Fe						0.42	11.07
K	4.27	4.23	4.88	9.38	0.96	6.99	1.59
Mg							0.95
Mn							0.52
Na	0.94	1.99	1.98	1.46	7.89	2.38	1.95
Ti							0.74

Table 7. *Mineral chemistry data from Deadman sample 3, from EDS analyses (all measured in weight percent). Sample: (1) orthoclase; (2,3) albite; (4) possible Fe-spinel; (5) REE-bearing apatite; (6) biotite; (7,8) REE-bearing minerals.*

	1	2	3	4	5	6	7	8
O	61.77	60	50.59	47.78	63.09	55.15	64.32	50.84
Si	23.03	18.03	17.92		1.21	14.81	13.94	14.43
Al	8.16	11.8	15.8	29.6		11.3	9.82	10
Ca		2.45	1.16		18.39		3.52	5.47
Ce					1.09		4.71	8.8
Fe				16.4		9.8	2.19	5.2
K	5.62		2.7			5.96		
La							1.5	3.66
Mg						1.44		
Mn				0.86		0.33		
Na	1.42	7.71	11.8		1.16			
Nd					0.65			1.59
P					14.4			
Ti						1.22		
Zn				5.34				

Accessory minerals, found petrographically and through the SEM, show that the Tombstone pluton contains titanite (Fig. 6), magnetite, and in one sample, nepheline. Within the Deadman pluton apatite and spinel, and possibly hercynite ($FeAl_2O_4$) are common.

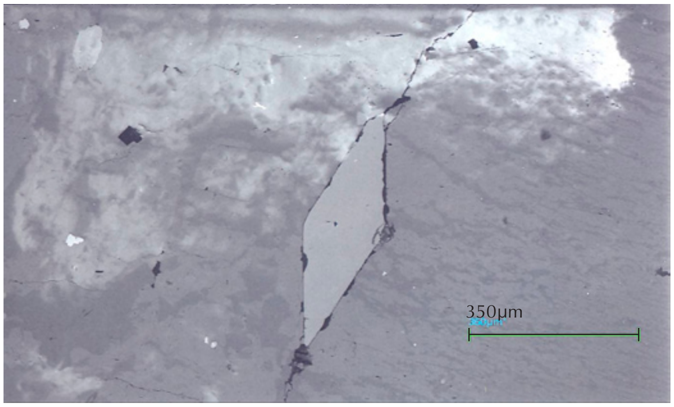

Figure 6. *Backscatter-electron image of a titanite crystal from the Tombstone pluton.*

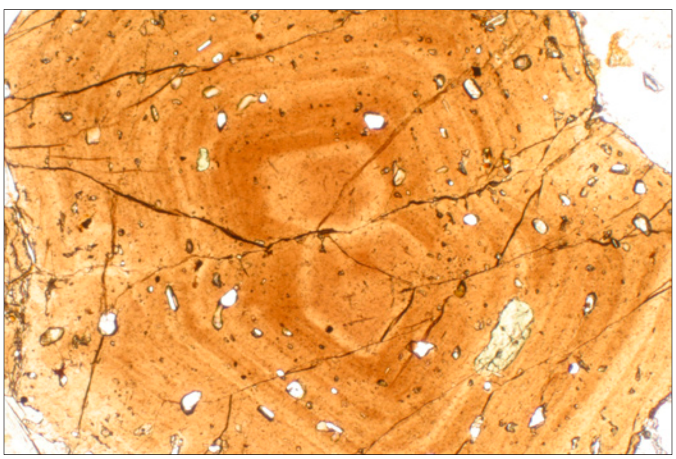

Figure 7. *Backscatter-electron image of the zoned garnet from the Tombstone 22 sample.*

CONCLUSIONS

The *ca.* 91 Ma Deadman and Tombstone plutons were emplaced into the ancient North American continental margin during the mid-Cretaceous, following a period of terrane collision, crustal thickening and lower greenschist-facies metamorphism. The plutons are related to extensional events following the compressional events. There are multiple variations in mineral composition of the intrusions, even though they are from one contemporaneous belt. This is likely due to the heterogeneity of source material, as is common of A-type granites. As has been suggested by Behnia *et al.* (2004), A-type granites are associated with either continental or oceanic plate interiors, in a tensional anorogenic regime, or even immediately post-orogenic environment (Pitcher, 1993), with definite alkaline and anhydrous imprints. Although more chemical data from other plutons would provide more confidence on the A-type nature of the granitoids, the location of the Tombstone-Tungsten Belt and the two plutons, well inboard, and formed very late within the suites, suggests quite a different environment than most other types of granitoids.

REFERENCES

Anderson, R.G., 1987. Plutonic rocks in the Dawson map area, Yukon Territory. *In:* Current Research, Part A, Geological Survey of Canada, Paper 87-1A, p. 689-697.

Armstrong, R.L., 1988. Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera. *In:* Processes in Continental Lithospheric Deformation, S.P. Clark Jr., B.C. Burchfiel and J. Suppe (eds.), Geological Society of America Special Paper, vol. 218, p. 55-92.

Behnia, P., Darvishzadey, A. and Collins, L.G., 2004. Geochemical peculiarities in K- and Si-metasomatic processes of Qooshchi Complex, Northwest Iran. Iranian International Journal of Science, vol. 5, no. 1, p. 77-90.

Eby, G.N., 1990. The A-type granitoids: A review of their occurrence and chemical characteristics, speculation on the petrogenesis. Lithos, vol. 26, 115-134.

Hart, C.J.R., McCoy, D.T., Goldfarb, R.J., Smith, M., Roberts, R., Hulstein, R., Bakke, A.A. and Bundtzen, T.K., 2002. Geology, exploration and discovery in the Tintina Gold Province. *In:* Geology, Exploration and Discovery in the Tintina Gold Province, Alaska and Yukon, R.J. Goldfarb and R. Neilson (eds.), Geological Society of America Special Paper, vol. 9, p. 241-274.

Hart, C.J.R., Goldfarb, R.J., Lewis, L.L. and Mair, J.L., 2004a. The northern Cordilleran mid-Cretaceous plutonic province: Ilmenite/magnetite series granitoids and intrusion-related mineralization. Resource Geology, vol. 54, p. 253-280.

Hart, C.J.R., Mair, J.L., Goldfarb, R.J. and Groves, D.I., 2004b. Source and redox controls on metallogenic variations in intrusion-related ore systems, Tombstone-Tungsten Belt, Yukon Territory, Canada. Transactions of the Royal Society of Edinburgh: Earth Sciences, vol. 95, p. 339-356.

Hess, P.C., 1989. Origins of Igneous Rocks. Harvard University Press, Massachusetts, 336 p.

Ishihara, S., 1981. The granitoid series and mineralization. Economic Geology, 75th Anniversary Volume, p. 458-484.

Loiselle, M.C. and Wones, D.R., 1979. Characteristics and origin of anorogenic granites. Geological Society of America, Abstracts, 11, p. 468.

Mair, J.L., Hart, C.J.R. and Stephens, J., 2006. Deformation history of the western Selwyn Basin, Yukon, Canada: Implications for orogen evolution and mid-Cretaceous magmatism. Geological Association of America, Bulletin, vol. 118, p. 304-323.

Martin, R.F., 2006. A-type granites of crustal origin ultimately result from open-system fenitization-type reactions in an extensional environment. Lithos, vol. 91, p. 125-136.

Pitcher, W.S., 1993. The Nature and Origin of Granites. Blackie Academic & Professional, London, 321 p.

Symons, D.T.A., Harris, M.J., Hart, C.J.R. and McCausland, P.J.A., 2006. Paleomagnetism of the ~91 Ma Deadman pluton: Post-mid-Cretaceous tectonic motion in central Yukon. *In:* Yukon Exploration and Geology 2005, D.S. Emond, G.D. Bradshaw, L.L. Lewis and L.H. Weston (eds.), Yukon Geological Survey, p. 299-313.