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WinAmptb: A Windows program for calcic amphibole thermobarometry

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ABSTRACT

WinAmptb is a Microsoft® Visual Basic software developed for electron microprobe calcic amphibole analyses to calculate the pressure (*P*), temperature (*T*) and oxygen fugacity (fO_2) conditions of amphibole-bearing alkaline to calc-alkaline rocks. The program estimates the structural formulae of calcic group amphibole analyses on the basis of IMA-04 nomenclature scheme, predicts cation site allocations and calculates stoichiometric H_2O and ferric iron contents based on different normalization procedures. WinAmptb does not only estimate the *P-T* conditions of calcic amphiboles, but also the exchange reactions between amphibole and plagioclase pairs and amphibole-liquid equilibria. The program provides the user to type and load multiple amphibole, plagioclase and liquid compositions in the data entry section, to edit and load Microsoft® Excel files in calculating, classifying and naming calcic amphiboles, and to store all the calculated parameters including amphibole cations, liquid cation fractions, plagioclase cations, thermobarometric and chemometric results in the Microsoft® Excel file for further evaluations by the users.

Keywords: Amphibole; plagioclase; liquid; pressure; temperature; fugacity; software.

INTRODUCTION

Thermobarometry is the calculation of *P-T* conditions of igneous and metamorphic rocks by using the conventional and pseudosection approaches. While the conventional thermometry method takes into account the equilibrium thermodynamics of equivalent reaction between end-members of minerals, the pseudosection approach comprise a forward estimation of mineral equilibria for the rock composition. Although both conventional and pseudosection methods use the same thermodynamic data as well as activities, the pseudosection approach provides a valuable additional thermobarometric information on mineral assemblages, proportions and compositions (Powell, 1985; Powell and Holland, 2008). Successful thermometers tested for the igneous and metamorphic rocks comprises a calibration of univariant equilibria revised for solid solutions (Essene, 2009). Although some of these empirically calibrated thermobarometers, in estimating the *P-T* conditions of metamorphic and igneous rocks, are developed from calorimetric and volumetric data, most derive from regression analysis of experimental data (Putirka, 2008).

Compared to the metamorphic rocks, many igneous rocks lack suitable mineral assemblages or pairs that are used in thermobarometric estimations (Anderson et al., 2008). Amphiboles that occur with a wide range of chemical composition in igneous and metamorphic rocks are an important petrogenetic indicator in estimating the *P-T* conditions. Helz (1973) presented the results of an experimental study of hornblende compositions from different basaltic magmas at 5 kbar and 700-1000 ºC conditions and stated that variation of hornblende composition as a function of temperature is mainly controlled by the crystal-chemical limitations. Otten (1984) demonstrated that the titanium composition of amphibole can be used in calculation of crystallization temperature estimate of magmatic and subsolidus hornblends. Blundy and Holland (1990) suggested a pressure-dependent thermometer considering the albite content of coexisting plagioclase that applicable to a variety of silica-saturated rocks equilibrated at temperatures in the range 500-1100 ºC from igneous to metamorphic settings. Holland and Blundy (1994) later improved the amphibole-plagioclase thermometer for *P-T* conditions of 1-15 kbar and 400-1000 ºC, which is based on two exchange equilibria for silica-saturated and silica-unsaturated rocks. Ernst and Lui (1998) proposed a semiquantitative thermometer as well as barometer for calcic amphiboles from mid-ocean ridge basalts based on the experimental studies in *P-T* conditions ranging from 0.8-2.2 GPa and 650-950 ºC at fayalite-magnetite-quartz oxygen fugacity buffer. Féménias et al. (2006) proposed a quantitative Ti thermometer for amphibole in titanium-saturated calc-alkaline magma that reflects *P-T* conditions ranging from 0.6 to 1.0 GPa and 600 to 1000 ºC.

Ridolfi et al. (2010) introduced a new amphibole-only thermometer model, including temperature, pressure, oxygen fugacity and hygrometric formulations based on the major cation values and valid up to about 1 GPa and 1050 °C, for amphiboles from calc-alkaline products of subduction-related systems. Ridolfi and Renzulli (2012) revised the previous empirical amphibole-only formulations and presented new thermobarometric and chemometric empirical equations for calcic amphiboles in calc-alkaline and alkaline magmas valid up to 2.2 GPa and 1130 ºC *P-T* conditions. Molina et al. (2015) developed liquid-only and calcic amphibole-liquid thermometers and temperature-dependent calcic amphibole-plagioclase barometer for metamorphic and igneous rocks based on the Al-Si partitioning between plagioclase and amphibole, and the Mg partitioning between amphibole and liquid. Putirka (2016) recently recommended a serious of liquid-only, calcic amphibole-only and calcic amphibole-liquid thermometers as well as tentative calcic amphibole-liquid barometers for igneous systems to deduce the eruption mechanisms of felsic magmas at arc volcanoes.

The Al-in-hornblende barometer, which was first proposed by Hammarstrom and Zen (1986) in estimating the pressure and depth of emplacement conditions of calc-alkaline igneous rocks has been subjected to many calibrations (Hollister et al., 1987; Johnson and Rutherford, 1989; Schmidt, 1992; Anderson and Smith, 1995; Ague, 1997; Ernst and Lui, 1998; Larocque and Canil, 2010; Krawczynski et al., 2012; Putirka, 2016; Mutch et al., 2016) for the assemblage quartz+alkali feldspar+plagioclase +hornblende+biotite+iron titanium oxide+titanite+melt+fluid. Among these barometers, the Anderson and Smith (1995) calibration is temperature-dependent and the pressure estimate is corrected for temperature effect by using the experimental data of Johnson and Rutherford (1989) and Schmidt (1992) due to its great influence in increasing of the tetrahedral aluminum content of hornblende. Hence, Anderson et al. (2008) explained the early uses of Al-in-barometers with caution due to their lack of temperature corrections.

As the amphibole group minerals are one of the most complex rock-forming double-chain silicates, several classification schemes with necessary revisions were proposed following the first published report by the International Mineralogical Association (IMA) (Leake, 1978; Leake et al., 1997, 2004; Hawthorne and Oberti, 2006; Hawthorne et al., 2012). Computer programs on calculation and classification of amphibole group minerals also progressed parallel with the revised IMA reports in literature (Mogessie et al., 1990, 2001, 2004; Currie, 1991, 1997; Tindle and Webb, 1994; Yavuz, 1996, 1999, 2007; Esawi, 2004, 2011; Oberti et al., 2012; Locock, 2014). Despite the extensity of software on amphibole classification, thermobarometry related programs based on calcic amphibole-only, amphibole-plagioclase and amphibole-liquid pairs are limited in literature that reflect the *P-T* conditions of igneous rocks (e.g. Hora et al., 2013; Ridolfi, 2017; Putirka, 2017; Anderson, 2017). In this study, a Microsoft® Visual Basic program, called WinAmptb, has been developed to estimate calcic amphibole-only, amphibole-plagiocalse and amphibole-liquid thermometers and barometers for igneous systems based on the standard cation normalizations. The program also allows the user to allocate iron from microprobe-derived analysis to Fe^{2+} and Fe^{3+} based on different cation normalization procedures, to share out the recalculated cations at different sites (e.g. T, C, B, A, OH or T, *M*1,2,3, *M*4, A, OH sites) to separate amphibole groups with calcic amphibole names according to the IMA-04 guidelines. All the calculated amphibole, liquid and plagioclase data can be displayed in a single window (i.e. *Calculation Screen*) and stored in a Microsoft® Excel file, called Output.xlsx, for further data manipulation purpose.

PROGRAM DESCRIPTION

A variety of computer programs have been published in literature for calculation and classification of rock-forming silicate minerals intended for general (e.g. Brandelik, 2009) and specific purposes including amphibole (Yavuz, 2007; Locock, 2014), mica (Yavuz and Öztaş, 1997; Yavuz, 2003 a,b), pyroxene (Yavuz, 2001), garnet (Locock, 2008), tourmaline (Yavuz et al., 2006, 2014) and chlorite (Yavuz et al., 2015) in recent years. However, only a number of thermobarometry software based on the mineral chemistry were appeared in estimation the *P-T* conditions of igneous rocks (Soto and Soto, 1995; Yavuz, 1998; Lepage, 2003; Hora et al., 2013; Yavuz, 2013; Lanari et al., 2014). WinAmptb is a user-friendly compiled program package (≈ 13 Mb) for amphibole, liquid and plagioclase analyses developed for personal computers running in the Microsoft® Windows operating system.

The program calculates cations (*apfu*) from electron-microprobe amphibole and plagioclase analyses as well as liquid compositions and estimates numerous amphibole-only, amphibole-plagioclase and amphibole-liquid thermometers and barometers based on the empirical equations. WinAmptb optionally provides the user to estimate amphibole-plagioclase thermometers (Blundy and Holland, 1990; Holland and Blundy, 1994) for an arbitary pressure (kbar) values between 1 and 5 and to calculate a variety of Al-in-hornblende barometers based on the recalculation and site allocation procedures by Holland and Blundy (1994; Appendix B) by selecting the options from pull-down menu of *Geothermometer* in the *Data Entry Screen*. Similarly, by selecting options from the pull-down menu of *Oxygen Fugacity* in the *Data Entry Screen*, the program estimates oxygen fuacity (fO_2) as a function of *T* (°C) and *P* (kbar) for the Quartz-Fayalite-Magnetite (QFM), Nickel-Nickel Oxide (NNO), and Hematite-Magnetite (HM) buffers (from Fegley, 2013) by using the Putirka's (2016), Ridolfi and Renzulli's (2012) and Ridolfi et al.'s (2010) *P-T* calibrations. Oxygen fuacity estimation parameters for QFM, NNO, and HM buffers are displayed in columns 256-264 of the *Calculation Screen* and in an Excel file (Output.xlsx).

A list of the calculation steps in the *Calculation Screen* of developed program is given in Table 1. WinAmptb presents ten binary plots for the *P-T* conditions of calcic-amphibole-only amphibole analyses. These plots are displayed by the Golden Software's Grapher program by selecting diagram types from the pull-down menu of *Graph* in the *Calculation Screen* of WinAmptb.

Data entry of amphibole, liquid, and plagioclase analyses

Upon successful installation of WinAmptb, the start-up screen with various pull-down menus and equivalent shortcuts appears on the screen. The program allows the user to edit amphibole (Figure 1a), liquid (Figure 1b) and plagioclase analyses (Figure 1c) by clicking the *New* icon on the tool bar, by selecting the *New File* from the pull-down menu of *File* option or pressing the *Ctrl+N* keys. The standard 14, 13 and 11 variables are used by the program for calculation of amphibole (Figure 2), liquid (Figure 3) and plagioclase (Figure 4) analyses (wt%) in the following order:

Sample No(a), $SiO_{2(a)}$, TiO_{2}(a), Al_2O_3(a), V_2O_3(a), $Cr_2O_{3(a)}$, $FeO_{(tot)}$(a), MnO(a), MgO(a), CaO(a), Na_2O(a), K_2O(a), F(a) and Cl(a),

Table 1. Description of column numbers in the Calculation Screen window of WinAmptb program and an output Excel file.

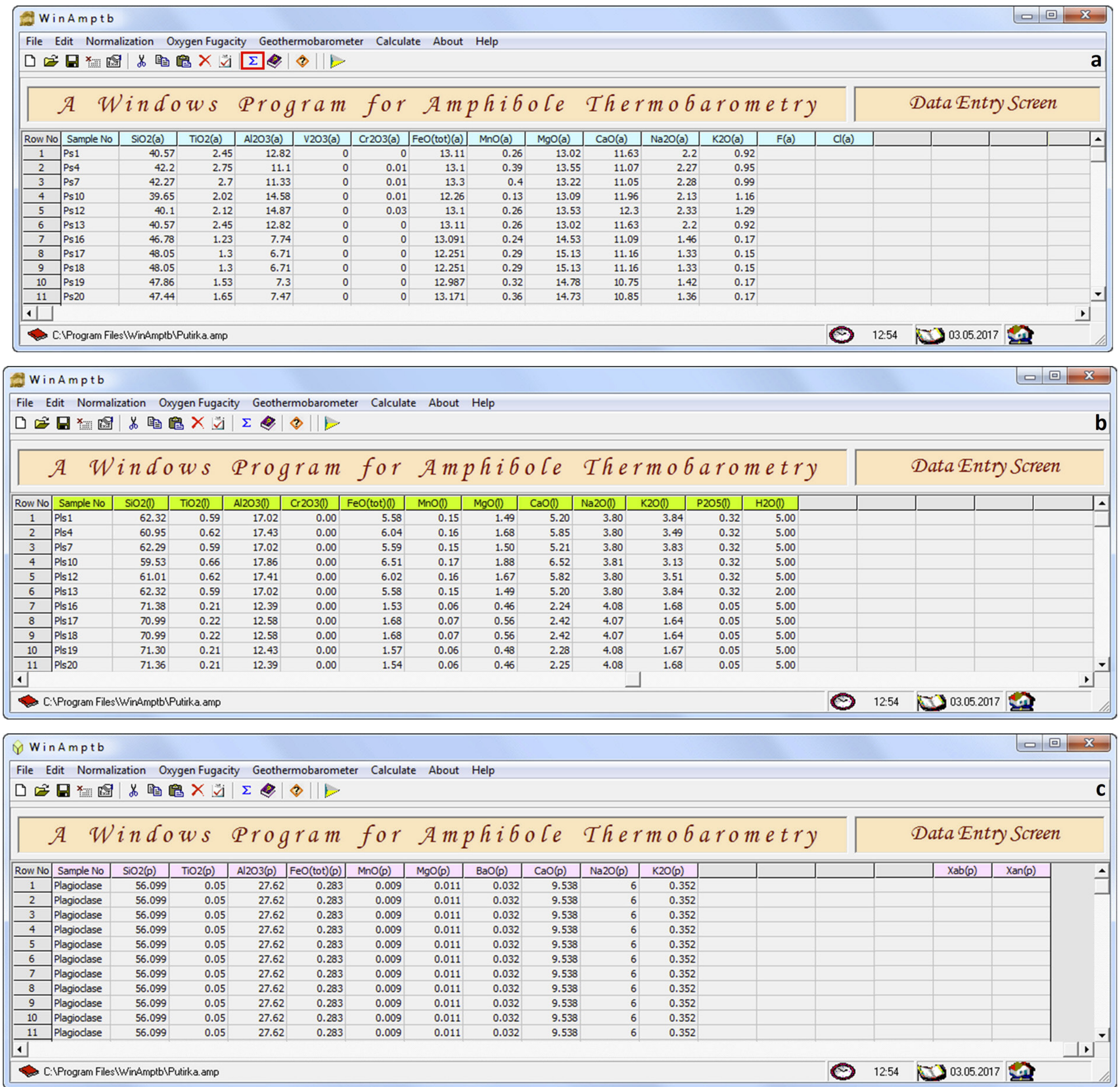
Row	Explanations	Column Numbers
1	Major oxide amphibole composition analyses (wt%)	1-15
2	Recalculated cations of amphibole analyses (*apfu*)	16-28
3	Recalculated cations in the T, C, B, A, and OH sites	29-58
4	Recalculated cations in the T, *M1,2,3, M4*, A, and OH sites [from Anderson (2016)]	59-84
5	Total cations, stoichiometric estimation of Fe_2O_3, FeO and H_2O (wt%) contents and cation charges	85-89
6	Recalculated cations in the T, C, B, and A sites [from Putirka (2016)]	90-109
7	Amphibole groups and calcic amphibole names according to the IMA-04 nomenclature scheme	110-111
8	Blank	112
9	Major oxide (wt%) liquid composition analyses	113-124
10	Recalculated liquid cation fractions	125-135
11	Blank	136
12	Major oxide plagioclase composition analyses (wt%)	137-146
13	Recalculated cations of plagioclase analyses (*apfu*)	147-156
14	Molar fractions of albite, anorthite and orthoclase (%)	157-159
15	Blank	160
16	Amphibole-only, amphibole-liquid and amphibole-palgioclase thermobarometers and related calculations	161-264

Sample No(l), SiO_2(l), TiO_2(l), Al_2O_3(l), Cr_2O_3(l), $FeO_{(tot)}$(l), MnO(l), MgO(l), CaO(l), Na_2O(l), K_2O(l), P_2O_5(l) and H_2O(l),

Sample No(p), SiO_2(p), TiO_2(p), Al_2O_3(p), $FeO_{(tot)}$(p), MnO(p), MgO(p), BaO(p), CaO(p), Na_2O(p) and K_2O(p)

where (a), (l) and (p) denote amphibole, liquid and plagioclase, respectively. In the *New File*, *Data Entry Screen* and *Calculation Screen*, these parameters are highlighted by the ice blue, moon green and faded pink colors, respectively. Without typing the complete plagioclase analyses in the *New File* and *Data Entry Screen*, WinAmtb also allows the user to edit X_{ab} and X_{an} values that were *Calculate*d from plagioclase analyses to estimate the amphibole-plagioclase and amphibole-liquid thermometers and barometers. However, by typing the only calculated X_{ab} and X_{an} values at the end of last two columns in the *New File* and *Data Entry Screen*, WinAmptb does not estimate some of thermometers and barometers (e.g. amphibole-liquid empirical equations by Molina et al., 2015) as they require a complete plagioclase analysis.

Amphibole, liquid and plagioclase analyses typed in an Excel file with the extension of ".xls" and ".xlsx" as in



Row No	Sample No	SiO2(a)	TiO2(a)	Al2O3(a)	V2O3(a)	Cr2O3(a)	FeO(tot)(a)	MnO(a)	MgO(a)	CaO(a)	Na2O(a)	K2O(a)	F(a)	Cl(a)
1	Ps1	40.57	2.45	12.82	0	0	13.11	0.26	13.02	11.63	2.2	0.92		
2	Ps4	42.2	2.75	11.1	0	0.01	13.1	0.39	13.55	11.07	2.27	0.95		
3	Ps7	42.27	2.7	11.33	0	0.01	13.3	0.4	13.22	11.05	2.28	0.99		
4	Ps10	39.65	2.02	14.58	0	0.01	12.26	0.13	13.09	11.96	2.13	1.16		
5	Ps12	40.1	2.12	14.87	0	0.03	13.1	0.26	13.53	12.3	2.33	1.29		
6	Ps13	40.57	2.45	12.82	0	0	13.11	0.26	13.02	11.63	2.2	0.92		
7	Ps16	46.78	1.23	7.74	0	0	13.091	0.24	14.53	11.09	1.46	0.17		
8	Ps17	48.05	1.3	6.71	0	0	12.251	0.29	15.13	11.16	1.33	0.15		
9	Ps18	48.05	1.3	6.71	0	0	12.251	0.29	15.13	11.16	1.33	0.15		
10	Ps19	47.86	1.53	7.3	0	0	12.987	0.32	14.78	10.75	1.42	0.17		
11	Ps20	47.44	1.65	7.47	0	0	13.171	0.36	14.73	10.85	1.36	0.17		

Row No	Sample No	SiO2(l)	TiO2(l)	Al2O3(l)	Cr2O3(l)	FeO(tot)(l)	MnO(l)	MgO(l)	CaO(l)	Na2O(l)	K2O(l)	P2O5(l)	H2O(l)
1	Pls1	62.32	0.59	17.02	0.00	5.58	0.15	1.49	5.20	3.80	3.84	0.32	5.00
2	Pls4	60.95	0.62	17.43	0.00	6.04	0.16	1.68	5.85	3.80	3.49	0.32	5.00
3	Pls7	62.29	0.59	17.02	0.00	5.59	0.15	1.50	5.21	3.80	3.83	0.32	5.00
4	Pls10	59.53	0.66	17.86	0.00	6.51	0.17	1.88	6.52	3.81	3.13	0.32	5.00
5	Pls12	61.01	0.62	17.41	0.00	6.02	0.16	1.67	5.82	3.80	3.51	0.32	5.00
6	Pls13	62.32	0.59	17.02	0.00	5.58	0.15	1.49	5.20	3.80	3.84	0.32	2.00
7	Pls16	71.38	0.21	12.39	0.00	1.53	0.06	0.46	2.24	4.08	1.68	0.05	5.00
8	Pls17	70.99	0.22	12.58	0.00	1.68	0.07	0.56	2.42	4.07	1.64	0.05	5.00
9	Pls18	70.99	0.22	12.58	0.00	1.68	0.07	0.56	2.42	4.07	1.64	0.05	5.00
10	Pls19	71.30	0.21	12.43	0.00	1.57	0.06	0.48	2.28	4.08	1.67	0.05	5.00
11	Pls20	71.36	0.21	12.39	0.00	1.54	0.06	0.46	2.25	4.08	1.68	0.05	5.00

Row No	Sample No	SiO2(p)	TiO2(p)	Al2O3(p)	FeO(tot)(p)	MnO(p)	MgO(p)	BaO(p)	CaO(p)	Na2O(p)	K2O(p)	Xab(p)	Xan(p)
1	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
2	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
3	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
4	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
5	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
6	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
7	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
8	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
9	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
10	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		
11	Plagioclase	56.099	0.05	27.62	0.283	0.009	0.011	0.032	9.538	6	0.352		

Figure 1. Screenshot of the WinAmptb *Data Entry Screen* window showing data edits of calcic amphibole (Figure 1a), liquid (Figure 1b), and plagioclase (Figure 1c) analyses.

a

WinAmptb	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58
Sample No	[Si	Al(IV)	Ti	Total(apfu)]T-site(a)	[Al(VI)	Ti	Fe3+	V	Cr	Mg	Fe2+	Mn	Total(apfu)]C-site(a)	[Mn	Fe2+	Mg	Cr	V	Fe3+	Ca	Na	Total(apfu)]B-site(a)	[Na	Ca	K	Total(apfu)]A-site(a)	[F	Cl	OH	Total]OH-site(a)
Pas1	6.088	1.912	0.000	8.000	0.356	0.276	0.000	0.000	0.000	2.913	1.455	0.000	5.000	0.033	0.190	0.000	0.000	0.000	0.000	1.777	0.000	2.000	0.640	0.093	0.176	0.910	0.000	0.000	2.000	2.000
Pas4	6.289	1.711	0.000	8.000	0.239	0.308	0.000	0.000	0.001	3.011	1.441	0.000	5.000	0.049	0.192	0.000	0.000	0.000	0.000	1.759	0.000	2.000	0.656	0.009	0.181	0.845	0.000	0.000	2.000	2.000
Pas7	6.293	1.707	0.000	8.000	0.281	0.302	0.000	0.000	0.001	2.934	1.482	0.000	5.000	0.050	0.176	0.000	0.000	0.000	0.000	1.763	0.011	2.000	0.647	0.000	0.188	0.835	0.000	0.000	2.000	2.000
Pas10	5.936	2.064	0.000	8.000	0.509	0.227	0.000	0.000	0.001	2.922	1.341	0.000	5.000	0.016	0.194	0.000	0.000	0.000	0.000	1.789	0.000	2.000	0.618	0.129	0.222	0.969	0.000	0.000	2.000	2.000
Pas12	5.863	2.137	0.000	8.000	0.425	0.233	0.000	0.000	0.003	2.949	1.390	0.000	5.000	0.032	0.212	0.000	0.000	0.000	0.000	1.756	0.000	2.000	0.660	0.171	0.241	1.072	0.000	0.000	2.000	2.000
Pas13	6.088	1.912	0.000	8.000	0.356	0.276	0.000	0.000	0.000	2.913	1.455	0.000	5.000	0.033	0.190	0.000	0.000	0.000	0.000	1.777	0.000	2.000	0.640	0.093	0.176	0.910	0.000	0.000	2.000	2.000
Pas16	6.928	1.072	0.000	8.000	0.279	0.137	0.000	0.000	0.000	3.208	1.377	0.000	5.000	0.030	0.244	0.000	0.000	0.000	0.000	1.725	0.000	2.000	0.419	0.034	0.032	0.486	0.000	0.000	2.000	2.000
Pas17	7.070	0.930	0.000	8.000	0.234	0.144	0.000	0.000	0.000	3.319	1.303	0.000	5.000	0.036	0.204	0.000	0.000	0.000	0.000	1.759	0.000	2.000	0.379	0.000	0.028	0.408	0.000	0.000	2.000	2.000
Pas18	7.070	0.930	0.000	8.000	0.234	0.144	0.000	0.000	0.000	3.319	1.303	0.000	5.000	0.036	0.204	0.000	0.000	0.000	0.000	1.759	0.000	2.000	0.379	0.000	0.028	0.408	0.000	0.000	2.000	2.000
Pas19	7.007	0.993	0.000	8.000	0.267	0.168	0.000	0.000	0.000	3.226	1.339	0.000	5.000	0.040	0.254	0.000	0.000	0.000	0.000	1.686	0.020	2.000	0.383	0.000	0.032	0.415	0.000	0.000	2.000	2.000
Pas20	6.954	1.046	0.000	8.000	0.245	0.182	0.000	0.000	0.000	3.219	1.354	0.000	5.000	0.045	0.260	0.000	0.000	0.000	0.000	1.695	0.000	2.000	0.387	0.009	0.032	0.428	0.000	0.000	2.000	2.000

b

WinAmptb	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84
Sample No	[Si	Al(IV)	Total(apfu)]T-site(a)	[Al(VI)	Ti	Fe3+	Cr	V	Mg	Mn	Fe2+	Ca	Total(apfu)]M1,2,3-sites(a)	[Fe2+	Ca	Na	Total(apfu)]M4-site(a)	[Ca	Na	K	Total(apfu)]A-site(a)	[F	Cl	OH	Total]OH-site(a)	[Total Cations](a)
Pas1	5.995	2.005	8.000	0.228	0.272	0.705	0.000	0.000	2.868	0.033	0.895	0.000	5.000	0.021	1.841	0.138	2.000	0.000	0.492	0.173	0.666	0.000	0.000	2.000	2.000	15.666
Pas4	6.207	1.793	8.000	0.131	0.304	0.606	0.001	0.000	2.971	0.049	0.939	0.000	5.000	0.067	1.744	0.189	2.000	0.000	0.458	0.178	0.637	0.000	0.000	2.000	2.000	15.637
Pas7	6.216	1.784	8.000	0.179	0.299	0.565	0.001	0.000	2.898	0.050	1.009	0.000	5.000	0.062	1.741	0.197	2.000	0.000	0.453	0.186	0.639	0.000	0.000	2.000	2.000	15.639
Pas10	5.841	2.159	8.000	0.373	0.224	0.738	0.001	0.000	2.875	0.016	0.774	0.000	5.000	0.000	1.888	0.112	2.000	0.000	0.496	0.218	0.714	0.000	0.000	2.000	2.000	15.714
Pas12	5.753	2.247	8.000	0.268	0.229	0.857	0.003	0.000	2.894	0.032	0.718	0.000	5.000	0.000	1.891	0.109	2.000	0.000	0.539	0.236	0.775	0.000	0.000	2.000	2.000	15.775
Pas13	5.995	2.005	8.000	0.228	0.272	0.705	0.000	0.000	2.868	0.033	0.895	0.000	5.000	0.021	1.841	0.138	2.000	0.000	0.492	0.173	0.666	0.000	0.000	2.000	2.000	15.666
Pas16	6.822	1.178	8.000	0.152	0.135	0.701	0.000	0.000	3.159	0.030	0.823	0.000	5.000	0.072	1.733	0.195	2.000	0.000	0.218	0.032	0.249	0.000	0.000	2.000	2.000	15.249
Pas17	6.980	1.020	8.000	0.128	0.142	0.592	0.000	0.000	3.276	0.036	0.826	0.000	5.000	0.070	1.737	0.193	2.000	0.000	0.182	0.028	0.209	0.000	0.000	2.000	2.000	15.209
Pas18	6.980	1.020	8.000	0.128	0.142	0.592	0.000	0.000	3.276	0.036	0.826	0.000	5.000	0.070	1.737	0.193	2.000	0.000	0.182	0.028	0.209	0.000	0.000	2.000	2.000	15.209
Pas19	6.904	1.096	8.000	0.145	0.166	0.677	0.000	0.000	3.178	0.039	0.795	0.000	5.000	0.096	1.661	0.243	2.000	0.000	0.154	0.031	0.185	0.000	0.000	2.000	2.000	15.185
Pas20	6.849	1.151	8.000	0.120	0.179	0.698	0.000	0.000	3.170	0.044	0.789	0.000	5.000	0.103	1.678	0.218	2.000	0.000	0.162	0.031	0.194	0.000	0.000	2.000	2.000	15.194

c

WinAmptb	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111
Sample No	[Fe2O3(calc)	FeO(calc)	H2O(calc)	Total](a)	[Cation Charge](a)	[Si	Al(IV)	Ti	Total(apfu)]T-site(a)	[Al(VI)	Cr	V	Fe3+	Ti	Mg	Fe2+	Mn	Total(apfu)]C-site(a)	[FM	Ca	Na	Total(apfu)]B-site(a)	Na	K	Total(apfu)]A-site(a)	[Amphibole Groups]	[Calcic Amphibole Names]
Pas1	6.338	7.407	1.998	99.614	46.000	6.088	1.912	0.000	8.000	0.356	0.000	0.000	0.142	0.276	2.913	1.313	0.000	5.000	0.223	1.777	0.000	2.000	0.640	0.176	0.816	Calcic amphibole	Pargasite
Pas4	5.473	8.176	2.012	99.951	46.000	6.289	1.711	0.000	8.000	0.239	0.001	0.000	0.134	0.308	3.011	1.307	0.000	5.000	0.241	1.759	0.000	2.000	0.656	0.181	0.837	Calcic amphibole	Pargasite
Pas7	5.103	8.709	2.014	100.076	46.000	6.293	1.707	0.000	8.000	0.281	0.001	0.000	0.139	0.302	2.934	1.342	0.000	5.000	0.225	1.763	0.013	2.000	0.645	0.188	0.833	Calcic amphibole	Pargasite
Pas10	6.656	6.280	2.003	99.669	46.002	5.936	2.064	0.000	8.000	0.509	0.001	0.000	0.138	0.227	2.922	1.203	0.000	5.000	0.211	1.789	0.000	2.000	0.618	0.222	0.840	Calcic amphibole	Pargasite
Pas12	7.936	5.981	2.051	102.797	46.005	5.863	2.137	0.000	8.000	0.425	0.003	0.000	0.148	0.233	2.949	1.241	0.000	5.000	0.244	1.756	0.000	2.000	0.660	0.241	0.901	Calcic amphibole	Pargasite
Pas13	6.338	7.407	1.998	99.614	46.000	6.088	1.912	0.000	8.000	0.356	0.000	0.000	0.137	0.276	2.913	1.318	0.000	5.000	0.223	1.777	0.000	2.000	0.640	0.176	0.816	Calcic amphibole	Pargasite
Pas16	6.392	7.339	2.025	98.996	46.000	6.928	1.072	0.000	8.000	0.279	0.000	0.000	0.113	0.137	3.208	1.264	0.000	5.000	0.275	1.725	0.000	2.000	0.419	0.032	0.451	Calcic amphibole	Magnesiohornblende
Pas17	5.413	7.380	2.038	98.951	46.000	7.070	0.930	0.000	8.000	0.234	0.000	0.000	0.109	0.144	3.319	1.194	0.000	5.000	0.241	1.759	0.000	2.000	0.379	0.028	0.408	Calcic amphibole	Magnesiohornblende
Pas18	5.413	7.380	2.038	98.951	46.000	7.070	0.930	0.000	8.000	0.234	0.000	0.000	0.109	0.144	3.319	1.194	0.000	5.000	0.241	1.759	0.000	2.000	0.379	0.028	0.408	Calcic amphibole	Magnesiohornblende
Pas19	6.234	7.381	2.048	99.793	46.000	7.007	0.993	0.000	8.000	0.267	0.000	0.000	0.113	0.168	3.226	1.226	0.000	5.000	0.291	1.686	0.023	2.000	0.380	0.032	0.412	Calcic amphibole	Magnesiohornblende
Pas20	6.421	7.393	2.045	99.889	46.000	6.954	1.046	0.000	8.000	0.245	0.000	0.000	0.113	0.182	3.219	1.241	0.000	5.000	0.305	1.695	0.000	2.000	0.387	0.032	0.418	Calcic amphibole	Magnesiohornblende

Figure 2. Screenshot of an Excel file (i.e. Output.xlsx) created by program for calculation, classification, and prediction of site allocations of electron-microprobe calcic amphibole-only analyses (see text for explanations).

WinAmptb	113	114	115	116	117	118	119	120	121	122	123
Sample No	[SiO2	TiO2	Al2O3	Cr2O3	FeO(Total)	MnO	MgO	CaO	Na2O	K2O	P2O5
Pas1	62.3170	0.5930	17.0150	0.0000	5.5790	0.1470	1.4940	5.1990	3.8000	3.8400	0.3210
Pas4	60.9540	0.6240	17.4300	0.0000	6.0370	0.1570	1.6820	5.8460	3.8020	3.4930	0.3210
Pas7	62.2910	0.5930	17.0230	0.0000	5.5880	0.1480	1.4970	5.2110	3.8000	3.8330	0.3210
Pas10	59.5340	0.6560	17.8620	0.0000	6.5140	0.1680	1.8770	6.5200	3.8050	3.1320	0.3210
Pas12	61.0080	0.6220	17.4140	0.0000	6.0190	0.1570	1.6740	5.8200	3.8020	3.5070	0.3210
Pas13	62.3170	0.5930	17.0150	0.0000	5.5790	0.1470	1.4940	5.1990	3.8000	3.8400	0.3210
Pas16	71.3750	0.2100	12.3880	0.0000	1.5350	0.0640	0.4600	2.2430	4.0840	1.6780	0.0470
Pas17	70.9930	0.2220	12.5760	0.0000	1.6830	0.0670	0.5610	2.4150	4.0670	1.6450	0.0510
Pas18	70.9930	0.2220	12.5760	0.0000	1.6830	0.0670	0.5610	2.4150	4.0670	1.6450	0.0510
Pas19	71.2950	0.2120	12.4270	0.0000	1.5660	0.0650	0.4810	2.2790	4.0800	1.6710	0.0480
Pas20	71.3630	0.2100	12.3940	0.0000	1.5400	0.0650	0.4630	2.2480	4.0830	1.6770	0.0470

WinAmptb	124	125	126	127	128	129	130	131	132	133	134	135
Sample No	H2O](l)	[Si	Ti	Al	Cr	Fe(Total)	Mn	Mg	Ca	Na	K	P](l)
Pas1	5.0000	0.5773	0.0041	0.1858	0.0000	0.0432	0.0012	0.0206	0.0516	0.0683	0.0454	0.0025
Pas4	5.0000	0.5643	0.0043	0.1902	0.0000	0.0467	0.0012	0.0232	0.0580	0.0682	0.0413	0.0025
Pas7	5.0000	0.5771	0.0041	0.1859	0.0000	0.0433	0.0012	0.0207	0.0517	0.0683	0.0453	0.0025
Pas10	5.0000	0.5507	0.0046	0.1947	0.0000	0.0504	0.0013	0.0259	0.0646	0.0682	0.0370	0.0025
Pas12	5.0000	0.5648	0.0043	0.1900	0.0000	0.0466	0.0012	0.0231	0.0577	0.0682	0.0414	0.0025
Pas13	2.0000	0.5773	0.0041	0.1858	0.0000	0.0432	0.0012	0.0206	0.0516	0.0683	0.0454	0.0025
Pas16	5.0000	0.7091	0.0016	0.1450	0.0000	0.0128	0.0005	0.0068	0.0239	0.0787	0.0213	0.0004
Pas17	5.0000	0.7036	0.0017	0.1469	0.0000	0.0139	0.0006	0.0083	0.0256	0.0782	0.0208	0.0004
Pas18	5.0000	0.7036	0.0017	0.1469	0.0000	0.0139	0.0006	0.0083	0.0256	0.0782	0.0208	0.0004
Pas19	5.0000	0.7079	0.0016	0.1454	0.0000	0.0130	0.0005	0.0071	0.0242	0.0786	0.0212	0.0004
Pas20	5.0000	0.7089	0.0016	0.1451	0.0000	0.0128	0.0005	0.0069	0.0239	0.0786	0.0213	0.0004

Figure 3. Screenshot of an Excel file (i.e. Output.xlsx) created by program for liquid composition with calculation of cation fractions.

WinAmptb	137	138	139	140	141	142	143	144	145	146	147	148
Sample No	[SiO2	TiO2	Al2O3	FeO(Total)	MnO	MgO	BaO	CaO	Na2O	K2O](p)	[Si	Ti
Pas1	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas4	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas7	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas10	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas12	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas13	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas16	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas17	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas18	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas19	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007
Pas20	56.099	0.050	27.620	0.283	0.009	0.011	0.032	9.538	6.000	0.352	10.106	0.007

WinAmptb	149	150	151	152	153	154	155	156	157	158	159
Sample No	Al	Fe(Total)	Mn	Mg	Ba	Ca	Na	K](p)	[Ab	An	Or](p)
Pas1	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas4	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas7	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas10	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas12	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas13	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas16	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas17	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas18	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas19	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014
Pas20	5.864	0.043	0.001	0.003	0.002	1.841	2.096	0.081	52.163	45.823	2.014

Figure 4. Screenshot of an Excel file (i.e. Output.xlsx) created by program for calculation of plagioclase analyses.

the above order, can be loaded into the program's *Data Entry Screen* by clicking the *Open Excel File* option from the pull-down menu of *File*. By selecting the *Edit Excel File* option from the pull-down menu of *File*, amphibole, liquid and plagioclase analyses can be typed in a blank Excel file (i.e. WinAmptb), stored in a different file name with the extension of ".xls" or ".xlsx", and then loaded into the program's *Data Entry Screen* by clicking the *Open Excel File* option from the pull-down menu of *File*. Additional information about data entry or similar topics can be accessed by pressing the F1 function key to display the WinAmptb.hlp file on the screen.

Normalization and ferric iron estimation

The ferromagnesian rock-forming silicate minerals in metamorphic and igneous rocks are used in a variety of thermometers and barometers. Although electron-microprobe technique provides fast and high-quality major oxide analyses, it still requires ferric and ferrous iron separation by means of the stoichiometry criteria. Compared to the other ferromagnesian minerals such as pyroxenes and garnets, an estimation of ferric iron in amphiboles according to the stoichiometric criteria may show an acceptable range of upper and lower limits that result in maximum and minimum value of ferric iron contents (Schumacher, 1991). In electron-microprobe-derived amphibole analysis, the ferric iron content is estimated either minimum (e.g. 16CAT and 15eNK) or maximum (e.g. 13eCNK and 15eK) on the basis of 23 oxygens anhydrous cations within the stoichiometric limits (see Figure 2).

WinAmptb calculates microprobe-derived amphibole analyses on the basis of 23 oxygens anhydrous cations and estimates Fe_2O_3 and FeO (wt%) from total FeO (wt%) as well as H_2O (wt%) contents based on the stoichiometric criteria (see Figure 2c). However, the program also allows the user to select the normalization option for the calculation of structural formulae based on 13eCNK, 15eNK, 15eK, and average (i.e. [(15eNK+15eK)]/2) cations with stoichiometric ferric estimates from the pull-down menu of *Normalization* in the *Data Entry Screen*. In some thermometers (e.g. amphibole-plagioclase thermometry by Holland and Blundy, 1994), recalculation of amphibole formulae for ferric iron estimations and site allocations may need special crystal-chemical constraints. In such cases, the program considers the required calculation steps for the thermometers regardless of the selected normalization option from the pull-down menu of *Normalization*.

WORKED EXAMPLES

The following examples explain how WinAmptb can be used for a variety of calcic amphibole-only, amphibole-plagioclase and amphibole-liquid thermometry and barometry estimations in igneous and metamorphic rocks. Amphibole-only, amphibole-plagioclase and amphibole-liquid thermobarometric and chemometric estimations by program are listed in Table 2. Validity of WinAmptb outputs has been tested for numerous data sets, and results are given in Tables 3-5. Once the calcic amphibole, liquid and plagioclase analyses are processed by clicking the *Calculate* icon (i.e. ∑) in the *Data Entry Section* of the program (see Figure 1a), all estimation parameters are displayed in columns 1-264 (see Table 1) of the *Calculation Screen*. Pressing the *Ctrl+F* keys or clicking the *Open File to Calculate* option from the *Calculate* menu also executes the data processing for a selected data file with the extension of ".amp". By clicking, the *Send results to Excel file* icon in the *Calculation Screen*, all calculations can be stored in an Excel file (Output.xlsx) and then displayed by clicking the *Open and edit Excel file* icon.

Amphibole-only thermobarometers, oxygen fugacity and hygrometric formulations

Based on the results of an experimental study of hornblende from three different basaltic magmas at 5 kbar and 700 to 1000 ºC *P-T* conditions, Helz (1973) proposed that the Ti (*apfu*) content from magmatic as well as subsolidus hornblendes can be used as a thermometer if the oxygen fugacity was near the quartz-fayalite-magnetite (QFM) buffer and calcic amphiboles are associated with Ti-rich minerals such as ilmenite, rutile and titanite. Using the data by Helz (1973), Otten (1984) formulated the semi-empirical Ti-in-hornblende thermometer equation by averaging hornblende compositions at a particular temperature that comprises two segments.

$$[T]_{O_{84}}(^{o}C) = 273 * (Ti/23\ O) + 877 \quad \text{for } T > 970\ ^{o}C$$
$$[T]_{O_{84}}(^{o}C) = 1204 * (Ti/23\ O) + 545 \quad \text{for } T < 970\ ^{o}C \qquad (1)$$

In Eq. 1, the Ti/23 O denotes the number of Ti (*apfu*) cations of calcic amphibole that calculated per unit formula of 23 oxygens. In the screenshot of an output Excel file (Figure 5a), calculation by program for the Otten's (1984) thermometer is listed in column number 161 (see row 28 in Table 3). Calibration conditions and compositional bounds for all equations referenced in text are given in Appendix.

The correlation between total aluminum content of hornblende rim and pressure condition was investigated by Hammarstrom and Zen (1986) using the simple linear regression fit for low-pressure (i.e. ~1-2 kbar; magmatic epidote absence) and high-pressure (i.e. ~8 kbar; magmatic epidote presence) calc-alkaline intrusive complexes having mineral assemblages consist of plagioclase,

Table 2. Description of column numbers in the *Calculation Screen* window of WinAmptb program and an output Excel file for thermobarometric and chemometric formulations.

Row	Explanations	Column Numbers
1	Amp-only thermometer (ºC) by Otten (1984)	161
2	Al-in-hbl barometer (kbar) by Anderson and Smith (1995) using the *T* (ºC) by Otten (1984)	162
3	Al-in-hbl barometer (kbar) by Hammarstrom and Zen (1986)	163
4	Al-in-hbl barometer (kbar) by Hollister et al. (1987)	164
5	Al-in-hbl barometer (kbar) by Johnson and Rutherford (1989)	165
6	Al-in-hbl barometer (kbar) by Thomas and Ernst (1990)	166
7	Al-in-hbl barometer (kbar) by Schmidt (1992)	167
8	Al-in-hbl barometer (kbar) by Ague (1997) computed using the calibration of Johnson and Rutherford (1989)	168
9	Al-in-hbl barometer (kbar) by Ague (1997) computed using the calibration of Schmidt (1992)	169
10	Al-in-hbl barometer (kbar) by Ernst and Lui (1998)	170
11	Amp-only thermometer (ºC) by Ernst and Lui (1998)	171
12	Amp-only thermometer (ºC) by Féménias et al. (2006)	172
13	Al-in-hbl barometer (kbar) by Anderson and Smith (1995) using the *T* (ºC) by Féménias et al. (2006)	173
14	Al-in-hbl barometer (MPa) by Larocque and Canil (2010)	174
15	Amp-only thermometer (ºC) by Ridolfi et al. (2010)	175
16	Amp-only ΔNNO (log units) by Ridolfi et al. (2010)	176
17	Amp-only H_2O_{melt} (%) by Ridolfi et al. (2010)	177
18	Amp-only barometer (MPa) by Ridolfi et al. (2010)	178
19	Oxygen fugacity NNO buffer (log fO_2) from Hirschmann et al. (2008; Table 7) using the amp-only *T* (ºC) and *P* (kbar) values by Ridolfi et al. (2010)	179
20	Amp crystallization depth (km) using the *P* (MPa) by Ridolfi et al. (2010) for oceanic crust based on an average specific weigths of 2.89 g/cm^3	180
21	Amp crystallization depth (km) using the *P* (MPa) by Ridolfi et al. (2010) for continental crust based on an average specific weigths of 2.70 g/cm^3	181
22	Amp species by Ridolfi (2016)	182
23	Amp-only barometer 1a (MPa) by Ridolfi and Renzulli (2012)	183
24	Amp-only barometer 1b (MPa) by Ridolfi and Renzulli (2012)	184
25	Amp-only barometer 1c (MPa) by Ridolfi and Renzulli (2012)	185
26	Amp-only barometer 1d (MPa) by Ridolfi and Renzulli (2012)	186
27	Amp-only barometer 1e (MPa) by Ridolfi and Renzulli (2012)	187
28	Amp-only confining pressure (MPa) by Ridolfi and Renzulli (2012)	188
29	Amp-only thermometer (ºC) using the barometer 1a (MPa) by Ridolfi and Renzulli (2012)	189
30	Amp-only thermometer (ºC) using the barometer 1b (MPa) by Ridolfi and Renzulli (2012)	190
31	Amp-only thermometer (ºC) using the barometer 1c (MPa) by Ridolfi and Renzulli (2012)	191
32	Amp-only thermometer (ºC) using the barometer 1d (MPa) by Ridolfi and Renzulli (2012)	192
33	Amp-only thermometer (ºC) using the barometer 1e (MPa) by Ridolfi and Renzulli (2012)	193
34	Amp-only thermometer (ºC) using the confining P (MPa) by Ridolfi and Renzulli (2012)	194
35	Amp-only ΔNNO (log units) by Ridolfi and Renzulli (2012)	195
36	Amp-only H_2O_{melt} (%) by Ridolfi and Renzulli (2012)	196

Table 2. ...Continued

Row	Explanations	Column Numbers
37	Amp-only SiO_{2melt} (%) by Ridolfi and Renzulli (2012)	197
38	Oxygen fugacity NNO buffer (log fO_2) from Hirschmann et al. (2008; Table 7) using the amp-only confining *T* (ºC) and *P* (kbar) values by Ridolfi and Renzulli (2012)	198
39	Amp crystallization depth (km) using confining *P* (MPa) by Ridolfi and Renzulli (2012) for oceanic crust based on an average specific weigths of 2.89 g/cm^3	199
40	Amp crystallization depth (km) using confining *P* (MPa) by Ridolfi and Renzulli (2012) for continental crust based on an average specific weigths of 2.70 g/cm^3	200
41	Al-in-hbl barometer (MPa) by Krawczynski et al. (2012)	201
42	H_2O *P* [P_{H2O} (MPa)] by Krawczynski et al. (2012) using the amp composition	202
43	Si-in-hbl-only thermometer (ºC) by Putirka (2016)	203
44	Amp-only thermometer (ºC) by Putirka (2016; Eqn. 5)	204
45	Al-in-hbl barometers (i.e. a and b in an Excel output) (kbar) by Putirka (2016) after the calibration of Hammarstrom and Zen (1986)	205-206
46	Al-in-hbl barometer (kbar) by Mutch et al. (2016)	207
47	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using an arbitrary *P* (kbar) value between 1 and 5	208
48	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using the calibration of Hammarstrom and Zen (1986)	209
49	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using the calibration of Hollister et al. (1987)	210
50	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using the calibration of Johnson and Rutherford (1989)	211
51	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using the calibration of Schmidt (1992)	212
52	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using the calibration of Ague (1997) after Johnson and Rutherford (1989)	213
53	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using the calibration of Ague (1997) after Schmidt (1992)	214
54	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using the calibration of Putirka (2016) after Hammarstrom and Zen (1986)	215-216
55	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using an arbitrary *P* (kbar) value between 1 and 5	217
56	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using the calibration of Hammarstrom and Zen (1986)	218
57	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using the calibration of Hollister et al. (1987)	219
58	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using the calibration of Johnson and Rutherford (1989)	220
59	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using the calibration of Schmidt (1992)	221
60	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using the calibration of Ague (1997) after Johnson and Rutherford (1989)	222
61	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using the calibration of Ague (1997) after Schmidt (1992)	223
62	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using the calibration of Putirka (2016) after Hammarstrom and Zen (1986)	224-225
63	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using an arbitrary *P* (kbar) value between 1 and 5	226
64	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using the calibration of Hammarstrom and Zen (1986)	227
65	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using the calibration of Hollister et al. (1987)	228
66	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using the calibration of Johnson and Rutherford (1989)	229

Table 2. ...Continued

Row	Explanations	Column Numbers
67	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using the calibration of Schmidt (1992)	230
68	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using the calibration of Ague (1997) after Johnson and Rutherford (1989)	231
69	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using the calibration of Ague (1997) after Schmidt (1992)	232
70	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using the calibration of Putirka (2016) after Hammarstrom and Zen (1986)	233-234
71	Amp-pl thermometer (ºC) by Blundy and Holland (1990) using the prior *P* (kbar) for new *T* (ºC) at third iteration by Anderson (2016)	235-236
72	Amp-pl thermometer (ºC) for ed-tr by Holland and Blundy (1994) using the prior *P* (kbar) for new *T* (ºC) at third iteration by Anderson (2016)	237-238
73	Amp-pl thermometer (ºC) for ed-rct by Holland and Blundy (1994) using the prior *P* (kbar) for new *T* (ºC) at third iteration by Anderson (2016)	239-240
74	Amp-liq barometer (kbar) by Molina et al. (2015) using the amp-liq *T* (ºC) of Molina et al. (2015)	241
75	Amp-liq barometer (kbar) by Molina et al. (2015) using the liq-only *T* (ºC) of Molina et al. (2015)	242
76	Liq-only thermometer (ºC) by Molina et al. (2015)	243
77	Amp-liq thermometer (ºC) by Molina et al. (2015)	244
78	Liquid-only thermometer (ºC) by Putirka (2016; Eqn. 3)	245
79	Amp-liq thermometer (ºC) by Putirka (2016; Eqn. 4a)	246
80	Amp-liq thermometer (ºC) by Putirka (2016; Eqn. 4b)	247
81	Amp-liq thermometer (ºC) by Putirka (2016; Eqn. 9)	248
82	Amp-liq thermometer (ºC) by Putirka (2016; Eqn. 6)	249
83	Amp-liq thermometer (ºC) by Putirka (2016; Eqn. 8)	250
84	Amp-liq barometer (kbar) by Putirka (2016; Eqn. 7a)	251
85	Amp-liq barometer (kbar) by Putirka (2016; Eqn. 7b)	252
86	Amp-liq barometer (kbar) by Putirka (2016; Eqn. 7c)	253
87	H_2O liq at saturation (wt%) by Putirka (2016)	254
88	Prediction of SiO_2 (wt%) using the amp composition in coexisting with liq by Putirka (2016)	255
89	Oygen fugacity QFM buffer (logfO_2) estimation from Fegley (2013) for Putirka's (2016) *P-T* calibrations	256
90	Oygen fugacity NNO buffer (logfO_2) estimation from Fegley (2013) for Putirka's (2016) *P-T* calibrations	257
91	Oygen fugacity HM buffer (logfO_2) estimation from Fegley (2013) for Putirka's (2016) P*P-T* calibrations	258
92	Oygen fugacity QFM buffer (logfO_2) estimation from Fegley (2013) for Ridolfi and Renzulli's (2012) *P-T* calibrations	259
93	Oygen fugacity NNO buffer (logfO_2) estimation from Fegley (2013) for Ridolfi and Renzulli's (2012) *P-T* calibrations	260
94	Oygen fugacity HM buffer (logfO_2) estimation from Fegley (2013) for Ridolfi and Renzulli's (2012) *P-T* calibrations	261
95	Oygen fugacity QFM buffer (logfO_2) estimation from Fegley (2013) for Ridolfi et al.'s (2010) *P-T* calibrations	262
96	Oygen fugacity NNO buffer (logfO_2) estimation from Fegley (2013) for Ridolfi et al.'s (2010) *P-T* calibrations	263
97	Oygen fugacity HM buffer (logfO_2) estimation from Fegley (2013) for Ridolfi et al.'s (2010) *P-T* calibrations	264

Notes: Amp = amphibole; hbl = hornblende; pl = plagioclase; ed = edenite; tr = tremolite; rct = richterite; liq = liquid; *T* = temperature; *P* = pressure; QFM = Quartz-Fayalite-Magnetite; NNO = Nickel-Nickel Oxide; HM = Hematite-Magnetite. Explanations for each column number are given in the second row of an output Excel file (i.e. Output.xlsx) as a comment mark.

hornblende, biotite, K-feldspar, quartz, sphene, magnetite or ilmenite, ± epidote:

$$[P]_{HZ_{86}} (\pm 3 \text{ kbar}) = -3.92 + 5.03 * Al_{Tot} \quad (R^2 = 0.80) \tag{2}$$

In this barometer (see column 163 in Figure 5a and row 30 in Table 3), amphibole is recalculated on the basis of 23 oxygens anhydrous formula. The Al-in-hornblende barometer has subsequently been empirically and experimentally calibrated and used by earth scientists for granitoids and adjacent aureole rocks as a powerful petrologic tools.

Hollister et al. (1987) tested the proposed Al-in-hornblende barometer especially for calc-alkaline plutons that crystallized at intermediate pressures (i.e. 4-6 kbar) and proposed a new barometer with a decreased error of estimation and high correlation coefficient:

$$[P]_{H_{87}} (\pm 1 \text{ kbar}) = -4.76 + 5.64 * Al_{Tot} \quad R^2 = 0.97 \tag{3}$$

In this barometer (see column 164 in Figure 5a and row 31 in Table 3), amphibole analyses were normalized to the 15eNK normalization scheme. Hollister et al. (1987) also concluded that to get a reliable pressure value from an empirically calibrated barometer, the following conditions should be met: i) the quartz, plagioclase, hornblende, biotite, orthoclase, sphene, and magnetite phases must have crystallized together from a melt; ii) only the rim compositions of hornblende should be used in estimation; iii) the pressure that used for the samples should be above ~2 kbar; and iv) the rim plagioclase composition should be between ~An_{25} and An_{35}.

Johnson and Rutherford (1989) proposed a new experimentally calibrated Al-in-hornblende barometer over a 2-8 kbar at 740-780 ºC for igneous hornblendes in equilibrium with melt, fluid, biotite, quartz, K-feldspar, plagioclase, sphene, and magnetite/ilmenite phases:

$$[P]_{JR_{89}} (\pm 0.5 \text{ kbar}) = -3.46 + 4.23 * Al_{Tot} \quad R^2 = 0.99 \tag{4}$$

Experiments for the barometer (see column 165 in Figure 5a and row 32 in Table 3) were carried out in water-undersaturated conditions and structural formula of amphibole was calculated to the 23 oxygens with stoichiometric ferric and ferrous iron separation based on 15 cations. The validity of Johnson and Rutherford (1989) barometer depends on hornblende being in equilibrium of quartz, otherwise high pressures are calculated by the equation.

Thomas and Ernst (1990) calibrated experimentally Al-in-hornblende barometer for a natural, but more aluminous hornblende-bearing tonalite in equilibrium with quartz, K-feldspar, plagioclase, biotite, epidote, sphene, Fe-Ti oxide, melt and fluid at 750 ºC as a function of pressure in the range of 6-12 kbar:

$$[P]_{TE90} (\pm 1.0 \text{ kbar}) = -6.23 + 5.34 * Al_{Tot} \quad R^2 = 0.94 \tag{5}$$

The Thomas and Ernst (1990) calibration gives similar pressures values at 6-8 kbar those with the Johnson and Rutherford (1989) calibration. The pressures estimated from the Thomas and Ernst (1990) method are applicable to granitoids melts crystallizing at ~750 ºC, but hornblendes that crystallized in 1-2 kbar may not show appropriate results due to the absence of adjustment of rim composition at the experimental conditions (e.g. column 166 in Figure 5a). Hence, the Thomas and Ernst (1990) calibration should be applied for amphibole samples in granitoids that crystallized above the 2.5 kbar pressure conditions.

Schmidt (1992) experimentally calibrated the Al-in-hornblende barometer under water-saturated and *P-T* conditions ranging from 2.5 to13 kbar and temperatures from 655 to 700 ºC for the equilibrium assemblages of hornblende, biotite, plagioclase, K-feldspar, quartz, sphene, Fe-Ti oxides, melt, and vapor in finely ground tonalite and granodiorite:

$$[P]_{S_{92}} (\pm 0.6 \text{ kbar}) = -3.01 + 4.76 * Al_{Tot} \quad R^2 = 0.99 \tag{6}$$

Amphibole compositions that used in barometry (see column 167 in Figure 5a and row 33 in Table 3) were normalized by assuming: i) fixed $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ ratio of 0.3 and 23 oxygens, and ii) the 13eCNK method. In a variation of *P* with total aluminum content of calcic amphibole, an experimental calibration of Schimdt (1992) shows a very close trend to the calibration of Hammarstrom and Zen (1986).

Although the Al-in-hornblende barometers provide a basis in estimation of crystallization pressure of granitic plutons, they are sensitive to variations in oxygen fugacity and temperature. Hence, Anderson and Smith (1995) proposed a revised barometer incorporating the effect of temperature using experimental data by Johnson and Rutherford (1989) at ~760 ºC and Schmidt (1992) at ~675 ºC:

$$[P]_{AS95} (\pm 0.6 \text{ kbar}) = 4.76 * Al_{Tot} - 3.01 - \left\{ \frac{[T(^{o}C) - 675]}{85} \right\} * \left\{ 0.53 * Al_{Tot} + 0.005294 * [T(^{o}C) - 675] \right\} \tag{7}$$

Table 3. Amphibole-only thermobarometer, oxygen fugacity and chemometric estimations by WinAmptb program.

Row	Amphibole compositions	Aas1	Aas2	Aas3	Aas4	Aas5	Aas6	Aas7	Aas8	Aas9	Aas10	Aas11	Aas12	Aas13
1	SiO_2	46.42	45.82	46.78	46.01	47.27	48.90	48.66	48.59	49.21	48.80	48.88	47.27	46.97
2	TiO_2	1.27	1.31	1.30	1.27	1.26	0.52	0.64	0.60	0.81	0.58	0.75	0.75	1.29
3	Al_2O_3	6.81	6.87	6.69	6.45	6.31	6.31	5.84	5.20	5.79	5.32	5.69	6.07	7.14
4	FeO_{Total}	14.21	14.29	14.45	13.94	14.63	13.68	14.31	13.68	14.24	13.48	14.53	14.34	14.76
5	MnO	0.76	0.69	0.70	0.75	0.80	0.80	0.89	0.87	0.81	0.85	0.81	0.73	0.69
6	MgO	13.67	13.44	13.68	13.27	13.55	14.34	14.39	14.49	14.23	14.61	14.27	14.01	13.54
7	CaO	11.59	11.28	11.59	11.30	11.29	11.64	11.66	11.06	11.41	11.64	12.01	11.76	11.88
8	Na_2O	1.36	1.47	1.47	1.40	1.23	1.24	1.24	1.11	1.29	1.08	1.20	1.34	1.53
9	K_2O	0.90	0.93	0.95	0.86	0.70	0.59	0.59	0.56	0.64	0.53	0.68	0.69	0.90
10	F	0.12	0.20	0.18	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	Cl	0.25	0.15	0.30	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	O=F,Cl	0.11	0.12	0.14	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	Total (wt%)	97.25	96.33	97.95	95.39	97.04	98.02	98.22	96.16	98.43	96.89	98.82	96.96	98.70
	Cations per 23 oxygens													
14	Si	6.93	6.91	6.95	6.99	7.04	7.15	7.13	7.24	7.18	7.22	7.14	7.05	6.91
15	Ti	0.14	0.15	0.14	0.14	0.14	0.06	0.07	0.07	0.09	0.07	0.08	0.08	0.14
16	Al	1.20	1.22	1.17	1.16	1.11	1.09	1.01	0.91	1.00	0.93	0.98	1.07	1.24
17	Fe	1.78	1.80	1.79	1.77	1.82	1.67	1.76	1.71	1.74	1.67	1.77	1.79	1.81
18	Mn	0.10	0.09	0.09	0.10	0.10	0.10	0.11	0.11	0.10	0.11	0.10	0.09	0.09
19	Mg	3.04	3.02	3.03	3.00	3.01	3.13	3.15	3.22	3.10	3.22	3.11	3.12	2.97
20	Ca	1.86	1.82	1.84	1.84	1.80	1.82	1.83	1.77	1.78	1.85	1.88	1.88	1.87
21	Na	0.39	0.43	0.42	0.41	0.35	0.35	0.35	0.32	0.36	0.31	0.34	0.39	0.44
22	K	0.171	0.179	0.180	0.167	0.133	0.110	0.110	0.106	0.119	0.100	0.127	0.131	0.169
23	F	0.057	0.095	0.085	0.048	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
24	Cl	0.063	0.038	0.076	0.026	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25	OH	1.880	1.866	1.840	1.926	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
26	Total cations (*apfu*)	15.611	15.619	15.610	15.577	15.503	15.480	15.520	15.456	15.469	15.480	15.527	15.601	15.639
27	Amphibole names	Ed	Ed	Ed	Ed	Mhb	Mhb	Mhb	Mhb	Mhb	Mhb	Mhb	Ed	Ed
	Amphibole-only thermobarometers and chemometers													
28	†T_{O84} (ºC)	717	724	720	720	715	614	630	626	652	623	644	646	717
29	‡P_{AS95_O84} (kbar)	2.20	2.20	2.04	1.98	1.80	2.27	1.86	1.38	1.77	1.46	1.71	2.13	2.38
30	†P_{HZ86} (kbar)	2.11	2.23	1.97	1.89	1.65	1.55	1.16	0.67	1.09	0.74	1.01	1.45	2.30
31	xP_{H87} (kbar)	2.00	2.13	1.84	1.75	1.49	1.37	0.93	0.39	0.86	0.47	0.76	1.26	2.22
32	†P_{JR89} (kbar)	1.61	1.71	1.49	1.42	1.22	1.14	0.81	0.40	0.75	0.46	0.68	1.05	1.77
33	‡P_{S92} (kbar)	2.70	2.81	2.56	2.49	2.26	2.17	1.79	1.34	1.73	1.40	1.65	2.07	2.88
34	†P_{A97_JR89} (kbar)	2.81	2.89	2.71	2.65	2.48	2.41	2.13	1.79	2.09	1.84	2.03	2.34	2.95
35	†P_{A97_S92} (kbar)	2.85	2.93	2.75	2.69	2.53	2.45	2.18	1.84	2.13	1.89	2.07	2.38	2.98
36	†T_{EL98} (ºC)	613	619	608	595	579	543	548	514	533	522	548	576	621
37	†P_{EL98} (kbar)	1.46	1.52	1.29	1.63	1.68	2.92	1.64	1.78	2.27	1.65	1.26	1.25	1.65
38	†T_{F06} (ºC)	714	722	717	717	712	571	598	592	632	586	620	623	714
39	†P_{AS95_F06} (kbar)	2.24	2.23	2.08	2.01	1.84	2.11	1.82	1.29	1.81	1.35	1.73	2.17	2.42

Table 3. ... Continued

Row	Amphibole compositions	Aas1	Aas2	Aas3	Aas4	Aas5	Aas6	Aas7	Aas8	Aas9	Aas10	Aas11	Aas12	Aas13
40	$^{\dagger}P_{LC10}$ (MPa)	259	266	239	279	285	434	281	297	338	282	235	234	281
41	$^{\ddagger}T_{R10}$ (ºC)	815	816	811	804	788	778	775	754	765	763	776	794	820
42	$^{\ddagger}\Delta NNO_{R10}$	1.32	1.29	1.29	1.25	1.37	1.66	1.71	1.91	1.6	1.84	1.59	1.57	1.16
43	$^{\ddagger}H_2Omelt_{R10}$ (%)	3.64	3.47	3.34	3.67	4.13	4.7	4.12	3.96	4.1	4.14	3.86	3.82	3.79
44	$^{\ddagger}P_{R10}$ (MPa)	105	108	101	99	92	90	80	70	79	71	77	87	111
45	$^{\ddagger}\log (fO_2)_{R10}$	-12.23	-12.23	-12.35	-12.53	-12.74	-12.68	-12.70	-12.99	-13.03	-12.86	-12.81	-12.42	-12.28
46	$ACDOC_{R10}$ (km)	3.04	3.13	2.92	2.86	2.66	2.59	2.31	2.01	2.27	2.06	2.23	2.52	3.22
47	$ACDCC_{R10}$ (km)	2.84	2.93	2.73	2.67	2.48	2.42	2.16	1.88	2.13	1.93	2.08	2.35	3.01
48	$^{\ddagger}P1a_{RR12}$ (MPa)	173	192	172	169	142	134	136	125	131	104	109	130	172
49	$^{\ddagger}P1b_{RR12}$ (MPa)	125	127	117	118	115	110	101	95	100	92	92	101	123
50	$^{\ddagger}P1c_{RR12}$ (MPa)	150	149	126	127	114	86	82	55	62	43	48	72	135
51	$^{\ddagger}P1e_{RR12}$ (MPa)	332	355	353	359	265	339	285	247	301	257	278	312	385
52	$^{\ddagger}P_{RR12}$ (MPa)	125	127	117	118	115	110	101	95	100	92	92	101	123
53	$^{\ddagger}T1a_{RR12}$ (MPa)	848	854	842	844	833	807	825	818	815	798	796	811	838
54	$^{\ddagger}T1b_{RR12}$ (MPa)	840	844	833	835	828	802	818	812	808	795	792	805	830
55	$^{\ddagger}T1b_{RR12}$ (MPa)	844	848	835	837	828	796	813	798	796	776	776	797	832
56	$^{\ddagger}T1e_{RR12}$ (MPa)	864	869	860	862	848	830	843	835	835	820	819	833	858
57	$^{\ddagger}T_{RR12}$ (MPa)	840	844	833	835	828	802	818	812	808	795	792	805	830
58	$^{\ddagger}\Delta NNO_{RR12}$	2.49	2.56	2.57	2.44	1.59	2.38	2.32	2.20	2.11	2.12	2.12	2.37	2.40
59	$^{\ddagger}H_2Omelt_{RR12}$ (%)	5.35	5.43	5.36	5.23	4.89	5.68	5.30	4.91	5.11	5.04	5.24	5.57	5.63
60	$^{\ddagger}SiO_2melt_{RR12}$ (%)	78.84	79.05	78.66	78.79	78.06	79.81	77.56	76.23	77.36	74.28	73.96	76.62	78.63
61	$^{\ddagger}\log (fO_2)_{RR12}$	-10.54	-10.39	-10.61	-10.69	-11.69	-11.43	-11.17	-11.42	-11.58	-11.85	-11.92	-11.38	-10.84
62	$ACDOC_{R12}$ (km)	3.61	3.67	3.39	3.40	3.31	3.19	2.93	2.74	2.88	2.66	2.66	2.90	3.56
63	$ACDCC_{R12}$ (km)	3.37	3.43	3.17	3.18	3.09	2.98	2.74	2.56	2.69	2.48	2.49	2.71	3.33
64	$^{\dagger}P_{K12}$ (MPa)	172	179	151	192	199	351	194	211	252	195	147	146	195
65	$^{\dagger}TSi\text{-}in\text{-}hbl_{P16}$ (ºC)	824	828	822	814	805	785	788	769	780	773	788	803	829
66	$^{\dagger}T_{P16}$ (ºC)	794	799	794	789	773	758	756	742	754	746	755	770	799
67	$^{\dagger}P_{P16a\_HZ86}$ (kbar)	1.83	1.90	1.74	1.70	1.56	1.50	1.29	1.06	1.26	1.09	1.22	1.45	1.95
68	$^{\dagger}P_{P16b\_HZ86}$ (kbar)	1.53	1.59	1.47	1.44	1.34	1.30	1.16	1.00	1.14	1.03	1.11	1.26	1.62
69	$^{\Delta}P_{M16}$ (kbar)	2.30	2.36	2.23	2.19	2.06	2.02	1.82	1.61	1.80	1.64	1.76	1.96	2.41

Notes: Amphibole compositions are taken from Anderson (2016). *apfu* = atomic per formula unit; Ed = Edenite; Mhb = Magnesiohornblende; (†) = Cations based on 23 O; (‡) = Cations based on 13eCNK normalization; (x) = Cations based on 15eNK normalization; (Δ) = Cations based on a modification to the method of Holland and Blundy (1994); ACDOC = Amphibole crystallization depth (km) for oceanic crust; ACDCC = Amphibole crystallization depth (km) for continental crust; T_{O84} (row 28) from Otten (1998), P_{AS95_O84} (row 29) from Anderson and Smith (1995) using T (°C) by Otten (1984), P_{HZ86} (row 30) from Hammarstrom and Zen (1986), P_{H87} (row (31) from Hollister et al. (1987), P_{JR89} (row 32) from Johnson and Rutherford (1989), P_{S92} (row 33) from Schmidt (1992), P_{A97_JR89} (row 34) from Ague (1997) after Johnson and Rutherford (1989), P_{A97_S92} (row (35) from Ague (1997) after Schmidt (1992), T_{EL98} (row 36) from Ernst and Liu (1998), P_{EL98} (row 37) from Ernst and Liu (1998), T_{F06} (row 38) from Féménias et al. (2006), P_{AS95_F06} (row 39) from Anderson and Smith (1995) using T (°C) by Féménias et al. (2006), P_{LC10} (row 40) from Larocque and Canil (2010), T_{R10} (row 41) from Ridolfi et al. (2010), ΔNNO_{R10} (row 42) from Ridolfi et al. (2010), H_2Omelt_{R10} (row 43) from Ridolfi et al. (2010), P_{R10} (row 44) from Ridolfi et al. (2010), log $(fO2)_{R10}$ (row 45) after Hirchhmann et al. (2008), $P1a_{RR12}$ to P_{RR12} (rows 48-52) from Ridolfi and Renzulli (2012), $T1a_{RR12}$ to T_{RR12} (rows 53-57) from Ridolfi and Renzulli (2012) by using the corresponding P (MPa) values, ΔNNO_{RR12} (row 58) from Ridolfi and Renzulli (2012), H_2Omelt_{RR12} (row 59) from Ridolfi and Renzulli (2012), SiO_2melt_{RR12} (row 60) from Ridolfi and Renzulli (2012), log $(fO2)_{RR12}$ (row 61) after Hirchhmann et al. (2008), P_{K12} (row 64) from Krawczynski et al. (2012), $TSi\text{-}in\text{-}hbl_{P16}$ (row 65) from Putirka (2016), T_{P16} (row 66) from Putirka (2016), P_{P16a_HZ86} (row 67) from Putirka (2016) after Hammarstrom and Zen (1986), P_{P16b_HZ86} (row 68) from Putirka (2016) after Hammarstrom and Zen (1986), $^{\Delta}P_{M16}$ (row 69) from Mutch et al. (2016).

Table 4. Amphibole-plagioclase thermobarometer estimations by WinAmptb program.

Row	Amphibole compositions	Aas1	Aas2	Aas3	Aas4	Aas5	Aas6	Aas7	Aas8	Aas9	Aas10	Aas11	Aas12	Aas13
1	SiO_2	46.42	45.82	46.78	46.01	47.27	48.90	48.66	48.59	49.21	48.80	48.88	47.27	46.97
2	TiO_2	1.27	1.31	1.30	1.27	1.26	0.52	0.64	0.60	0.81	0.58	0.75	0.75	1.29
3	Al_2O_3	6.81	6.87	6.69	6.45	6.31	6.31	5.84	5.20	5.79	5.32	5.69	6.07	7.14
4	FeO_{Total}	14.21	14.29	14.45	13.94	14.63	13.68	14.31	13.68	14.24	13.48	14.53	14.34	14.76
5	MnO	0.76	0.69	0.70	0.75	0.80	0.80	0.89	0.87	0.81	0.85	0.81	0.73	0.69
6	MgO	13.67	13.44	13.68	13.27	13.55	14.34	14.39	14.49	14.23	14.61	14.27	14.01	13.54
7	CaO	11.59	11.28	11.59	11.30	11.29	11.64	11.66	11.06	11.41	11.64	12.01	11.76	11.88
8	Na_2O	1.36	1.47	1.47	1.40	1.23	1.24	1.24	1.11	1.29	1.08	1.20	1.34	1.53
9	K_2O	0.90	0.93	0.95	0.86	0.70	0.59	0.59	0.56	0.64	0.53	0.68	0.69	0.90
10	F	0.12	0.20	0.18	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	Cl	0.25	0.15	0.30	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	O=F,Cl	0.11	0.12	0.14	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	Total (wt%)	97.25	96.33	97.95	95.39	97.04	98.02	98.22	96.16	98.43	96.89	98.82	96.96	98.70
14	Fe_2O_3 $_{(Calculated)}$ (wt%)	3.924	3.706	3.310	3.573	4.041	4.953	4.553	4.219	4.641	4.403	3.836	3.972	4.133
15	FeO $_{(Calculated)}$ (wt%)	10.680	10.956	11.473	10.725	10.994	9.224	10.214	9.884	10.065	9.519	11.079	10.766	11.042
16	H_2O $_{(Calculated)}$ (wt%)	1.887	1.854	1.857	1.901	2.013	2.050	2.045	2.012	2.054	2.027	2.054	2.011	2.039
17	Total (wt%)	99.534	98.558	100.136	97.645	99.459	100.567	100.722	98.595	100.950	99.359	101.259	99.369	101.154
18	Plagioclase compositions	Aps1	Aps2	Aps3	Aps4	Aps5	Aps6	Aps7	Aps8	Aps9	Aps10	Aps11	Aps12	Aps13
19	X_{Ab}	0.781	0.777	0.738	0.745	0.722	0.731	0.763	0.787	0.722	0.715	0.768	0.748	0.715
20	X_{An}	0.188	0.204	0.233	0.231	0.247	0.230	0.214	0.188	0.252	0.253	0.202	0.219	0.258
	Amphibole formulae and site allocations [from Holland and Blundy (1994)]													
21	Si	6.867	6.851	6.892	6.927	6.971	7.067	7.058	7.167	7.104	7.142	7.072	6.981	6.839
22	Al^{IV}	1.133	1.149	1.108	1.073	1.029	0.933	0.942	0.833	0.896	0.858	0.928	1.019	1.161
23	Total T-site (*apfu*)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
24	Al^{VI}	0.054	0.062	0.054	0.072	0.068	0.142	0.057	0.071	0.090	0.059	0.042	0.038	0.065
25	Ti	0.141	0.147	0.144	0.144	0.140	0.057	0.070	0.067	0.088	0.064	0.082	0.083	0.141
26	Fe^{3+}	0.437	0.417	0.367	0.405	0.448	0.539	0.497	0.468	0.504	0.485	0.418	0.441	0.453
27	Mg	3.015	2.996	3.005	2.978	2.979	3.090	3.112	3.186	3.063	3.187	3.078	3.085	2.939
28	Mn	0.095	0.087	0.087	0.096	0.100	0.098	0.109	0.109	0.099	0.105	0.099	0.091	0.085
29	Fe^{2+}	1.258	1.291	1.343	1.306	1.265	1.076	1.156	1.099	1.157	1.099	1.281	1.261	1.317
30	Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
31	Total *M1,2,3* sites (*apfu*)	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
32	Fe^{2+}	0.063	0.079	0.071	0.045	0.091	0.039	0.083	0.121	0.059	0.066	0.059	0.068	0.027
33	Ca	1.837	1.807	1.830	1.823	1.784	1.802	1.812	1.748	1.765	1.825	1.862	1.861	1.853
34	Na	0.100	0.114	0.100	0.133	0.125	0.158	0.105	0.132	0.177	0.109	0.079	0.071	0.119
35	Total *M4*-site (*apfu*)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
36	Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
37	Na	0.290	0.312	0.320	0.276	0.227	0.189	0.244	0.186	0.185	0.197	0.258	0.313	0.313
38	K	0.170	0.177	0.179	0.165	0.132	0.109	0.109	0.105	0.118	0.099	0.126	0.130	0.167
39	Total A-site (*apfu*)	0.460	0.490	0.499	0.441	0.358	0.298	0.353	0.291	0.302	0.296	0.383	0.443	0.480
40	F	0.057	0.095	0.085	0.048	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
41	Cl	0.063	0.038	0.076	0.026	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
42	OH	1.880	1.866	1.840	1.926	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
43	Total OH-site	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
	Amphibole-plagioclase thermobarometers													
44	T_{BH90_*ap} (°C)	694	698	698	689	686	662	658	629	656	649	654	677	714
45	T_{BH90_PHZ86} (°C)	706	709	712	704	703	682	682	660	682	679	680	698	724
46	T_{BH90_PH87} (°C)	708	710	714	706	706	684	685	663	685	683	683	701	725
47	T_{BH90_PJR89} (°C)	713	716	719	711	709	687	687	663	686	683	685	704	732
48	T_{BH90_PS92} (°C)	698	700	704	696	695	674	674	651	673	670	672	690	716
49	$T_{BH90\_PA97\_PJR89}$ (°C)	696	699	702	694	692	670	669	645	668	665	667	686	715

Table 4. ... Continued

Row	Amphibole compositions	Aas1	Aas2	Aas3	Aas4	Aas5	Aas6	Aas7	Aas8	Aas9	Aas10	Aas11	Aas12	Aas13
50	$T_{BH90\_PA97\_PS92}$ (ºC)	696	699	701	693	691	670	669	645	668	664	666	685	714
51	$T_{BH90\_PP16a\_PHZ86}$ (ºC)	710	713	715	707	705	682	680	655	679	675	677	698	729
52	$T_{BH90\_PP16b\_PHZ86}$ (ºC)	714	718	719	711	708	685	682	655	681	676	679	701	734
53	$T1_{HB94\_*ap}$ (ºC)	750	753	756	740	735	694	721	684	699	708	720	746	768
54	$T1_{HB94\_PHZ86}$ (ºC)	761	763	769	753	751	707	742	708	719	732	744	766	777
55	$T1_{HB94\_PH87}$ (ºC)	763	764	770	755	753	709	745	711	721	735	747	768	778
56	$T1_{HB94\_PJR89}$ (ºC)	767	769	775	759	756	711	746	711	722	735	748	771	784
57	$T1_{HB94\_PS92}$ (ºC)	754	755	761	746	744	701	735	702	712	725	736	758	770
58	$T1_{HB94\_PA97\_PJR89}$ (ºC)	753	754	759	744	741	699	731	697	709	720	732	754	769
59	$T1_{HB94\_PA97\_PS92}$ (ºC)	752	754	759	744	741	699	731	696	708	720	731	754	768
60	$T1_{HB94\_PP16a\_PHZ86}$ (ºC)	765	767	772	756	752	707	741	705	717	728	742	766	781
61	$T1_{HB94\_PP16b\_PHZ86}$ (ºC)	768	771	775	759	754	709	742	705	718	729	743	768	786
62	$T2_{HB94\_*ap}$ (ºC)	686	702	707	710	709	682	679	664	710	688	659	674	728
63	$T2_{HB94\_PHZ86}$ (ºC)	685	702	706	709	708	679	678	662	707	686	658	673	728
64	$T2_{HB94\_PH87}$ (ºC)	685	702	706	709	708	678	678	662	707	685	658	673	728
65	$T2_{HB94\_PJR89}$ (ºC)	685	701	706	709	708	678	677	662	707	685	658	673	727
66	$T2_{HB94\_PS92}$ (ºC)	685	702	706	710	709	680	678	663	708	686	659	674	728
67	$T2_{HB94\_PA97\_PJR89}$ (ºC)	685	702	706	710	709	681	678	663	709	687	659	674	728
68	$T2_{HB94\_PA97\_PS92}$ (ºC)	685	702	707	710	709	681	679	663	709	687	659	674	728
69	$T2_{HB94\_PP16a\_PHZ86}$ (ºC)	685	701	706	709	708	679	678	662	707	686	658	673	727
70	$T2_{HB94\_PP16b\_PHZ86}$ (ºC)	684	701	706	709	708	678	678	662	707	686	658	673	727
71	T_{BH90_PAS95} (ºC)	702	705	709	700	698	674	674	650	674	671	672	692	724
72	P_{AS95_TBH90} (kbar)	2.40	2.48	2.21	2.23	2.02	2.11	1.75	1.39	1.69	1.38	1.63	1.89	2.32
73	$T1_{HB94\_P1AS95}$ (ºC)	770	772	779	759	755	704	744	704	716	731	745	774	791
74	$P1_{AS95\_T1HB94}$ (kbar)	1.44	1.50	1.16	1.44	1.30	1.86	1.04	1.08	1.32	0.85	0.89	0.81	1.20
75	$T2_{HB94\_P2AS95}$ (ºC)	685	702	706	710	708	680	678	663	708	686	659	674	728
76	$P2_{AS95\_T2HB94}$ (kbar)	2.56	2.50	2.23	2.12	1.91	2.07	1.72	1.35	1.41	1.29	1.69	2.03	2.25

Notes: Amphibole and plagioclase compositions are taken from Anderson (2016). *apfu* = atomic per formula unit; X_{Ab} = Molar fraction of albite; X_{An} = Molar fraction of anorthite; T_{BH90_*ap} (row 44) from Blundy and Holland (1990) where *ap = arbitrary pressure of 2 (kbar), T_{BH90_PHZ86} (row 45) from Blundy and Holland (1990) using the Hammarstrom and Zen (1986) calibration, T_{BH90_PH87} (row 46) from Blundy and Holland (1990) using the Hollister et al. (1987) calibration, T_{BH90_PJR89} (row 47) from Blundy and Holland (1990) using the Johnson and Rutherford (1989) calibration, T_{BH90_PS92} (row 48) from Blundy and Holland (1990) using the Schmidt (1992) calibration, $T_{BH90\_PA97\_PJR89}$ (row 49) from Blundy and Holland (1990) using the Ague (1997) calibration after Johnson and Rutherford (1989), $T_{BH90\_PA97\_PS92}$ (row 50) from Blundy and Holland (1990) using the Ague (1997) calibration after Schmidt (1992), $T_{BH90\_PP16a\_PHZ86}$ (row 51) from Blundy and Holland (1990) using the Putirka (2016) calibration after Hammarstrom and Zen (1986), $T_{BH90\_PP16b\_PHZ86}$ (row 52) from Blundy and Holland (1990) using the Putirka (2016) calibration after Hammarstrom and Zen (1986), $T1_{HB94\_*ap}$ (row 53) from Holland and Blundy (1994) where *ap = arbitrary pressure of 2 (kbar), $T1_{HB94\_PHZ86}$ (row 54) from Holland and Blundy (1994) using the Hammarstrom and Zen (1986) calibration, $T1_{HB94\_PH87}$ (row 55) from Holland and Blundy (1994) using the Hollister et al. (1987) calibration, $T1_{HB94\_PJR89}$ (row 56) from Holland and Blundy (1994) using the Johnson and Rutherford (1989) calibration, $T1_{HB94\_PS92}$ (row 57) from Holland and Blundy (1994) using the Schmidt (1992) calibration, $T1_{HB94\_PA97\_PJR89}$ (row 58) from Holland and Blundy (1994) using the Ague (1997) calibration after Johnson and Rutherford (1989), $T1_{HB94\_PA97\_PS92}$ (row 59) from Holland and Blundy (1994) using the Ague (1997) calibration after Schmidt (1992), $T1_{HB94\_PP16a\_PHZ86}$ (row 60) from Holland and Blundy (1994) using the Putirka (2016) calibration after Hammarstrom and Zen (1986), $T1_{HB94\_PP16b\_PHZ86}$ (row 61) from Holland and Blundy (1994) using the Putirka (2016) calibration after Hammarstrom and Zen (1986), $T2_{HB94\_*ap}$ (row 62) from Holland and Blundy (1994) where *ap = arbitrary pressure of 2 (kbar), $T2_{HB94\_PHZ86}$ (row 63) from Holland and Blundy (1994) using the Hammarstrom and Zen (1986) calibration, $T2_{HB94\_PH87}$ (row 64) from Holland and Blundy (1994) using the Hollister et al. (1987) calibration, $T2_{HB94\_PJR89}$ (row 65) from Holland and Blundy (1994) using the Johnson and Rutherford (1989) calibration, $T2_{HB94\_PS92}$ (row 66) from Holland and Blundy (1994) using the Schmidt (1992) calibration, $T2_{HB94\_PA97\_PJR89}$ (row 67) from Holland and Blundy (1994) using the Ague (1997) calibration after Johnson and Rutherford (1989), $T2_{HB94\_PA97\_PS92}$ (row 68) from Holland and Blundy (1994) using the Ague (1997) calibration after Schmidt (1992), $T2_{HB94\_PP16a\_PHZ86}$ (row 69) from Holland and Blundy (1994) using the Putirka (2016) calibration after Hammarstrom and Zen (1986), $T2_{HB94\_PP16b\_PHZ86}$ (row 70) from Holland and Blundy (1994) using the Putirka (2016) calibration after Hammarstrom and Zen (1986), TB_{H90_PAS95} (row 71) from Holland and Blundy (1994) using the Anderson and Smith (1995) calibration (row 72; P_{AS95_TBH90}) at second iteration, $T1_{HB94\_P1AS95}$ (row 73) from Holland and Blundy (1994) using the Anderson and Smith (1995) calibration (row 74; $P1_{AS95\_T1HB94}$) at second iteration, $T2_{HB94\_P2AS95}$ (row 75) from Holland and Blundy (1994) using the Anderson and Smith (1995) calibration (row 76; $P2_{AS95\_T2HB94}$) at second iteration.

Table 5. Amphibole-liquid and liquid-only thermobarometer estimations by WinAmptb program.

Row	Amphibole compositions (wt%)	Pas1	Pas4	Pas7	Pas10	Pas12	Pas13	Pas16	Pas17	Pas18	Pas19	Pas20
1	SiO_2	40.57	42.20	42.27	39.65	40.10	40.57	46.78	48.05	48.05	47.86	47.44
2	TiO_2	2.45	2.75	2.70	2.02	2.12	2.45	1.23	1.30	1.30	1.53	1.65
3	Al_2O_3	12.82	11.10	11.33	14.58	14.87	12.82	7.74	6.71	6.71	7.30	7.47
4	Cr_2O_3	0.00	0.01	0.01	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00
5	FeO_{Total}	13.11	13.10	13.30	12.26	13.10	13.11	13.09	12.25	12.25	12.99	13.17
6	MnO	0.26	0.39	0.40	0.13	0.26	0.26	0.24	0.29	0.29	0.32	0.36
7	MgO	13.02	13.55	13.22	13.09	13.53	13.02	14.53	15.13	15.13	14.78	14.73
8	CaO	11.63	11.07	11.05	11.96	12.30	11.63	11.09	11.16	11.16	10.75	10.85
9	Na_2O	2.20	2.27	2.28	2.13	2.33	2.20	1.46	1.33	1.33	1.42	1.36
10	K_2O	0.92	0.95	0.99	1.16	1.29	0.92	0.17	0.15	0.15	0.17	0.17
11	Total (wt%)	96.98	97.39	97.55	96.99	99.93	96.98	96.33	96.37	96.37	97.12	97.20
	Amphibole cations per 23 oxygens											
12	Si	6.088	6.289	6.293	5.936	5.863	6.088	6.928	7.070	7.070	7.007	6.954
13	Al^{IV}	1.912	1.711	1.707	2.064	2.137	1.912	1.072	0.930	0.930	0.993	1.046
14	Total T-site (*apfu*)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
15	Al^{VI}	0.356	0.239	0.281	0.509	0.425	0.356	0.279	0.234	0.234	0.267	0.245
16	Cr	0.000	0.001	0.001	0.001	0.003	0.000	0.000	0.000	0.000	0.000	0.000
17	V	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	Fe^{3+}	0.142	0.134	0.139	0.138	0.148	0.137	0.113	0.109	0.109	0.113	0.113
19	Ti	0.276	0.308	0.302	0.227	0.233	0.276	0.137	0.144	0.144	0.168	0.182
20	Mg	2.913	3.011	2.934	2.922	2.949	2.913	3.208	3.319	3.319	3.226	3.219
21	Fe^{2+}	1.313	1.307	1.342	1.203	1.241	1.318	1.264	1.194	1.194	1.226	1.241
22	Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	Total C-site (*apfu*)	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
24	FM	0.223	0.241	0.225	0.211	0.244	0.223	0.275	0.241	0.241	0.291	0.305
25	Ca	1.777	1.759	1.763	1.789	1.756	1.777	1.725	1.759	1.759	1.686	1.695
26	Na	0.000	0.000	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.000
27	Total B-site (*apfu*)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
28	Na	0.640	0.656	0.645	0.618	0.660	0.640	0.419	0.379	0.379	0.380	0.387
29	K	0.176	0.181	0.188	0.222	0.241	0.176	0.032	0.028	0.028	0.032	0.032
30	Total A-site (*apfu*)	0.816	0.837	0.833	0.840	0.901	0.816	0.451	0.408	0.408	0.412	0.418
31	Amphibole names	Prg	Prg	Prg	Prg	Prg	Prg	Mhb	Mhb	Mhb	Mhb	Mhb
	Liquid compositions (wt%)	Pls1	Pls4	Pls7	Pls10	Pls12	Pls13	Pls16	Pls17	Pls18	Pls19	Pls20
32	SiO_2	62.317	60.954	62.291	59.534	61.008	62.317	71.375	70.993	70.993	71.295	71.363
33	TiO_2	0.593	0.624	0.593	0.656	0.622	0.593	0.210	0.222	0.222	0.212	0.210
34	Al_2O3	17.015	17.430	17.023	17.862	17.414	17.015	12.388	12.576	12.576	12.427	12.394
35	FeO_{Total}	5.579	6.037	5.588	6.514	6.019	5.579	1.535	1.683	1.683	1.566	1.540
36	MnO	0.147	0.157	0.148	0.168	0.157	0.147	0.064	0.067	0.067	0.065	0.065
37	MgO	1.494	1.682	1.497	1.877	1.674	1.494	0.460	0.561	0.561	0.481	0.463
38	CaO	5.199	5.846	5.211	6.520	5.820	5.199	2.243	2.415	2.415	2.279	2.248
39	Na_2O	3.800	3.802	3.800	3.805	3.802	3.800	4.084	4.067	4.067	4.080	4.083
40	K_2O	3.840	3.493	3.833	3.132	3.507	3.840	1.678	1.645	1.645	1.671	1.677
41	P_2O_5	0.321	0.321	0.321	0.321	0.321	0.321	0.047	0.051	0.051	0.048	0.047
42	H_2O	5.000	5.000	5.000	5.000	5.000	2.000	5.000	5.000	5.000	5.000	5.000
	Liquid cation fractions											
43	Si	0.5773	0.5643	0.5771	0.5507	0.5648	0.5773	0.7091	0.7036	0.7036	0.7079	0.7089
44	Ti	0.0041	0.0043	0.0041	0.0046	0.0043	0.0041	0.0016	0.0017	0.0017	0.0016	0.0016
45	Al	0.1858	0.1902	0.1859	0.1947	0.1900	0.1858	0.1450	0.1469	0.1469	0.1454	0.1451
46	Cr	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
47	Fe_{Total}	0.0432	0.0467	0.0433	0.0504	0.0466	0.0432	0.0128	0.0140	0.0140	0.0130	0.0128
48	Mn	0.0012	0.0012	0.0012	0.0013	0.0012	0.0012	0.0005	0.0006	0.0006	0.0005	0.0005

Table 5. ... Continued

Row	Liquid compositions (wt%)	Pls1	Pls4	Pls7	Pls10	Pls12	Pls13	Pls16	Pls17	Pls18	Pls19	Pls 20
49	Mg	0.0206	0.0232	0.0207	0.0259	0.0231	0.0206	0.0068	0.0083	0.0083	0.0071	0.0069
50	Ca	0.0516	0.0580	0.0517	0.0646	0.0577	0.0516	0.0239	0.0256	0.0256	0.0242	0.0239
51	Na	0.0682	0.0682	0.0682	0.0683	0.0682	0.0682	0.0787	0.0781	0.0781	0.0786	0.0786
52	K	0.0454	0.0413	0.0453	0.0370	0.0414	0.0454	0.0213	0.0208	0.0208	0.0212	0.0212
53	P	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0004	0.0004	0.0004	0.0004	0.0004
	Amphibole-liquid and liquid-only thermobarometers											
54	$T1_{Liq\_M15}$ (ºC)	934	938	934	943	938	934	862	877	877	865	862
55	$T2_{Amp\text{-}Liq\_M15}$ (ºC)	914	913	913	921	916	914	835	846	846	838	836
56	$T1_{Liq\_P16Eq3}$ (ºC)	942	945	942	946	944	945	828	838	838	830	828
57	$T2_{Amp\text{-}Liq\_P16Eq4a}$ (ºC)	956	960	958	956	961	957	831	832	832	830	825
58	$T3_{Amp\text{-}Liq\_P16Eq4b}$ (ºC)	927	942	931	942	930	921	798	812	812	808	809
59	$T4_{Amp\text{-}Liq\_P16Eq9}$ (ºC)	963	951	944	985	997	959	834	823	823	830	834
60	$T5_{Amp\text{-}Liq\_P16Eq6}$ (ºC)	952	932	930	976	986	949	804	795	795	800	804
61	$T6_{Amp\text{-}Liq\_P16Eq8}$ (ºC)	955	946	940	970	987	950	822	820	820	823	827
62	$P1_{Amp\text{-}Liq\_P16Eq7a}$ (kbar)	6.17	5.01	5.26	9.00	9.52	4.83	0.22	1.56	1.56	0.81	0.36
63	$P2_{Amp\text{-}Liq\_P16Eq7b}$ (kbar)	4.25	2.60	2.85	5.76	5.75	3.04	0.15	n.d.	n.d.	n.d.	n.d.
64	$P3_{Amp\text{-}Liq\_P16Eq7c}$ (kbar)	6.69	5.33	5.74	9.59	10.39	6.69	1.01	2.29	2.29	1.60	1.08

Notes: Amphibole and liquid compositions are taken from Putirka (2016). *apfu* = atomic per formula unit; FM = Total Fe^{2+}, Mg and Mn contents at B-site; $T1_{Liq\_M15}$ (row 54) from Molina et al. (2015; see Eq. 32 in text), $T2_{Amp\text{-}Liq\_M15}$ (row 55) from Molina et al. (2015; see Eq. 31 in text), $T1_{Liq\_P16Eq3}$ (row 56) from Putirka (2016; see Eq. 33 in text), $T2_{Amp\text{-}Liq\_P16Eq4a}$ (row 57) from Putirka (2016; see Eq. 34 in text), $T3_{Amp\text{-}Liq\_P16Eq4b}$ (row 58) from Putirka (2016; see Eq. 35 in text), $T4_{Amp\text{-}Liq\_P16Eq9}$ (row 59) from Putirka (2016; see Eq. 36 in text), $T5_{Amp\text{-}Liq\_P16Eq6}$ (row 60) from Putirka (2016; see Eq. 37 in text), $T6_{Amp\text{-}Liq\_P16Eq8}$ (row 61) from Putirka (2016; see Eq. 38 in text), $P1_{Amp\text{-}Liq\_P16Eq7a}$ (row 62) from Putirka (2016; see Eq. 39 in text), $P2_{Amp\text{-}Liq\_P16Eq7b}$ (row 63) from Putirka (2016; see Eq. 40 in text), $P3_{Amp\text{-}Liq\_P16Eq7c}$ (row 64) from Putirka (2016; see Eq. 41 in text); n.d. = not determined.

The total aluminum content of amphibole used in the pressure (kbar) estimation is determined based on the 13eCNK normalization method (Figure 6 a,b). Anderson and Smith (1995) pointed out that without temperature control, Al-in-hornblende barometry may show exaggerated estimates of pluton thickness and tilt. Other factors, apart from temperature and oxygen fugacity, such as $Fe_{Tot}/(Fe_{Tot}+Mg) < 0.65$ and $Fe^{3+}/(Fe^{3+}+Fe^{2+}) = \sim 0.2\text{-}0.25$ ratios in amphibole and plagioclase compositions ($\sim An_{25\text{-}35}$) should be considered when using the Anderson and Smith (1995) calibration. Even though this calibration potentially applicable to high-temperature intrusions, it should not be applied to plutons that crystallized over 800 ºC (see column 162 in Figure 5a and row 29 in Table 3).

Ague (1997) revised the Al-in-hornblende barometer as a combination of *P*-sensitive tremolite+ phlogopite+2an-orthite+2albite=2pargasite+6quartz+K-feldspar reaction and the amphibole-plagioclase thermometer equilibria (Holland and Blundy, 1994) in a plot as a function of *P* (kbar) computed using the thermodynamics-based method. He observed a strong positive correlation between the conventional pressure estimates (e.g. Johnson and Rutherford, 1989; Schmidt, 1992) and those computed using his new method (see columns 168 and 169 in Figure 5a and rows 34 and 35 in Table 3). In the Ague's (1997) model, the presence of sphene, Fe-Ti oxides and melt is not required to be the part of the assemblages; thus P (kbar) estimates can be carried out for igneous and amphibolites and granulite facies metamorphic mineral assemblages. The Ague (1997) approach can also be used in low-*P* settings that are outside the *P-T* range of experimental Al-in-hornblende calibrations (e.g. Thomas and Ernst, 1990). Despite these advantages, several other issues should be considered when using the Ague (1997) reaction model in estimation for the Al-in-hornblende barometer (see p. 565 in Ague, 1997).

Ernst and Liu (1998) carried out an experimental study at *P-T* conditions ranging from 0.8-2.2 GPa and 650-950 ºC that controlled by the QFM buffer for Al- and Ti-contents of calcic amphiboles from mid-ocean ridge basalts (MORB) and provided a semiquantitative thermobarometer. The Ernst and Liu (1998) thermobarometer (see columns 170 and 171 in Figure 5a and rows 36 and 37 in Table 3), in the *P-T* diagram with the combined Al_2O_3 and TiO_2 (wt%) isopleths, can be used for metabasaltic rocks at crustal pressures up to ~1.2 GPa and subsolidus temperatures.

Féménias et al. (2006) studied the amphiboles from a Late Pan-African calc-alkaline dike swarm, which is composed of basalt to rhyolite in the Alpine Danubian window, South Carpathians (Romania) and proposed a a

WinAmptb	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177
Sample No	[TO84(oC)a	PAS95_O84(kbar)a]	PHZ86(kbar)a	PH87(kbar)a	PJR89(kbar)a	PTE90(kbar)a	PS92(kbar)a	PA97_JR89(kbar)a	PA97_S92(kbar)a	[PEL98(kbar)a	TEL98(oC)a]	[TF06(oC)a	PAS95F06(kbar)a]	PLC10(MPa)a	[TR10(oC)a	DeltaNNOR10(a)	H2OmeltR10(%)a
Aas1	717	2.20	2.11	2.00	1.61	0.17	2.70	2.81	2.85	1.46	613	714	2.24	259	815	1.32	3.64
Aas2	724	2.20	2.23	2.13	1.71	0.29	2.81	2.89	2.93	1.52	619	722	2.23	266	816	1.29	3.47
Aas3	720	2.04	1.97	1.84	1.49	0.02	2.56	2.71	2.75	1.29	608	717	2.08	239	811	1.29	3.34
Aas4	720	1.98	1.89	1.75	1.42		2.49	2.65	2.69	1.63	595	717	2.01	279	804	1.25	3.67
Aas5	715	1.80	1.65	1.49	1.22		2.26	2.48	2.53	1.68	579	712	1.84	285	788	1.37	4.13
Aas6	614	2.27	1.55	1.37	1.14		2.17	2.41	2.45	2.92	543	571	2.11	434	778	1.66	4.70
Aas7	630	1.86	1.16	0.93	0.81		1.79	2.13	2.18	1.64	548	598	1.82	281	775	1.71	4.12
Aas8	626	1.38	0.67	0.39	0.40		1.34	1.79	1.84	1.78	514	592	1.29	297	754	1.91	3.96
Aas9	652	1.77	1.09	0.86	0.75		1.73	2.09	2.13	2.27	533	632	1.81	338	765	1.60	4.10
Aas10	623	1.46	0.74	0.47	0.46		1.40	1.84	1.89	1.65	522	586	1.35	282	763	1.84	4.14
Aas11	644	1.71	1.01	0.76	0.68		1.65	2.03	2.07	1.26	548	620	1.73	235	776	1.59	3.86
Aas12	646	2.13	1.45	1.26	1.05		2.07	2.34	2.38	1.25	576	623	2.17	234	794	1.57	3.82
Aas13	717	2.38	2.30	2.22	1.77	0.38	2.88	2.95	2.98	1.65	621	714	2.42	281	820	1.16	3.79

b

WinAmptb	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194
Sample No	PR10(MPa)a	logfO2(a)	ACDOC(km)a	ACDCCkm)a	Species(a)]	[P1aRR12(MPa)a	P1bRR12(MPa)a	P1cRR12(MPa)a	P1dRR12(MPa)a	P1eRR12(MPa)a	PRR12(MPa)a	TRR12P1a(oC)a	TRR12P1b(oC)a	TRR12P1c(oC)a	TRR12P1d(oC)a	TRR12P1e(oC)a	TRR12(oC)a
Aas1	105	-12.23	3.04	2.84	Mg-Hbl	173	125	150		332	125	848	840	844		864	840
Aas2	108	-12.23	3.13	2.93	Mg-Hbl	192	127	149		355	127	854	844	848		869	844
Aas3	101	-12.35	2.92	2.73	Mg-Hbl	172	117	126		353	117	842	833	835		860	833
Aas4	99	-12.53	2.86	2.67	Mg-Hbl	169	118	127		359	118	844	835	837		862	835
Aas5	92	-12.74	2.66	2.48	Mg-Hbl	142	115	114		265	115	833	828	828		848	828
Aas6	90	-12.68	2.59	2.42	Mg-Hbl	134	110	86		339	110	807	802	796		830	802
Aas7	80	-12.70	2.31	2.16	Mg-Hbl	136	101	82		285	101	825	818	813		843	818
Aas8	70	-12.99	2.01	1.88	Mg-Hbl	125	95	55		247	95	818	812	798		835	812
Aas9	79	-13.03	2.27	2.13	Mg-Hbl	131	100	62		301	100	815	808	796		835	808
Aas10	71	-12.86	2.06	1.93	Mg-Hbl	104	92	43		257	92	798	795	776		820	795
Aas11	77	-12.81	2.23	2.08	Mg-Hbl	109	92	48		278	92	796	792	776		819	792
Aas12	87	-12.42	2.52	2.35	Mg-Hbl	130	101	72		312	101	811	805	797		833	805
Aas13	111	-12.28	3.22	3.01	Mg-Hbl	172	123	135		385	123	838	830	832		858	830

c

WinAmptb	195	196	197	198	199	200	201	202	203	204	205	206	207
Sample No	DeltaNNORR12(a)	H2OmeltRR12(%)a	SiO2meltRR12(%)a	logfO2RR12(a)	ACDOC(km)a	ACDCC(km)a]	PK12(MPa)a	[PH2OK12(MPa)a]	[TP16SiinHbl(oC)a]	[TP16Eq5(oC)a	Put16a_PHZ86(kbar)a	Put16b_PHZ86(kbar)a	PM16(kbar)a
Aas1	2.49	5.35	78.84	-10.54	3.61	3.37	172		824	794	1.83	1.53	2.30
Aas2	2.56	5.43	79.05	-10.39	3.67	3.43	179		828	799	1.90	1.59	2.36
Aas3	2.57	5.36	78.66	-10.60	3.39	3.17	151		822	794	1.74	1.47	2.23
Aas4	2.44	5.23	78.79	-10.69	3.40	3.18	192		814	789	1.70	1.44	2.19
Aas5	1.59	4.89	78.06	-11.69	3.31	3.09	199		805	773	1.56	1.34	2.06
Aas6	2.38	5.68	79.81	-11.43	3.19	2.98	351		785	758	1.50	1.30	2.02
Aas7	2.32	5.30	77.56	-11.17	2.93	2.74	194		788	756	1.29	1.16	1.82
Aas8	2.20	4.91	76.23	-11.42	2.74	2.56	211		769	742	1.06	1.00	1.61
Aas9	2.11	5.11	77.36	-11.58	2.88	2.69	252		780	754	1.26	1.14	1.80
Aas10	2.12	5.04	74.28	-11.85	2.66	2.48	195		773	746	1.09	1.03	1.64
Aas11	2.12	5.24	73.96	-11.92	2.66	2.49	147		788	755	1.22	1.11	1.76
Aas12	2.37	5.57	76.62	-11.38	2.90	2.71	146		803	770	1.45	1.26	1.96
Aas13	2.40	5.63	78.63	-10.84	3.56	3.33	195		829	799	1.95	1.62	2.41

Figure 5. Screenshot of an Excel file (i.e. Output.xlsx) created by program in estimation of the *P-T* conditions based on the calcic amphibole-only composition (see text for explanations). WinAmptb checks the calibration ranges of equations and leaves it blank when calculating the meaningless values (e.g. column numbers 166, 186, 192 and 202 in Figure 5).

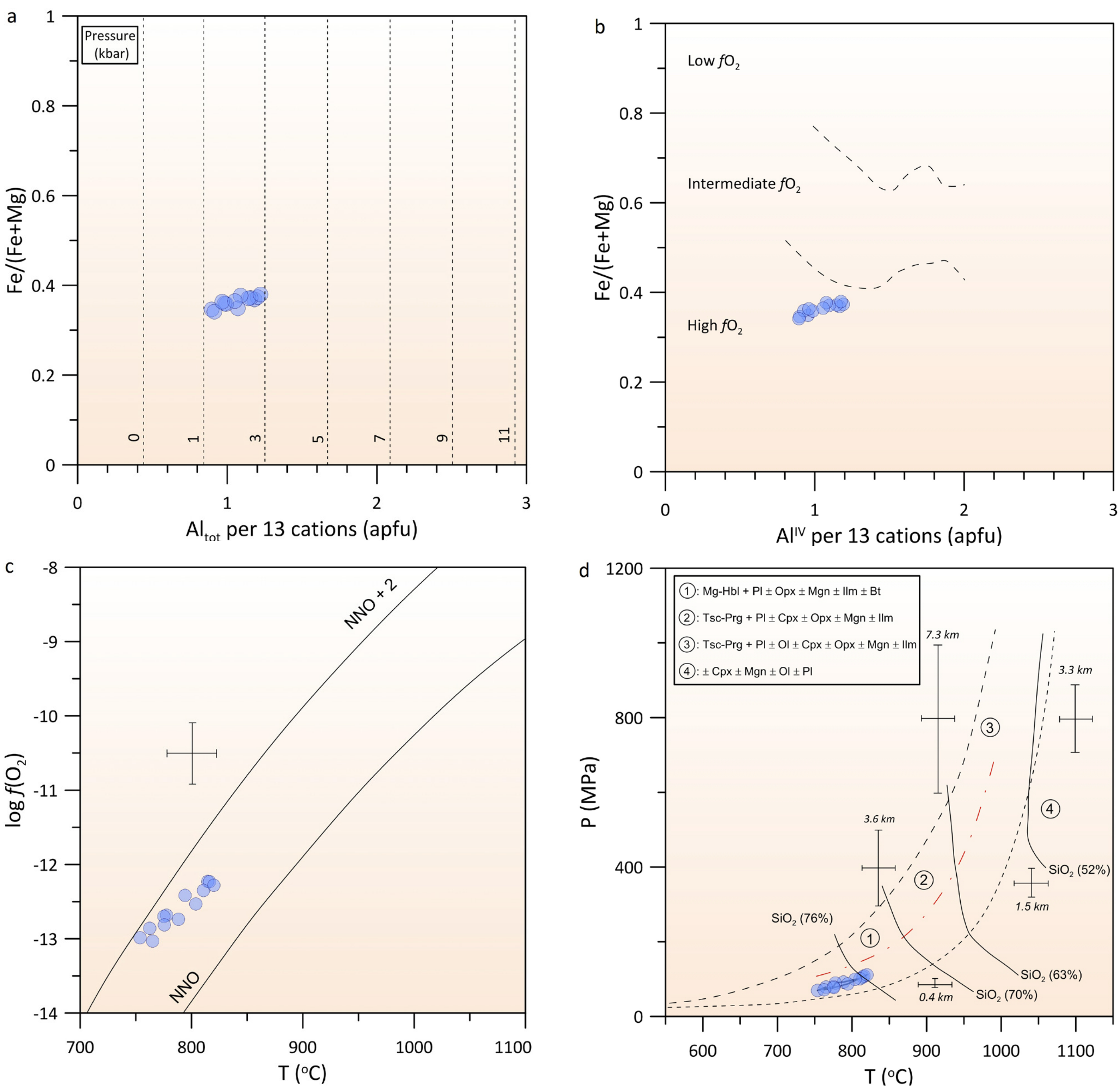


Figure 6. (a) Composition of calcic amphiboles (data from Anderson, 2017) on the Fe/(Fe+Mg) vs. Al$_{tot}$ diagram to estimate visually the *P* (kbar) conditions (from Anderson and Smith, 1995). (b) Composition of calcic amphiboles (data from Anderson, 2017) on the Fe/(Fe+Mg) vs. Al^{IV} diagram to estimate visually the fO_2 conditions (from Anderson and Smith, 1995). (c) Composition of calcic amphiboles (data from Anderson, 2017) on log fO_2 vs. *T* (°C) diagram to estimate fugacity fO_2 between NNO and NNO+2 buffer conditions (from Ridolfi et al., 2010). (d) Composition of calcic amphiboles (data from Anderson, 2017) on the *P* (MPa) vs. *T* (°C) diagram (from Ridolfi et al., 2010).

quantitative thermometer (see columns 172 and 173 in Figure 5a and rows 38 and 39 in Table 3) that applicable to high-T (>700 °C) calcic amphiboles crystallizing in Ti-saturated calc-alkaline magma:

$$[T]_{F_{06}}(^{\circ}C) = \frac{2600}{\ln(Ti) + 1.7} \quad (8)$$

where Ti cation (*apfu*) in structural formula of amphibole is calculated on an anhydrous basis assuming 23 oxygens atoms per half unit cell. Féménias et al. (2006) suggest that their Ti-in-amphibole thermometer estimates are globally in agreement with the Blundy and Holland (1990) amphibole-plagioclase thermometer in which samples where fresh plagioclase crystals are rare due to the strong deuteritic alteration.

Larocque and Canil (2010) studied the bodies of mafic and ultramafic cumulates within deeper parts of the Jurassic Bonanza arc, on Vancouver Island, British Columbia, and correlated with pressure for liquids amphiboles in experiments on high-Mg arc basalts with a trend that is fitted by a least squares regression of:

$$Al^{VI}\ (apfu) = 0.056 * P\ (MPa) + 0.008.$$

The calculated octahedrally coordinated Al atom in the structural amphibole formula is obtained by normalization to 23 oxygens. An empirical barometer (see column 174 in Figure 5a and row 40 in Table 3) is based on the octahedral aluminum contents of calcic amphiboles in high-Mg arc basalt and basaltic andesite systems which can be formulated as follows from the Larocque and Canil's (2010) Al^{VI} vs. P (MPa) diagram:

$$[P]_{LC_{10}}\ (MPa) = 1631.9462 * Al^{VI} + 45.0203 \tag{9}$$

Ridolfi et al. (2010) provided empirical thermobarometric formulations as well as relative oxygen fugacity (ΔNNO) and hygrometric (H_2O_{melt}) equations (see columns 175 to 182 in Figure 5 a,b and rows 41 to 47 in Table 3) for amphibole phase in calc-alkaline magmas of subduction-related systems based on the selected calcic amphiboles from experimental results within the *P-T* range of 100-1200 MPa and 750-1120 °C:

$$[T]_{R_{10}}\ (^{o}C) = -151.487 * Si^{*} + 2.041 \tag{10}$$

$$[P]_{R_{10}}\ (MPa) = 19.209 e^{(1.438 Al_{Tot})} \tag{11}$$

$$[\Delta NNO]_{R_{10}} = 1.644 * Mg^{*} - 4.01 \tag{12}$$

$$[H_2O]_{R_{10}}\ (\%) = 5.215 * {}^{[6]}Al^{*} + 12.28 \tag{13}$$

where:

$$Si^{*}\ (\text{silicon index}) = Si + \frac{^{[4]}Al}{15} + 2\,^{[4]}Ti - \frac{^{[6]}Al}{2} - \frac{^{[6]}Ti}{1.8} + \frac{Fe^{3+}}{9} + \frac{Fe^{2+}}{3.3} + \frac{Mg}{26} + \frac{^{B}Ca}{5} + \frac{^{B}Na}{1.3} - \frac{^{A}Na}{15} + \frac{A_{\square}}{2.3}$$

$$Mg^{*}\ (\text{magnesium index}) = Mg + \frac{Si}{47} - \frac{^{[6]}Al}{9} - 1.3\,^{[6]}Ti + \frac{Fe^{3+}}{3.7} + \frac{Fe^{2+}}{5.2} - \frac{^{B}Ca}{20} - \frac{^{A}Na}{2.8} + \frac{A_{\square}}{9.5}$$

$$^{[6]}Al^{*}\ (\text{octahedral aluminium index}) = {}^{[6]}Al + \frac{^{[4]}Al}{13.9} - \frac{Si + {}^{[6]}Ti}{5} - \frac{^{C}Fe^{2+}}{3} - \frac{Mg}{1.7} + \frac{^{B}Ca + {}^{A}}{1.2} + \frac{^{A}Na}{2.7} - 1.56K - \frac{Fe\#}{1.6}$$

$$Fe\#\ (\text{iron number}) = \frac{^{C}Fe^{3+}}{(^{C}Fe^{3+} + {}^{C}Mg + {}^{C}Fe^{2+} + {}^{C}Mn)}$$

In these equations, the calcic amphibole formula is calculated on the basis of 23 oxygens anhydrous, assuming a total of 13eCNK normalization procedure. Proposed formulations work independently with different compositional components of a single calcic amphibole phase and consequently can be applied to all types of calc-alkaline volcanic products including hybrid intermediate lavas (e.g. hybrid andesites). According to Ridolfi et al. (2010), these thermobarometric formulations (see Figure 6 c,d) provide an important clue to understand the pre-eruptive conditions of amphibole-bearing magmas in the whole-crust oceanic settings (i.e. island arcs) as well as upper-mid crust settings of continental volcanoes.

Considering these equations do not take into account the calcic amphiboles associated with alkaline magmas of oceanic intraplate and volcanoes located in complex geodynamic settings as well as any multivariate statistical techniques in estimating the *P* (MPa) conditions, Ridolfi and Renzulli (2012) presented new thermobarometric and chemometric empirical formulations (see columns 183 to 200 in Figure 5b, c and rows 48 to 63 in Table 3) for calcic amphiboles in calc-alkaline and alkaline magmas by using a large number of natural amphiboles and carefully selected experimental data from literature in a wide range of *P-T* conditions (130-2200 MPa and 800-1130 °C):

$$[T]_{RR_{12}}\ (^{o}C) = (17098 - 1322.2Si - 1035.1Ti - 1208.2Al - 1230.4Fe - 1152.9Mg - 130.4Ca + 200.54Na + 29.408K) + 24.41 * \ln P\ (MPa) \tag{14}$$

$$[\ln P_{1a}]_{RR_{12}}\ (MPa) = 125.93 - 9.5876Si - 10.116Ti - 8.1735Al - 9.2261Fe - 8.7934Mg - 1.6659Ca + 2.4835Na + 2.5192K \tag{15}$$

$$[\ln P_{1b}]_{RR_{12}}\ (MPa) = 38.723 - 2.6957Si - 2.3565Ti - 1.3006Al - 2.7780Fe - 2.4838Mg - 0.6614Ca - 0.2705Na + 0.1117K \tag{16}$$

$$[P_{1c}]_{RR_{12}}\ (MPa) = 24.023 - 1925.3Si - 1720.6Ti - 1478.5Al - 1843.2Fe - 1746.9Mg - 158.28Ca - 40.444Na + 253.52K \tag{17}$$

$$[P_{1d}]_{RR_{12}}\ (MPa) = 26.106 - 1991.9Si - 3035Ti - 1472.2Al - 2454.8Fe - 2125.8Mg - 830.64Ca + 2708.8Na + 2204.1K \tag{18}$$

$$[\ln P_{1e}]_{RR_{12}}\,(\text{MPa}) = 26.543 - 1.2085\text{Si} - 3.8593\text{Ti} - 1.1054\text{Al} - 2.9068\text{Fe} - 2.6483\text{Mg} + 0.5134\text{Ca} + 2.9752\text{Na} + 1.8147\text{K} \quad (19)$$

$$[\Delta\,\text{NNO}]_{RR_{12}}\,(\text{log units}) = 214.39 - 17.042\text{Si} - 26.08\text{Ti} - 16.389\text{Al} - 18.397\text{Fe} - 15.152\text{Mg} + 0.2162\text{Ca} + 6.1987\text{Na} + 14.389\text{K} \quad (20)$$

$$[\ln \text{H}_2\text{O}_{melt}]_{RR_{12}}\,(\text{wt\%}) = (-65.907 + 5.0981\text{Si} + 3.1308\text{Ti} + 4.9211\text{Al} + 4.9744\text{Fe} + 4.6536\text{Mg} + 1.0018\text{Ca} - 0.789\text{Na} - 0.539\text{K}) + 0.4642 * \ln P \quad (21)$$

Similarly, in these formulations, the mineral formula of calcic amphibole is estimated using the 13 cation method (i.e. 13eCNK). According to Ridolfi and Renzulli (2012), the revised thermobarometers and chemometric equations can be successfully used in understanding the pre-eruptive magma conditions and sub-volcanic processes from alkaline to calc-alkaline magmatic series with relatively low uncertainties. Erdmann et al. (2014) tested the Ridolfi et al. (2010) and Ridolfi and Renzulli (2012) calibrations for amphibole compositions from basaltic-andesitic pyroclasts erupted during the paroxysmal 2010 eruption of Mount Merapi in Java, Indonesia and suggested that although calculated crystallization temperature, fO_2 and melt SiO_2 contents provide potentially useful estimates at moderately reduced to moderately oxidized conditions and intermediate to felsic melt compositions, calculated crystallization pressure and melt H_2O contents may show untenable estimates due to the mixing of mafic to felsic magmas. Erdmann et al. (2014) also pointed out that a procedure recommended by Ridolfi and Renzulli (2012) for crystallization pressure estimate based on the given five equations (i.e. Eq. 15-19) may not reflect the appropriate value as these formulations were calibrated for different pressure ranges with variable uncertainties. It was for the reason that they decided to use average calculated pressure value obtained from Eq. 16 and 17 for the Merapi amphibole dataset.

Krawczynski et al. (2012) attempted to calibrate the Larocque and Canil (2010) empirical Al^{VI} (on basis of 23 oxygens) amphibole barometer (see column 201 in Figure 5c and row 64 in Table 3) for higher silica compositions by using their experimental amphiboles and those from other studies on andesitic liquids with high Mg#:

$$[P]_{K_{12}}\,(\text{MPa}) = 1675 * \text{Al}^{VI} - 48 \quad (22)$$

Krawczynski et al. (2012) also proposed an empirical calibration of amphibole barometer-hygrometer based on the Mg# of amphibole and relative oxygen fugacity (ΔNNO) for primitive arc basaltic andesite and andesite systems:

$$[P_{\text{H}_2\text{O}}]_{K_{12}}\,(\text{MPa}) = \left[\frac{Mg\,\#}{52.7} - 0.014 * \Delta\text{NNO}\right]^{15.12} \quad (23)$$

This barometer (column 202 in Figure 5c) is used for calcic amphiboles with Mg# ranging from 74 to 84 (i.e. Mg-rich amphiboles that crystallize at high temperatures and H_2O contents); otherwise, insignificant pressure values may be estimated that do not reflect the *P-T* conditions of formation.

Putirka (2016) developed calcic amphibole-only thermometers (see columns 203 and 204 in Figure 5c and rows 65 and 66 in Table 3) by using the step-wise linear and non-linear least-square regression models for natural amphibole compositions from Ridolfi and Renzulli (2012) and experimental data from LEPR (Hirschmann et al., 2008):

$$[T]_{P_{16}}\,(^{o}\text{C}) = 2061 - 178.4 * \text{Si} \quad (24)$$

$$[T]_{P_{16}}\,(^{o}\text{C}) = 1781 - 132.74 * \text{Si} + 116.6 * \text{Ti} - 69.41 * \text{Fe}_{tot} + 101.62 * \text{Na} \quad (25)$$

Although not a recommended model, Eq. 24 provides a notable simple amphibole-only thermometer (*T*) with relatively low standard error of estimate (± 44 ^{o}C). In *P*-independent (i.e. Eq. 24 and Eq. 25) amphibole-only thermometers, the mineral formula is calculated on the basis of 23 atoms. In an Excel file for calculating amphibole *P-T* conditions and components, Putirka (2016) also gave two Al-in-hornblende barometers for the Hammarstrom and Zen (1986) calibrations (see columns 205 and 206 in Figure 5 and rows 67 and 68 in Table 3).

Mutch et al. (2016) reported new experimental data on the magmatic amphiboles from a variety of granite bulk compositions at near-solidus temperature and pressure (0.8-10 kbar) conditions and proposed a revised Al-in-hornblende barometer.

$$[P]_{M_{16}}\,(\text{kbar}) = 0.5 + 0.331 * \text{Al}_{tot} + 0.995 * \text{Al}^2_{tot} \quad (26)$$

In this quadratic equation, amphibole structural formula was estimated based on a modified form of Holland and Blundy (1994) method that takes into account an approximation of octahedral site Fe^{3+} within the stoichiometric constraints for permissible minumum and maximum contents. The developed barometer is applicable to granitic rocks with the low-variance mineral assemblage; consisting of amphibole, plagioclase(An_{15-80}), biotite, quartz, alkali feldspar, ilmenite or titanite, magnetite, and apatite. According to Mutch et al. (2016), the developed barometer (see column

207 in Figure 5 and row 69 in Table 3) can be used for a wide bulk compositional range, if the appropriate mineral assemblages present in rock and amphibole-plagioclase temperatures have 725±75 °C (i.e. temperatures close to the haplogranite solidus).

Amphibole-plagioclase thermobarometers

Using the available experimental and empirical data, Blundy and Holland (1990) proposed a pressure-dependent thermometer (see columns 208 to 216 in Figure 7 and rows 44 to 52 in Table 4 for different pressure (kbar) calibrations) based on the Al^{IV} (apfu) content of calcic amphibole coexisting with plagioclase in silica saturated rocks for the equilibrium reactions of A) Edenite+4Quartz=Tremolite+Albite and B) Pargasite+4Quartz=Hornblende+Albite:

$$[T]_{BH_{90}}(K) = \frac{0.677 * P(\text{kbar}) - 48.98 + Y}{-0.0429 - 0.008314 * \ln\left(\frac{\text{Si}-4}{8-\text{Si}}\right) * X_{Ab}^{Plag}} \quad (27)$$

where Y represents plagioclase non-ideality from Darken's Quadratic formalism with Y=0 for X_{Ab}>0.5 and Y=-8.06+25.5*(1-X_{Ab})^2 for X_{Ab}<0.5. The thermometer is applicable for rocks including plagioclase (< An_{92}) and amphibole (7.8 < Si *apfu*) contents that equilibrated at temperatures in the range 500-1100 °C (±40 °C). Considering the calibration of amphibole-plagioclase thermometer (Eq. 26) yielding high temperatures, especially amphiboles coexisting with garnet, Holland and Blundy (1994) revised the thermometer and introduced a new calibration with the equilibrium reactions of 1) Edenite+4Quartz=Tremolite+Albite and 2) Edenite+Albite=Richterite+Anorthite:

$$[T1]_{BH_{94}}(K) = \frac{-76.95 + 0.79 * P(\text{kbar}) + Y_{Ab} + 39.4 * X_{Na}^{A} + 22.4 * X_{K}^{A} + (41.5 - 2.89 * P(\text{kbar}) * X_{Al}^{M2}}{-0.065 - R * \ln\left(\frac{27 * X^{A} * X_{Si}^{T1} * X_{Ab}^{Plag}}{256 * X_{Na}^{A} * X_{Al}^{T1}}\right)} \quad (28)$$

where R is the gas constant (0.0083143 kJK^{-1}) and the Y_{Ab} term is given by: for X_{Ab}>0.5 then Y_{Ab}=0; otherwise Y_{Ab}=12*(1- X_{Ab})^2-3 kJ.

$$[T2]_{BH_{94}}(K) = \frac{78.44 + Y_{Ab\text{-}An} - 33.6 * X_{Na}^{M4} - (66.8 - 2.92 * P(\text{kbar})) * X_{Al}^{M2} + 78.5 * X_{Al}^{T1} + 9.4 * X_{Na}^{A}}{0.0721 - R * \ln\left(\frac{27 * X_{Na}^{M4} * X_{Si}^{T1} * X_{An}^{Plag}}{64 * X_{Ca}^{M4} * X_{Al}^{T1} * X_{Ab}^{Plag}}\right)} \quad (29)$$

where the $Y_{Ab\text{-}An}$ term is given by: X_{Ab}>0.5 then $Y_{Ab\text{-}An}$=3 kJ; otherwise $Y_{Ab\text{-}An}$=12*(2*X_{Ab}-1)^2+3 kJ. In these equations, Holland and Blundy (1994) discarded the ideal solution model for amphibole and preferred to use a symmetrical formalism to explain the non-ideality in plagioclase. These thermometers can be used over a broad range of bulk compositions with *P-T* conditions in the range 1-15 kbar and 400-1100 °C (±40 °C). Current calibrations for amphibole-plagioclase thermometers (i.e. *T*1 and *T*2; see columns 217 to 240 in Figure 7 and rows 53 to 76 in Table 4 for different pressure (kbar) calibrations) are sensitive to the ferric iron contents that have an effect on the occupancy of sites. Hence, in the Holland and Blundy (1994) method, microprobe amphibole analyses that recalculated on the basis of 23 oxygens were subjected to a renormalization procedure in estimation of ferric iron content as well as site allocations (see Appendix B in Holland and Blundy, 1994).

Anderson (1996) tested the Blundy and Holland (1990) and Holland and Blundy (1994) calibrations for two groups of granitic plutons, one with low-alumina hornblende (i.e. Al_2O_3 <8 wt%) and the other with high-alumina hornblende (i.e. Al_2O_3>10 wt%) as a function of emplacement depth. According to Anderson (1996), samples from shallow intrusions show a high agreement in all three calibrations, but the Blundy and Holland (1990) method estimates high temperatures for samples from mid-crustal intrusions. Anderson (1996) also pointed out that, in the case of the comparison of temperatures for edenite-tremolite (Eq. 28; *T*1) and edenite-richterite (Eq. 29; *T*2) calibrations, results derived from the edenite-richterite calibration (*T*2) estimate the lowest and considered to be the most reliable.

Fershtater (1990) proposed an empirical barometer based on the Al/Si ratios in amphibole and plagioclase that can be used for amphibole-plagioclase assemblages in a variety of mafic metamorphic rocks and felsic to mafic igneous rocks. Molina et al. (2015) examined pressure and phase composition dependencies of the Al-Si partitioning between calcic amphibole and plagioclase and proposed a new temperature-dependent barometer for metamorphic and igneous rocks based on the compositional database for amphibole-plagioclase pairs compiled from the experimental studies in literature for the 650-1050 °C temperature range and precision ±1.5 to ±2.3 kbar:

WinAmptb	208	209	210	211	212	213	214	215	216	217	218	219
Sample No	[TBH90_ap(oC)a-p	TBH90_PHZ86(oC)a-p	TBH90_PH87(oC)a-p	TBH90_PJR89(oC)a-p	TBH90_PS92(oC)a-p	TBH90_PA97_PJR89(oC)a-p	TBH90_PA97_PS92(oC)a-p]	TBH90_PP16a_PHZ86(oC)a-p	TBH90_PP16b_PHZ86(oC)a-p	[T1HB94_ap(oC)a-p	T1HB94_PHZ86(oC)a-p	T1HB94_PH87(oC)a-p
Aas1	694	706	708	713	698	696	696	710	714	750	761	763
Aas2	698	709	710	716	700	699	699	713	718	753	763	764
Aas3	698	712	714	719	704	702	701	715	719	756	769	770
Aas4	689	704	706	711	696	694	693	707	711	740	753	755
Aas5	685	703	706	709	695	692	691	705	708	735	751	753
Aas6 a	662	682	684	687	674	670	670	682	685	694	707	709
Aas7	658	682	685	687	674	669	669	680	682	721	742	745
Aas8	629	660	663	663	651	645	645	655	655	684	708	711
Aas9	656	682	685	686	673	668	668	679	681	699	719	721
Aas10	649	679	683	683	670	665	664	675	676	708	732	735
Aas11	654	680	683	685	672	667	666	677	679	720	744	747
Aas12	677	698	701	704	690	686	685	698	701	746	766	768
Aas13	714	724	725	732	716	715	714	729	734	768	777	778

WinAmptb	220	221	222	223	224	225	226	227	228	229	230
Sample No	T1HB94_PJR89(oC)a-p	T1HB94_PS92(oC)a-p	T1HB94_PA97_PJR89(oC)a-p	T1HB94_PA97_PS92(oC)a-p]	T1HB94_PP16a_PHZ86(oC)a-p	T1HB94_PP16b_PHZ86(oC)a-p	[T2HB94_ap(oC)a-p	T2HB94_PHZ86(oC)a-p	T2HB94_PH87(oC)a-p	T2HB94_PJR89(oC)a-p	T2HB94_PS92(oC)a-p
Aas1	767	754	753	752	765	768	686	685	685	685	685
Aas2	769	755	754	754	767	771	702	702	702	701	702
Aas3	775	761	759	759	772	775	707	706	706	706	706
Aas4	759	746	744	744	756	759	710	709	709	709	710
Aas5	756	744	741	741	752	754	709	708	708	708	709
Aas6 b	711	701	699	699	707	709	682	679	678	678	680
Aas7	746	735	731	731	741	742	679	678	678	677	678
Aas8	711	702	697	696	705	705	664	662	662	662	663
Aas9	722	712	709	708	717	718	710	707	707	707	708
Aas10	735	725	720	720	728	729	688	686	685	685	686
Aas11	748	736	732	731	742	743	659	658	658	658	659
Aas12	771	758	754	754	766	768	674	673	673	673	674
Aas13	784	770	769	768	781	786	728	728	728	727	728

WinAmptb	231	232	233	234	235	236	237	238	239	240	241	242
Sample No	T2HB94_PA97_PJR89(oC)a-p	T2HB94_PA97_PS92(oC)a-p]	T2HB94_PP16a_PHZ86(oC)a-p	T2HB94_PP16b_PHZ86(oC)a-p	[TBH90_PAS95(oC)a-p	PAS95_TBH90(kbar)a]	[T1HB94_P1AS95(oC)a-p	P1AS95_T1HB94(kbar)a]	[T2HB94_P2AS95(oC)a-p	P2AS95_T2HB94(kbar)a]	[P1M15(kbar)a-p	P2M15(kbar)a-p]
Aas1	685	685	685	684	701	2.40	767	1.44	685	2.56		
Aas2	702	702	701	701	704	2.48	769	1.50	702	2.50		
Aas3	706	707	706	706	708	2.21	776	1.16	706	2.23		
Aas4	710	710	709	709	699	2.23	756	1.44	710	2.12		
Aas5	709	709	708	708	698	2.02	753	1.30	708	1.91		
Aas6 c	681	681	679	678	674	2.11	704	1.86	680	2.07		
Aas7	678	679	678	678	674	1.75	742	1.04	678	1.72		
Aas8	663	663	662	662	650	1.39	704	1.08	663	1.35		
Aas9	709	709	707	707	674	1.69	716	1.32	708	1.41		
Aas10	687	687	686	686	671	1.38	730	0.85	686	1.29		
Aas11	659	659	658	658	672	1.63	744	0.89	659	1.69		
Aas12	674	674	673	673	692	1.89	771	0.81	674	2.03		
Aas13	728	728	727	727	723	2.32	787	1.20	728	2.25		

Figure 7. Screenshot of an Excel file (i.e. Output.xlsx) created by program in estimation of the *P-T* conditions based on the calcic amphibole-plagioclase pairs (see text for explanations). *T* (ºC) values in column numbers 208, 217 and 226 (Figure 7 a,b) are estimated by selecting 3 (kbar) from the *Geothermobarometer* option.

$$[P]_{M_{15}}(\text{kbar}) = [8.3144 * T(K) * \ln D_{Al/Si}^{Plag/Amp} - 8.7 * T(K) + 23377 * X_{Al}^{Tl} + 7579 * X_{Ab} - 11302] / -274 \quad (30)$$

where $D_{\text{Al/Si}}^{\text{Plag/Amp}} = (X_{\text{Al}}^{\text{Plag}} / X_{\text{Si}}^{\text{Plag}}) / (X_{\text{Al}}^{\text{Amp}} / X_{\text{Si}}^{\text{Amp}})$

$X_{\text{Al}}^{\text{T1}}$ = Al fraction in T1-site in amphibole (i.e. $(8 - \text{Si}_{23\,\text{O}}^{\text{Amp}}) / 4$)

and X_{Ab} = Albite fraction in plagioclase (i.e. Na/(Na+Ca+K))

In the developed amphibole-plagioclase barometer, by using the robust regression method, the calcic amphibole formula is estimated based on the normalization scheme of 13 cation method (i.e. 13eCNK). The temperature-dependent barometers that require the amphibole-liquid and liquid-only thermometers (see Eqs. 31 and 32) by Molina et al. (2015) are displayed in columns 241 and 242 provided that amphibole, liquid and plagioclase compositions are all entered in the *Data Entry Screen*.

Amphibole-liquid and liquid-only thermobarometers

Compared to the prevalence of empirically calibrated thermobarometers on amphibole-only and amphibole-plagioclase pair, an experimental database on amphibole-liquid calibration is relatively scarce. Recently, considering a significant dependence on temperature and the logarithm of $X_{Ca}^{Liq}/(X_{Ca}^{Liq}+X_{Al}^{Liq})$ ratio of the molar amphibole/liquid Mg partitioning coefficient ($D_{Mg}^{Amp/Liq}$), Molina et al. (2015) proposed amphibole-liquid (temperature range: 800-1100 ºC) and liquid-only thermometers (see columns 243 and 244 in Figure 8a and rows 54 and 55 in Table 5) that applicable to alkaline and subalkaline igneous rocks:

$$[T_{\text{Amp-Liq}}]_{M_{15}}(^{\circ}\text{C}) = \frac{71975 - 11896 * \ln\left[\dfrac{X_{\text{Ca}}^{\text{Liq}}}{(X_{\text{Ca}}^{\text{Liq}} + X_{\text{Al}}^{\text{Liq}})}\right]}{8.3144 * \ln D_{\text{Mg}}^{\text{Amp/Liq}} + 58} - 273 \quad (31)$$

$$[T_{\text{Liq}}]_{M_{15}}(^{\circ}\text{C}) = 107 * \ln X_{\text{Mg}}^{\text{Liq}} - 108 * \ln\left[\frac{X_{\text{Ca}}^{\text{Liq}}}{(X_{\text{Ca}}^{\text{Liq}} + X_{\text{Al}}^{\text{Liq}})}\right] + 1184 \quad (32)$$

where $D_{\text{Mg}}^{\text{Amp/Liq}} = (X_{\text{Mg}}^{\text{Amp}} / X_{\text{Mg}}^{\text{Liq}})$;

$X_{\text{Ca}}^{\text{Liq}}, X_{\text{Al}}^{\text{Liq}}$ and $X_{\text{Mg}}^{\text{Liq}}$ = fraction of Ca, Al, and Mg cations in liquid, respectively.

The estimated precision for calibration and test data set ranges from ±33 to ±45 ºC for Eq. 31 and ±37 to ±42 ºC for Eq. 32, respectively. According to Molina et al. (2015), these two thermometers (i.e. Eq. 31 and Eq. 32) can be used together, both to confirm the extent of compositional equilibrium between amphibole and matrix glass in volcanic rocks and to examine the model compositions of amphibole-saturated liquids in volcanic and plutonic rocks.

a

WinAmptb	243	244	245	246	247	248	249	250	251	252	253
Sample No	[T1Mol15(oC)l	T2Mol15(oC)a-l]	[T1P16(oC)l	T2P16(oC)a-l	T3P16(oC)a-l	T4P16(oC)a-l	T5P16(oC)a-l	T6P16(oC)a-l	P1P16(kbar)a-l	P2P16(kbar)a-l	P3P16(kbar)a-l
Pas1	934	914	942	956	927	963	952	955	6.17	4.25	6.69
Pas4	938	913	945	960	942	951	932	946	5.01	2.60	5.33
Pas7	934	913	942	958	931	944	930	940	5.26	2.85	5.74
Pas10	943	921	946	956	942	985	976	970	9.00	5.76	9.59
Pas12	938	916	944	961	930	997	986	987	9.52	5.75	10.39
Pas13	934	914	945	957	921	959	949	950	4.83	3.04	6.69
Pas16	861	835	828	831	798	834	804	822	0.22	0.15	1.01
Pas17	877	846	838	832	812	823	795	820	1.56		2.29
Pas18	877	846	838	832	812	823	795	820	1.56		2.29
Pas19	865	838	830	830	808	830	800	823	0.81		1.60
Pas20	862	836	828	825	809	834	804	827	0.36		1.08

b

WinAmptb	254	255	256	257	258	259	260	261	262	263	264
Sample No	H2O(wt%)a-l	SiO2(wt%)a-l]	[QFM_P16(fO2)a	NNO_P16(fO2)a	HM_P16(fO2)a]	[QFM_RR12(fO2)a	NNO_RR12(fO2)a	HM_RR12(fO2)a]	[QFM_R10(fO2)a	NNO_R10(fO2)a	HM_R10(fO2)a]
Pas1	11.10	57.94	-11.43	-10.85	-6.17	-7.47	-8.83	-5.24	-6.63	-8.20	-4.70
Pas4	9.94	62.68	-11.85	-11.22	-6.53	-7.94	-8.89	-5.05	-8.68	-9.57	-5.74
Pas7	10.23	62.54	-11.87	-11.25	-6.56	-6.88	-8.35	-4.81	-8.16	-9.32	-5.64
Pas10	13.52	53.11	-10.84	-10.37	-5.73	-6.06	-8.21	-5.08	-4.36	-6.78	-3.73
Pas12	13.94	52.08	-10.65	-10.20	-5.57	-4.23	-6.96	-4.12	-5.24	-7.14	-3.78
Pas13	9.71	57.94	-11.58	-10.95	-6.24	-7.47	-8.83	-5.24	-6.63	-8.20	-4.70
Pas16	1.55	72.27	-14.69	-13.82	-9.08	-13.70	-13.44	-9.06	-10.10	-11.42	-7.92
Pas17	5.37	73.50	-14.75	-13.94	-9.24	-14.20	-13.84	-9.39	-11.17	-12.21	-8.55
Pas18	5.37	73.50	-14.75	-13.94	-9.24	-14.20	-13.84	-9.39	-11.17	-12.21	-8.55
Pas19	3.66	72.92	-14.70	-13.86	-9.14	-13.41	-13.14	-8.73	-10.60	-11.86	-8.34
Pas20	2.19	72.79	-14.66	-13.80	-9.06	-13.17	-12.92	-8.52	-10.75	-11.84	-8.22

Figure 8. Screenshot of an Excel file (i.e. Output.xlsx) created by program in estimation of the *P-T* conditions based on the liquid-only and calcic amphibole-liquid compositions (see text for explanations).

As in Molina et al. (2015), Putirka (2016) also developed a *P*-independent liquid-only thermometer (see column 245 in Figure 8a and row 56 in Table 5) with ±33 °C error in which amphibole should appear for a given liquid composition:

$$[T1_{\mathrm{Liq}}]_{\mathrm{P16}}(^{\circ}\mathrm{C}) = 24429.2/[2.31 + 42.1^{*}X^{\mathrm{Liq}}_{\mathrm{FeO_{Tot}}} + 32.2^{*}X^{\mathrm{Liq}}_{\mathrm{CaO}} + 2.21^{*}\ln\left(X^{\mathrm{Liq}}_{\mathrm{SiO_2}}\right) - 1.4^{*}\ln\left(X^{\mathrm{Liq}}_{\mathrm{SiO_2}}\right) - 2.666^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{FmAl}})] \quad (33)$$

where X_i^{Liq} are the hydrous mole fractions of oxides in an amphibole saturated liquid

(e.g. $X^{\mathrm{Liq}}_{\mathrm{FmAl}} = (\mathrm{FeO}^{\mathrm{Liq}}_{\mathrm{Tot}} + \mathrm{MgO}^{\mathrm{Liq}}) * \mathrm{Al_2O_3}^{\mathrm{Liq}})$.

The *P*-independent two amphibole-liquid thermometers (see columns 246 and 247 in Figure 8a and rows 57 and 58 in Table 5) based on the partitioning coefficients of Na and Ti (D_{Na} and D_{Ti}) were also proposed by Putirka (2016) that provide links to observed amphibole compositions having relatively low error by about 17 % with regard to liquid-only thermometer:

$$[T2_{\mathrm{Amp\text{-}Liq}}]_{\mathrm{P16}}(^{\circ}\mathrm{C}) = 6383.4/[-12.07 + 45.4^{*}X^{\mathrm{Liq}}_{\mathrm{Al_2O_3}} + 12.21^{*}X^{\mathrm{Liq}}_{\mathrm{FeO_{Tot}}} - 0.415^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{TiO_2}}) - 3.555^{*}\ln\left(X^{\mathrm{Liq}}_{\mathrm{Al_2O_3}}\right) - 0.832^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{Na_2O}}) - 0.481^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{FmO}}{}^{*}X^{\mathrm{Liq}}_{\mathrm{Al_2O_3}}) - 0.679^{*}\ln(D_{\mathrm{Na}}) \quad (34)$$

$$[T3_{\mathrm{Amp\text{-}Liq}}]_{\mathrm{P16}}(^{\circ}\mathrm{C}) = 8037.85/[3.69 + 2.62^{*}X^{\mathrm{Liq}}_{\mathrm{H_2O}} + 0.66^{*}\mathrm{Fe}^{\mathrm{Amp}}_{\mathrm{Tot}} - 0.416^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{TiO_2}}) - 0.37^{*}\ln\left(X^{\mathrm{Liq}}_{\mathrm{MgO}}\right) - 1.05^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{FmO}}{}^{*}X^{\mathrm{Liq}}_{\mathrm{Al_2O_3}}) - 0.462^{*}\ln(D_{\mathrm{Ti}}) \quad (35)$$

where FmO=($\mathrm{FeO_{Tot}}$+MgO+MnO);

$D_{\mathrm{Na}} = (\mathrm{Na}^{\mathrm{Amp}} / X^{\mathrm{Liq}}_{\mathrm{Na_2O}})$; $D_{\mathrm{Ti}} = (\mathrm{Ti}^{\mathrm{Amp}} / X^{\mathrm{Liq}}_{\mathrm{TiO_2}})$

Using a Na-K exchange coefficient ($K_D^{\mathrm{Na\text{-}K}}$) by Helz (1979), Putirka (2016) proposed another amphibole-liquid thermometer:

$$[T4_{\mathrm{Amp\text{-}Liq}}]_{\mathrm{P16}}(^{\circ}\mathrm{C}) = 10073.55/[9.75 + 0.934^{*}\mathrm{Si}^{\mathrm{Amp}} - 1.454^{*}\mathrm{Ti}^{\mathrm{Amp}} - 0.882^{*}\mathrm{Mg}^{\mathrm{Amp}} - 1.123^{*}\mathrm{Na}^{\mathrm{Amp}} - 0.322^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{FeO_{Tot}}}) - 0.15^{*}\ln(K_D^{\mathrm{Na-K}}) - 0.759^{*}\ln(D_{\mathrm{Al}})] \quad (36)$$

where $K_D^{\mathrm{Na\text{-}K}} = (\mathrm{K}^{\mathrm{Amp}} / \mathrm{Na}^{\mathrm{Amp}}) / (X^{\mathrm{Liq}}_{\mathrm{K_2O}} / X^{\mathrm{Liq}}_{\mathrm{Na_2O}})$;

$X^{\mathrm{Liq}}_{\mathrm{FeO_{Tot}}}$, $X^{\mathrm{Liq}}_{\mathrm{Na_2O}}$ and $X^{\mathrm{Liq}}_{\mathrm{K_2O}}$ = hydrous mole fractions of indicated oxides in liquid .

This thermometer (see column 248 in Figure 8a and row 59 in Table 5), with low standard error estimation (±27 °C), can be used to test the other thermometers proposed by Putirka (2016), when applied to natural systems. The *P*-dependent thermometers (i.e. Eq. 37 and Eq. 38) that require pressure as an input from the amphibole-liquid equilibria can be considered as the amphibole-liquid thermometers. In these equations (see columns 249 and 250 in Figure 8a and rows 60 and 61 in Table 5), the calcic amphibole cations are on basis of 23 oxygens.

$$[T5]_{\mathrm{P16}}(^{\circ}\mathrm{C}) = 1687 - 118.7 * \mathrm{Si} + 131.56 * \mathrm{Ti} - 71.41 * \mathrm{Fe_{tot}} + 86.13 * \mathrm{Na} + 22.44 * P\ (\mathrm{GPa}) \quad (37)$$

$$[T6]_{\mathrm{P16}}(^{\circ}\mathrm{C}) = 1201.4 - 97.93 * \mathrm{Si} + 201.82 * \mathrm{Ti} + 72.85 * \mathrm{Mg} + 88.9 * \mathrm{Na} + 40.65 * P\ (\mathrm{GPa}) \quad (38)$$

Putirka (2016) also proposed three tentative amphibole-liquid barometeres (see columns 251 to 253 in Figure 8a and rows 62 to 64 in Table 5):

$$[P1]_{\mathrm{P16}}(\mathrm{kbar}) = -30.93 - 42.74^{*}\ln(D_{\mathrm{Al}}) - 42.16^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{Al_2O_3}}) + 633^{*}X^{\mathrm{Liq}}_{\mathrm{P_2O_5}} + 12.64^{*}(X^{\mathrm{Liq}}_{\mathrm{H_2O}}) + 24.57^{*}\mathrm{Al}^{\mathrm{Amp}} + 18.6^{*}\mathrm{K}^{\mathrm{Amp}} + 4.0^{*}\ln(D_{\mathrm{Na}}) \quad (39)$$

$$[P2]_{\mathrm{P16}}(\mathrm{kbar}) = -64.79 - 6.064^{*}\ln(D_{\mathrm{Al}}) + 61.75^{*}X^{\mathrm{Liq}}_{\mathrm{SiO_2}} + 682^{*}X^{\mathrm{Liq}}_{\mathrm{P_2O_5}} - 101.9^{*}X^{\mathrm{Liq}}_{\mathrm{CaO}} + 7.85^{*}\mathrm{Al}^{\mathrm{Amp}} - 46.46^{*}\ln\left(X^{\mathrm{Liq}}_{\mathrm{SiO_2}}\right) - 4.8^{*}\ln(X^{\mathrm{Liq}}_{\mathrm{Na_2O}} + X^{\mathrm{Liq}}_{\mathrm{K_2O}}) \quad (40)$$

$$[P3]_{\mathrm{P16}}(\mathrm{kbar}) = -45.5 - 46.3^{*}\ln(D^{\mathrm{Anhydrous}}_{\mathrm{Al}}) - 51.1^{*}\ln(X^{\mathrm{Anhydrous}}_{\mathrm{Al_2O_3}}) + 439^{*}X^{\mathrm{Anhydrous}}_{\mathrm{P_2O_5}} + 26.6^{*}\mathrm{Al}^{\mathrm{Amp}} + 22.5^{*}\mathrm{K}^{\mathrm{Amp}} + 5.23^{*}\ln\left(D^{\mathrm{Anhydrous}}_{\mathrm{Na}}\right) \quad (41)$$

where in Eqs. 39 and 40 liquid (i.e. $X^{\mathrm{Liq}}_{\mathrm{Oxides}}$) composition terms show hydrous mole fractions of the indicated oxides, and the partition coefficient terms (i.e.$D_{\mathrm{Na}} = \mathrm{Na}^{\mathrm{Amp}}/X^{\mathrm{Liq}}_{\mathrm{Na_2O}}$ and $D_{\mathrm{Al}} = \mathrm{Al}^{\mathrm{Amp}}/X^{\mathrm{Liq}}_{\mathrm{Al_2O_3}}$) use hydrous mole fractions. In Eq. 41, terms including $X^{\mathrm{Anhydrous}}_{\mathrm{Al_2O_3}}$, $D^{\mathrm{Anhydrous}}_{\mathrm{Al}}$ and $D^{\mathrm{Anhydrous}}_{\mathrm{Na}}$ show the anhydrous mole fractions and anhydrous liquid components, respectively. Figure 8b shows estimation of the QFM, NNO, and HM buffers (from Fegley, 2013) for amphibole compositions based on the recent *P-T* calibrations (e.g. Putirka, 2016; Ridolfi and Renzulli, 2012; Ridolfi et al., 2010).

SUMMARY AND AVAILABILITY OF THE PROGRAM

WinAmptb is a user-friendly program, which is specially developed for personal computers running in the Windows operating system to estimate the *P-T* conditions of calcic amphiboles. The program performs a large number of thermometers and barometers using the exchange reactions between amphibole and plagioclase pairs and amphibole-liquid equilibria. WinAmptb separates amphibole analyses into groups and classify calcic group minerals according to the IMA-04 amphibole nomenclature scheme. The program calculates structural formulae of multiple electron-microprobe calcic amphibole analyses with different normalization schemes (i.e. 13eCNK, 15eNK and 15eK), estimates stoichiometric calculation of H_2O (wt%) and Fe_2O_3 (wt%) contents and predicts cation site-allocations at the different structural positions (e.g. T, C, B, A, OH or T, *M*1,2,3, *M*4, A, OH sites). WinAmptb also provides the user to recalculate microprobe-derived plagioclase analyses and to estimate liquid cation fractions in implementing the thermobarometers.

The program generates two main windows. The first window (i.e. *Start-up/Data Entry Screen*), with several pull-down menus and equivalent shortcuts, enables to edit amphibole, liquid and plagioclase analyses into the *Data Entry Section* as well as to carry out necessary arrangements for a desired calculation scheme. By clicking the *Calculate* icon (i.e., ∑) in the *Data Entry Screen*, all calculated parameters by WinAmptb are displayed in the second window (i.e. *Calculation Screen*). WinAmptb reports the output in a tabulated form with a numbered column number from 1 to 264 in the *Calculation Screen* window. Amphibole-related parameters indicated by light blue color are listed between 1 and 111 column numbers. Calculated liquid composition and plagioclase analyses are displayed by chartreuse and light pink colors in 113 to 135 and 137 to 159 column numbers in the *Calculation Screen*, respectively. Similarly, thermobarometric and chemometric results based on the amphibole-only, amphibole-palgioclase and amphibole-liquid compositions are listed by pale yellow color between 161 and 264 column numbers. The results in the *Calculation Screen* can be exported to Microsoft® Excel file (i.e. output.xlsx), by clicking the *Send Results to Excel File (Output.xlsx)* icon or selecting the *Send Results to Excel File (Output.xlsx)* option from the pull-down menu of *Excel* and then this file is opened by Excel by clicking the *Open and Edit Excel File (Output.xlsx)* icon or selecting the *Open Excel File (Output.xlsx)* option from the pull-down menu of *Excel*. WinAmptb is a compiled program that consists of a self-extracting setup file including all the necessary support files (i.e. dll and ocx) for the 32-bit system. By clicking the setup file, the program and its associated files (i.e., support files, help file, data files with the extension of amp, xls, xlsx and plot files with the extension of grf) are installed into the personel computer (i.e. the directory of C:\Program Files\WinAmptb) with the Windows XP and later operating systems. The self-extracting setup file is approximately 13 Mb and can be obtained from the journal server or from corresponding author on request.

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APPENDIX

Calibration conditions and compositional bounds for the P-T, oxygen fugacity and hygrometric formulations referenced in text.

Equation[†]	*Estimation*	*Calibration Conditions*	*Compositional Bounds*	*Column*[*]	*Reference*
1	*T* (ºC)	Up to 5 kbar and 700 to 1000 ºC *P-T* conditions. Thermometer can be used if the oxygen fugacity (fO_2) was near the QFM buffer and sufficient Ti was available in rock composition (e.g. ilmenite must be present).	Hornblende associated with Ti-rich minerals in gabbro and dolerite.	161	Otten (1984)
2	*P* (kbar)	In relatively oxidizing conditions (NB and HM buffers). The Al-in-hornblende barometer can be used in low-pressure (i.e. ~ 1-2 kbar; magmatic epidote absence) and high-pressure (i.e. ~ 8 kbar; magmatic epidote presence) conditions.	Calc-alkaline intrusive complexes with mineral assemblages consist of plagioclase, hornblende, biotite, K-feldspar, quartz, sphene, magnetite or ilmenite, ± epidote. Hornblende rims in equilibrium with quartz should be considered.	163	Hammarstrom and Zen (1986)
3	*P* (kbar)	Crystallization at intermediate pressures (i.e. 4-6 kbar). The Al-in-hornblende barometer is restricted to pressure above ~ 2 kbar due to the temperature of final crytallization increases rapidly with drop in in presseure below ~2 kbar.	Calc-alkaline plutons with mineral assemblages consist of quartz, plagioclase, hornblende, biotite, orthoclase, titanite and magnetite. The rim compositions of hornblende should be used. At the same time, the rim plagioclase compositions between ~An_{25} and An_{35} should be taken into consideration due to the high plagioclase anorthite content may increase Al_{Tot} content in hornblende independent of pressure.	164	Hollister et al. (1987)
4	*P* (kbar)	The Al-in-hornblende calibration was perfomed over the pressure range 2-8 kbar at 740-780 ºC. fO_2 was buffered by either MNO, NNO or AMQH.	Igneous (i.e. volcanic and plutonic) hornblendes in equilibrium with melt, fluid, biotite, quartz, sanidine, plagioclase, sphene, magnetite or ilmenite.	165	Johnson and Rutherford (1989)
5	*P* (kbar)	The Al-in-hornblende barometer was calibrated experimentally to 12 kbar at 750 ºC. Calibration should be applied for amphibole samples in granitoids that crystallized above the 2.5 kbar pressure conditions. fO_2 was buffered between NNO and HM.	Hornblende in granitoids with the mineral assemblage of quartz, K-feldspar, plagioclase, biotite, epidotite, sphene, Fe-Ti oxide minerals.	166	Thomas and Ernst (1990)
6	*P* (kbar)	The Al-in-hornblende barometer was calibrated experimentally under the water-saturated *P-T* conditions ranging from 2.5 to13 kbar and temperatures from 655 to 700 ºC. fO_2 was buffered at NNO.	Hornblende in tonalite and granodiorite in equilibrium with biotite, plagioclase, K-feldspar, quartz, sphene, Fe-Ti oxides, melt, and vapor.	167	Schmidt (1992)
7	*P* (kbar) *P* (kbar)	A revised Al-in-hornblende barometer considers the effect of temperature using experimental data by Johnson and Rutherford (1989) at ~760 ºC and Schmidt (1992) at ~675 ºC. See oxygen fugacity buffer conditions in Johnson and Rutherford (1989) and Schmidt (1992).	See rock compositions including hornblende in equilibrium with mineral assemblages listed in Johnson and Rutherford (1989) and Schmidt (1992). In using the Anderson and Smith (1995) calibration, $Fe_{Tot}/(Fe_{Tot}+Mg) <$ 0.65 and $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ = ~0.2-0.25 ratios in amphibole and plagioclase compositions (~An_{25-35}) should be considered.	162 173	Anderson and Smith (1995)

Equation†	*Estimation*	*Calibration Conditions*	*Compositional Bounds*	*Column**	*Reference*
ebp	*P* (kbar)	A revised Al-in-hornblende barometer was obtained in a plot as a function of *P* (kbar) computed using the thermodynamics-based method. Compared to the other conventional Al-in-hornblende barometers, Ague's (1997) model can be used in low-*P* settings (e.i. 1.2 to 7.4 kbar).	Hornblende in granitoids (e.g. tonalite, granodiorite, granite). In this calibration, the presence of sphene, Fe-Ti oxides and melt is not required as a part of mineral assemblage. Hence, *P* (kbar) estimates can be used for amphibolite and granulite facies metamorphic mineral assemblages. Hornblende and biotite have Mg/(Mg+Fe_{Tot}) in the range of 0.31 to 0.68. The Ca, Al_{Tot}, and calculated $Fe^{2+}/(Fe^{2+}+Fe^{3+})$ of hornblende range from 1.81 to 1.91, 0.74 to 2.49, and 0.68 to 0.85, respectively.	168	Ague (1997)
ebp	*P* (kbar)			169	
ebp	*P* (kbar)	An experimental semiquantitative thermobarometer based on the Al- and Ca-contents of calcic amphibole in mid-ocean ridge basalts (MORB) at *P-T* conditions ranging from 0.8-2.2 GPa and 650-950 ºC. fO_2 was buffered at QFM.	Metabasaltic assemblages coexisting with Al-rich and Ti-rich phases, and closely approached chemical equilibrium under the crustal or uppermost mantle conditions.	170	Ernst and Liu (1998)
ebp	*T* (ºC)			171	
8	*T* (ºC)	A quantitative thermometer that can be applicable to high-*T* (>700 ºC) calcic amphiboles crystallizing in Ti-saturated calc-alkaline magma at a nearly constant *P* of about 0.6±0.1 Gpa.	Hornblende in calc-alkaline dike swarm that is composed of basalt, andesite, dacite and rhyolite compositions.	172	Féménias et al. (2006)
9	*P* (MPa)	An empirical amphibole barometer for bodies of mafic and ultramafic cumulates within depeer parts of the arc environment. Barometer can be applied for hornblendes in H_2O-saturated primitive basaltic magmas at 200-700 MPa and NNO buffer conditions.	Hornblends in high-Mg basalt to andesite with the primary mineral assemblage of plagioclase, biotite, quartz, Fe-Ti oxides, olivine, pyroxene and associated accessory K-feldspar, titanite, apatite and zircon.	174	Larocque and Canil (2010)
10 to 13	*T* (ºC)	Empirical thermometer, barometer, relative oxygen fugacity (ΔNNO), and hygrometric (H_2O_{melt}) formulations based on the single calcic amphibole composition. Formulations can be applied within the *P-T* range of 100-1200 MPa and 750-1120 ºC at NNO to NNO+2 buffer conditions.	Calcic amphiboles in subduction-related calc-alkaline volcanoes that consist of basalt to rhyolite compositions in both continental and oceanic crust environments.	175	Ridolfi et al. (2010)
	ΔNNO			176	
	$H_2O_{[melt]}$ (%)			177	
	P (MPa)			178	
14 to 21	P_{1a} to P_{1e} (MPa)	New thermobarometric and chemometric empirical formulations based on a large number of natural calcic amphiboles and carefully selected experimental data from literature in a wide range of *P-T* conditions (130-2200 MPa and 800-1130 ºC) at -2.1 < ΔNNO< +3.6 (i.e. ~NNO-2 to NNO+2 buffers).	Calcic amphiboles associated with calc-alkaline and alkaline magmas of oceanic intraplate and volcanoes located in complex geodynamic settings. Proposed chemometric equations can be used in understanding the pre-eruptive conditions and sub-volcanic processes.	183 to 187	Ridolfi and Renzulli (2012)
	P (MPa)			188	
	T_{1a} to T_{1e} (ºC)			190 to 193	
	T (ºC)			194	
	ΔNNO			195	
	$H_2O_{[melt]}$ (%)			96	
	SiO_2 (%)			197	

Equation[†]	*Estimation*	*Calibration Conditions*	*Compositional Bounds*	*Column*[*]	*Reference*
22	*P* (MPa)	A new amphibole Mg# barometer-hygrometer for calcic amphiboles from less evolved arc magmas. An empirical calibration can be used within the *P*-*T* range of 0.1-800 MPa and 915-1070 ºC at NNO to NNO+3 buffer conditions.	The barometer is used for calcic amphiboles in andesitic to basaltic rocks with Mg# ranging from 74 to 84 (i.e. Mg-rich amphiboles that crystallize at high temperatures and H_2O contents).	201	Krawczynski et al. (2012)
23	P_{H2O} (MPa)			202	
24	$T_{si\text{-}in\text{-}Hbl}$ (ºC)	Empirical thermometers and tenative barometers based on the experimental and natural calcic amphibole compositions in igneous systems to better understand the solid-solution behavior as well as the eruption mechanisms of felsic magmas at arc volcanoes.	The experimental data collected in the Putirka's (2016) study, are not saturated in the 7-10 crystalline phases often reccomended for Al-in-hornblende barometers. Most of the current Al-in-hornblende barometers fare poorly when applied outside the conditions (i.e. *T* < 800 ºC and $Fe\#^{Amp}=Fe^{Amp}/(Fe^{Amp}+Mg^{Amp})$ <0.65) reccommended by Anderson and Smith (1995). Hence, experimentally grown and natural calcic amphibole compositions were used by Putirka (2016) to investigate amphibole solid solution behavior in igneous systems.	203	Putirka (2016)
25	$T_{Eq.5}$ (ºC)			204	
ebp	*P1* (kbar)			205	
ebp	*P2* (kbar)			206	
26	*P* (kbar)	A revised Al-in-hornblende barometer based on new experimental data for magmatic calcic amphiboles synthesised from a variety of granite bulk compositions at near-solidus temperature (i.e. 725±75 ºC) and pressure (0.8-10 kbar) conditions. Much et al. (2016) proposed a quadratic Al-in-hornblende barometer as the relationship between Al_{tot} and pressure shows nonlinear trend at low pressure	The barometer is applicable to granitic rocks with the low-variance mineral assemblage (e.g. consisting of amphibole, plagioclase ($An_{15\text{-}80}$), biotite, quartz, alkali feldspar, ilmenite or titanite, magnetite, and apatite). Amphibole analyses should be taken from rims, in contact with plagioclase.	207	Mutch et al. (2016)
27	*T* (ºC)	A pressure-dependent thermometer based on the tetrahedral Al (*apfu*) content of calcic amphibole coexisting with plagioclase in silica saturated rocks that equilibrated at temperatures in the range 500-1100 ºC (±40 ºC).	The thermometer is applicable for rocks (e.g. greenschist to granulite facies metamorphic rocks and a variety of mafic to acid intrusive and extrusive igneous rocks) including plagioclase (< An_{92}) and amphibole (7.8<Si *apfu*) contents for the equilibrium reactions Edenite + 4 Quartz = Tremolite + Albite and Pargasite + 4 Quartz = Hornblende + Albite.	208 to 216	Blundy and Holland (1990)
28 and 29	*T* (ºC)	Two new thermometers that can be used over a broad range of bulk compositions with *P*-*T* conditions in the range 1-15 kbar and 400-1100 ºC (±40 ºC). These two pressure-dependent thermometers can be used to a wider range of amphibole-plagioclase parageneses.	Thermometers for application to coexising amphibole and plagioclase pairs with new calibrations in equilibrium with Edenite + 4 Quartz = Tremolite + Albite (requires silaca saturation) and Edenite + Albite = Richterite + Anorthite (does not require silica suturation) reactions.	217 to 240	Holland and Blundy (1994)

Equation[†]	*Estimation*	*Calibration Conditions*	*Compositional Bounds*	*Column*[*]	*Reference*
30 31 32	*P* (kbar) *T1* (ºC) *T2* (ºC)	A temperature-dependent barometer based on the Al-Si partitioning between calcic amphibole and plagioclase for the 650-1050 ºC temperature range and precision ±1.5 to ±2.3 kbar. Molina et al. (2015) also proposed two amphibole-liquid (800-1100 ºC) and liquid-only thermometers that applicable to alkaline and subalkaline igneous rocks.	The barometer was proposed for metamorphic and igneous rocks using the compositional database for amphibole-plagioclase pairs that compiled from the experimental studies in literature. The barometer can only be used for calcic amphibole compositions normalized to 13eCNK, with >0.02 Ti and >0.05 Al^{VI} (*apfu*) contents.	241 to 242 243 244	Molina et al. (2015)
33	*T* (ºC)	A *P*-independent liquid-only thermometer with ±33 ºC error in which amphibole appears in a given liquid composition. According to Putirka (2016), pressure ranges from 0.5 to 25 kbar for the calibration data, but adding *P* (kbar) as a variable to Eq.33, does not improve the *T* (ºC) prediction.	See earlier explanations in this Table's Compositional Bounds (i.e. in the row of Equation 24).	245	Putirka (2016)
34 and 35	*T1* (ºC) *T2* (ºC)	*P*-independent two amphibole-liquid thermometers based on the partitioning coefficients of Na and Ti. *T2* is effectively a kaersutite-liquid thermometer.	See earlier explanations in this Table's Compositional Bounds (i.e. in the row of Equation 24).	246 247	Putirka (2016)
36	*T* (ºC)	Using a Na-K exchange coefficient ($K_D^{Na\text{-}K}$) by Helz (1979), another amphibole-liquid thermometer with low standard error estimation (±27 ºC) to test the other thermometers proposed by Putirka (2016).	See earlier explanations in this Table's Compositional Bounds (i.e. in the row of Equation 24).	248	Putirka (2016)
37 and 38	*T* (ºC)	The *P*-dependent two thermometers that require pressure as an input from the amphibole-liquid equilibria.	See earlier explanations in this Table's Compositional Bounds (i.e. in the row of Equation 24).	249 to 250	Putirka (2016)
39 to 41	*P1* (kbar) *P2* (kbar) *P3* (kbar)	Three tentative amphibole-liquid barometeres. *P1* and *P2* are calibrated for the hydrous forms of liquid composition and mole fractions of the indicated oxides, whereas *P3* denotes the anhydrous form. These empirical barometers which are based on the D_{Al} succesfully differentiate experimental amphiboles crystallized at 1 to 8 kbar.	See earlier explanations in this Table's Compositional Bounds (i.e. in the row of Equation 24).	251 252 253	Putirka (2016)

Note: (†) = Equation numbers in text; (*) = Column numbers in the "*Calculation Screen*" and an ouptup file (i.e. Output.xlsx); ebp = Estimated by program, but not given as an equation in text; QFM = Quartz-Fayalite-Magnetite buffer; NNO = Ni-NiO buffer; NB = Nickel-Brunsenite buffer; HM = Hematite-Magnetite buffer; MNO = MnO-Mn_3O_4 buffer; AMQS = Andradite-Magnetite-Quartz-Hedenbergite buffer (AMQH is an oxygen buffer about two log units above the NNO buffer at 750 °C).