WinMlgob: A Windows program for magnetite–ilmenite geothermometer and oxygen barometer †

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A Microsoft® Visual Basic software, called WinMlgob, has been developed for wet-chemical and electron-microprobe compositions of coexisting magnetite–ulvöspinel and ilmenite–hematite solid solutions to calculate the temperature (T, °C) and oxygen fugacity (fO2) conditions of magmatic and metamorphic rocks. The program allows the users to enter total of 34 input variables, including Sample No, SiO2, TiO2, Al2O3, V2O5, Cr2O3, Nb2O5, FeO, Fe2O3, MnO, NiO, ZnO, MgO, CaO, Na2O, K2O, BaO (wt. %) for each magnetite and ilmenite compositional data. WinMlgob enables to enter and load multiple magnetite and ilmenite analyses in the program’s data entry section. Alternatively, the composition of magnetite–ilmenite pairs can be typed in a blank Excel file as in the above order and then loaded into the program’s data entry screen for data processing. The ferric and ferrous iron contents from microprobe-derived total FeO (wt. %) of magnetite–ilmenite compositions are estimated by stoichiometric constraints based on three different approaches. Using the calculated multiple magnetite and ilmenite analyses, WinMlgob estimates molecular (%) and mole fractions of magnetite, ulvöspinel, ilmenite and hematite amounts. The program evaluates fourteen magnetite–ilmenite geothermometers, thirteen oxygen barometers and six relative to the nickel–nickel oxide (NNO) buffer values based on the different calibrations with various calculation methods. WinMlgob also allows the users to check if their magnetite–ilmenite pairs taken from rocks are within or departure from the Bacon–Hirschmann Mg/Mn exchange equilibrium line ± 2σ level. This program generates and stores all the calculated results in the Microsoft Excel file (i.e., Output.xlsx), which can be displayed and processed by any other software for further data presentation and graphing purposes. The compiled program code is distributed as a self-extracting setup file, including a help file, test data files and graphic files, which are intended to produce a high-quality printout.

Keywords: magnetite, ilmenite, geothermometer, oxygen fugacity, Bacon–Hirschmann, software

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1. Introduction

The two most common Fe–Ti oxide minerals with magnetite–ulvöspinel (mt) and ilmenite–hematite (ilm) solid solutions, hereafter referred to as magnetite and ilmenite, respectively, in a variety of rocks and mineral deposits provide the earth scientists valuable information about the temperature of equilibration and corresponding oxygen fugacity conditions (Misra 2012). Consequently, magnetite–ilmenite geothermometry and oxygen barometry have been studied and used widely in igneous and metamorphic petrology with numerous refinements to model the exchange and oxidation reactions since its conception was established in the early 1960s to estimate temperature and oxygen fugacity values, especially for extrusive and hypabyssal igneous rocks that were subjected to the relatively rapid cooling process (Buddington and Lindsley 1964; Carmichael 1967; Anderson 1968; Powell and Powell 1977; Spencer and Lindsley 1981; Lindsley and Spencer 1982; Stormer 1983; Andersen and Lindsley 1988; Ghiorsor and Sack 1991; Lattard et al. 2005; Ghiorsor and Evans 2008; Sauerzapf et al. 2008). However, at relatively temperature conditions of slow cooling of magmatic rocks or hydrothermal alteration, these minerals tend to display oxide–oxide, intraoxide and oxide–silicate re-equilibration processes after their crystallization history (Venezky and Rutherford 1999). Accordingly, Fe–Ti oxide minerals used in magnetite–ilmenite geothermometry and oxygen barometry studies rarely preserve their magmatic compositions in slowly cooled plutonic or hydrothermal rocks. Therefore, their application to plutonic igneous rocks and mineral deposits should be considered with caution (Misra 2012; Wang et al. 2014). On the other hand, in many natural magmas, magnetite and ilmenite may not have coprecipitated. Thus, an absence of ilmenite in these rocks prevents the application of magnetite–ilmenite oxygen barometry technique but allows to estimate it based on Fe and Ti’s partitioning between magnetite and silicate melt (Arató and Audétat 2017).

The magnetite–ilmenite geothermometer and oxygen barometer model, on a graphical solution, by Buddington...
and Lindsley (1964), was one of the first calibrated study based on temperature and redox-sensitive equilibria between magnetite–ulvöspinel and ilmenite–hematite solid solutions in the FeO–Fe$_2$O$_3$–TiO$_2$ system. Ghiorso and Carmichael (1981) developed a Fortran IV program for the calculation of temperature and oxygen fugacity using the mole fractions of ulvöspinel (Fe$_5$TiO$_7$) and hematite (Fe$_3$O$_4$) from compositions of coexisting Fe–Ti oxide pairs in rocks. Their approach depends essentially on the graphical interpolation from published smoothed calibration curves by Buddington and Lindsley (1964). Rao et al. (1991) presented an interactive Basic program of Fe–Ti oxide thermometry, called IHERM, to calculate temperatures of equilibration using the methods of Powell and Powell (1977), Spencer and Lindsley (1981), and Andersen and Lindsley (1985). Lepage (2003) developed an Excel spreadsheet (ILMAT) solely on the magnetite–ilmenite geothermometry, but also calculating oxygen fugacity based on the empirical approach proposed by several authors (e.g., Spencer and Lindsley 1981; Andersen and Lindsley 1985). The logic of ILMAT was taken from IHERM (Rao et al. 1991) with revision and correction on magnetite–ilmenite geothermometry estimations. Hora et al. (2013) presented three Excel spreadsheets for two mineral pairs, including magnetite–ilmenite (Ghiorso and Evans 2008), amphibole–plagioclase (Holland and Blundy 1994) and two feldspar (Putirka 2008) geothermometers with a technique facilitating geothermobarometry estimations on a large number of analyses. When compared to the other two amphibole–plagioclase and two feldspar geothermometers, magnetite–ilmenite geothermometer approach uses an AppleScript to transfer input magnetite and ilmenite analyses from Mac OSX Excel to the standalone application and to receive the calculated results back to the Excel platform (Hora et al. 2013).

In this paper, a new computer program, called WinMIgob, is developed using the Microsoft® Visual Basic programming language to calculate multiple magnetite and ilmenite mineral oxides, up to 350 analyses in each program execution, obtained by both wet-chemical and electron-microprobe techniques. The logic of WinMIgob is based on ILMAT, an Excel spreadsheet developed by Lepage (2003), with additional recent magnetite–ilmenite geothermometers and oxygen barometers (e.g., Sauerzapf et al. 2008). The program recalculates magnetite mineral analyses to four oxygens and three total cations and ilmenite analyses to three oxygens and two total cations. WinMIgob is capable of estimating the Fe$^{3+}$ and Fe$^{2+}$ contents from electron microprobe-derived total FeO (wt. %) analysis based on stoichiometric considerations using different procedures outlined by Carmichael (1967), Stormer (1983) and Droop (1987). Using the recalculated magnetite and ilmenite compositions, the program provides users various geothermometer ($T$, °C), oxygen fugacity (log $f_{O_2}$) and relative to the nickel–nickel oxide (NNO) buffer (ΔNNO) estimations (e.g., Powell and Powell 1977; Spencer and Lindsley 1981; Andersen and Lindsley 1985; Sauerzapf et al. 2008). WinMIgob also calculates magnetite–ilmenite geothermometer and ANNO developed by Ghiorso and Evans (2008) based on the selected magnetite–ilmenite analyses from literature through linear regression equations between the Andersen and Lindsley (1985) and Sauerzapf et al. (2008) calibrations. WinMIgob provides the user to display magnetite–ilmenite compositions in various binary (e.g., $T$ (°C)–log $f_{O_2}$) and ternary (e.g., Ti–R$^{2+}$–R$^{3+}$) diagrams by using the Golden Software’s Grapher program. Compared to the previously published computer programs and Excel spreadsheets on Fe–Ti oxides, the current version of program presents the quick evaluation and comparison of multiple magnetite–ilmenite analyses for numerous geothermometry and oxygen fugacity calculations.

2. Program description

In comparison of executable computer programs and Excel spreadsheets solely based on the calculation and classification of rock-forming silicate group minerals, a limited number of studies appeared in literature for geothermobarometry estimations (e.g., Yavuz 1998; Putirka 2008; Hora et al. 2013; Yavuz 2013; Lanari et al. 2014; Yavuz and Döner 2017; Li et al. 2019; Yavuz and Yıldırım 2020).

WinMIgob is a compiled program presented for running in the Microsoft® Windows platform to estimate the different Fe–Ti oxide geothermometer and oxygen fugacity calibrations. The program comes up with a self-extracting setup file (~20 Mb), which is created by the Inno Setup Compiler (https://jrsoftware.org/isinfo.php). It runs as a single executable file, WinMIgob.exe (3.17 Mb), on the condition that the Microsoft® Visual Studio package is installed into the same personal computer. On the other hand, with the help of necessary “.ocx” and “.dll” support files came up with a setup file, the users of this program can execute WinMIgob without requiring the Microsoft® Visual Studio package. Following the successful installation of the program, the start-up screen with various pull-down menus and shortcuts appears. A list of the calculation steps in the program’s Calculation Screen and in an Excel output file is given in Tab. 1. The current version of the program presents ten binary and ternary magnetite–ilmenite–related plots. These plots are displayed by selecting a desired diagram type from the pull-down menu of Graph in the Calculation Screen window of WinMIgob.
**Tab. 1** Description of column numbers in the *Calculation Screen* window of WinMIgob program and an output Excel file

| Row | Explanation |
|-----|-------------|
| 1   | Major oxide magnetite mineral analyses (wt. %) |
| 2   | Stoichiometric Fe$_3$O$_4$ and FeO (wt. %) contents from microprobe magnetite analyses |
| 3   | Recalculated cations of magnetite mineral analyses (apfu) |
| 4   | Blank |
| 5   | Major oxide ilmenite mineral analyses (wt. %) |
| 6   | Stoichiometric Fe$_3$O$_4$ and FeO (wt. %) contents from microprobe ilmenite analyses |
| 7   | Recalculated cations of ilmenite mineral analyses (apfu) |
| 8   | Blank |
| 9   | Sum of atomic mole proportion of magnetite and ilmenite analyses |
| 10  | Molecular ulvöspinel and magnetite amounts (%) by Carmichael (1967) |
| 11  | Molecular ilmenite and hematite amounts (%) by Carmichael (1967) |
| 12  | Molecular ulvöspinel and ilmenite amounts (%) by Anderson (1968) |
| 13  | Molecular ulvöspinel and ilmenite amounts (%) by Lindsley and Spencer (1982) |
| 14  | Molecular ulvöspinel and ilmenite amounts (%) by Stormer (1983) |
| 15  | Mole fraction of ulvöspinel and magnetite amounts by Spencer and Lindsley (1981) |
| 16  | Mole fraction of ilmenite and hematite amounts by Spencer and Lindsley (1981) |
| 17  | Mole fraction of ulvöspinel and magnetite amounts by Sauerzapf et al. (2008) |
| 18  | Mole fraction of ilmenite and hematite amounts by Sauerzapf et al. (2008) |
| 19  | Blank |
| 20  | Magnetite–ilmenite geothermometer (°C) by Powell and Powell (1977) using the Carmichael (1967) calculation method |
| 21  | Magnetite–ilmenite geothermometer (°C) by Powell and Powell (1977) using the Anderson (1968) calculation method |
| 22  | Magnetite–ilmenite geothermometer (°C) by Powell and Powell (1977) using the Stormer (1983) calculation method |
| 23  | Magnetite–ilmenite geothermometer (°C) by Powell and Powell (1977) using the Stormer (1983) calculation method |
| 24  | Magnetite–ilmenite geothermometer (°C) by Spencer and Lindsley (1981) using the Stormer (1983) calculation method |
| 25  | Magnetite–ilmenite geothermometer (°C) by Spencer and Lindsley (1981) using the Anderson (1968) calculation method |
| 26  | Magnetite–ilmenite geothermometer (°C) by Spencer and Lindsley (1981) using the Stormer (1983) calculation method |
| 27  | Magnetite–ilmenite geothermometer (°C) by Spencer and Lindsley (1981) using the Stormer (1983) calculation method |
| 28  | Magnetite–ilmenite geothermometer (°C) by Andersen and Lindsley (1985) using the Carmichael (1967) calculation method |
| 29  | Magnetite–ilmenite geothermometer (°C) by Andersen and Lindsley (1985) using the Anderson (1968) calculation method |
| 30  | Magnetite–ilmenite geothermometer (°C) by Andersen and Lindsley (1985) using the Anderson (1968) calculation method |
| 31  | Magnetite–ilmenite geothermometer (°C) by Andersen and Lindsley (1985) using the Stormer (1983) calculation method |
| 32  | Magnetite–ilmenite geothermometer (°C) by Andersen and Lindsley (1985) using the Stormer (1983) calculation method |
| 33  | Magnetite–ilmenite geothermometer (°C) by Ghiorso and Evans (2008) based on the linear regression equation $T_{\text{calc}}$ (°C) = 1.09826 × $T_{\text{obs}}$ − 67.18938 |
| 34  | Blank |
| 35  | Log oxygen fugacity (f$_{O_2}$) by Powell and Powell (1977) using the Carmichael (1967) calculation method |
| 36  | Log oxygen fugacity (f$_{O_2}$) by Powell and Powell (1977) using the Anderson (1968) calculation method |
| 37  | Log oxygen fugacity (f$_{O_2}$) by Powell and Powell (1977) using the Lindsley and Spencer (1982) calculation method |
| 38  | Log oxygen fugacity (f$_{O_2}$) by Powell and Powell (1977) using the Stormer (1983) calculation method |
| 39  | Log oxygen fugacity (f$_{O_2}$) by Spencer and Lindsley (1981) using the Carmichael (1967) calculation method |
| 40  | Log oxygen fugacity (f$_{O_2}$) by Spencer and Lindsley (1981) using the Anderson (1968) calculation method |
| 41  | Log oxygen fugacity (f$_{O_2}$) by Spencer and Lindsley (1981) using the Lindsley and Spencer (1982) calculation method |
| 42  | Log oxygen fugacity (f$_{O_2}$) by Spencer and Lindsley (1981) using the Stormer (1983) calculation method |
| 43  | Log oxygen fugacity (f$_{O_2}$) by Andersen and Lindsley (1985) using the Carmichael (1967) calculation method |
| 44  | Log oxygen fugacity (f$_{O_2}$) by Andersen and Lindsley (1985) using the Anderson (1968) calculation method |
| 45  | Log oxygen fugacity (f$_{O_2}$) by Andersen and Lindsley (1985) using the Lindsley and Spencer (1982) calculation method |
| 46  | Log oxygen fugacity (f$_{O_2}$) by Andersen and Lindsley (1985) using the Stormer (1983) calculation method |
| 47  | Log oxygen fugacity (f$_{O_2}$) by Sauerzapf et al. (2008) |
| 48  | Blank |
| 49  | Log oxygen fugacity (f$_{O_2}$, relative to buffer) by Andersen and Lindsley (1985) using the Carmichael (1967) calculation method |
| 50  | Log oxygen fugacity (f$_{O_2}$, relative to buffer) by Andersen and Lindsley (1985) using the Anderson (1968) calculation method |
| 51  | Log oxygen fugacity (f$_{O_2}$, relative to buffer) by Andersen and Lindsley (1985) using the Stormer (1983) calculation method |
| 52  | Log oxygen fugacity (f$_{O_2}$, relative to buffer) by Andersen and Lindsley (1985) using the Stormer (1983) calculation method |
2.1. Data entry

This program's users can type both magnetite and ilmenite analyses by clicking the New File from the pull-down menu of File option or pressing the Ctrl+N keys. The standard 17 variables are defined by WinMIgob for calculation of magnetite–ilmenite pairs in the following order:

Sample No[M], SiO$_2$[M], TiO$_2$[M], Al$_2$O$_3$[M], V$_2$O$_3$[M], Cr$_2$O$_3$[M], Nb$_2$O$_5$[M], Fe$_3$O$_4$[M], FeO[M], MnO[M], NiO[M], ZnO[M], MgO[M], CaO[M], Na$_2$O[M], K$_2$O[M], BaO[M] and

Sample No[I], SiO$_2$I, TiO$_2$I, Al$_2$O$_3$I, V$_2$O$_3$I, Cr$_2$O$_3$I, Nb$_2$O$_5$I, Fe$_3$O$_4$I, FeO[I], MnO[I], NiO[I], ZnO[I], MgO[I], CaO[I], Na$_2$O[I], K$_2$O[I], BaO[I], where M and I show the abbreviations of magnetite and ilmenite, respectively. In the data entry section, WinMIgob thus permits the user to enter a total of 34 variables. Magnetite and ilmenite compositions typed in Excel files with the extension of “.xls” and “.xlsx” in the above order can be loaded into the program’s data entry section (i.e., Data Entry Screen) by clicking the Open Excel File option from the pull-down menu of File. However, using the copy–paste options, these data in the above order from a Microsoft® Excel spreadsheet can be included in the data entry section of WinMIgob more quickly. By selecting the Edit Excel File option from the pull-down menu of File, magnetite and ilmenite compositions can be typed in a blank Excel file (i.e., MyMI) in the (C:\Program Files\WinMIgob) folder, stored in a different file name with the extension of “.xls” or “.xlsx”, and then loaded into the WinMIgob’s data entry section by clicking the Open Excel File option from the pull-down menu of File for further data evaluations. Once the analyses in an Excel file are displayed on the screen by using the Open Excel File option, they can be stored with the extension of “.mi” by clicking the Save As 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 program’s help file on the screen. For example, selecting the File menu section from the index of WinMIgob.chm file, it displays the necessary information concerning the magnetite–ilmenite file operations on the screen.

2.2. Normalization, ferric iron estimation, geothermometer, oxygen barometer and Bacon–Hirschmann equilibrium test

Once the program is executed, WinMIgob calculates magnetite analyses to four oxygens and three total cations and ilmenite to three oxygens and two total cations. Magnetite–ilmenite analyses with measured FeO$_3$ (wt. %) and FeO (wt. %) contents (e.g., wet-chemical) are calculated by program as Fe$^{3+}$ (\textit{apfu}) and Fe$^{2+}$ (\textit{apfu}) separately. However, if these analyses are given as FeO$_3$ (wt. %) = 0 and FeO (wt. %) > 0, then the program considers FeO (wt. %) content as FeO$_{tot}$ (wt. %) and estimates the ferric and ferrous iron contents stoichiometrically based on the procedure proposed by Stormer (1983) (Fig. 1a). The ferric iron estimation (Fe$^{3+}$, \textit{apfu}) from a total iron content (FeO$_{tot}$, wt. %) of electron-microprobe magnetite–ilmenite analysis is also carried out using two other different empirical equations (e.g., Carmichael 1967; Droop 1987) by selecting one of these from the pull-down menu of Ferric iron estimation option in the Data Entry Screen of WinMIgob.

In the estimation of log \textit{f}$_{O_2}$, the program assumes input pressure as 2000 bars. However, WinMIgob provides the user to select 1, 1000, 3000 and 5000 bars options from the pull-down menu of Buffer in the Data Entry Screen (Fig. 1b). The program displays \textit{T} (°C)–log \textit{f}$_{O_2}$ graph based on the Andersen and Lindley (1985) calibration using the calculation model by Stormer (1983) as default (Fig. 1c). By selecting other calibrations (e.g., Powell and Powell 1977; Spencer and Lindsley 1981) using different calculation methods (e.g., Carmichael 1967; Anderson 1968; Lindsley and Spencer 1982) from the pull-down menu of Method, WinMIgob displays the corresponding graph on screen with the help of Golden Software’s Grapher program. The program provides various geothermometers based on different calibrations (e.g., Powell and Powell 1977; Spencer and Lindsley 1981; Andersen and Lindsley 1985; Sauerzapf et al. 2008). On the other hand, by selecting the second option from the pull-down menu of Geothermometer (see Fig. 1d) in the Data Entry Screen window, WinMIgob also presents the user to estimate Ghiorso and Evans (2008) geothermometer with a high correlation coefficient ($r = 0.98$) based on the linear regression equation [$T_{\text{GE08}}$ (°C) = 1.53448 × $T_{\text{ABS}}$ − 458.13356] using the model by
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WinMIgob calculates the ΔNNO values with a high correlation ($r = 0.95$) through a linear regression equation $[\Delta NNO_{GE08} = 0.99157 \times \Delta NNO_{AL85} - 0.04250]$ using the Andersen and Lindsley’s (1985) and Ghiorso and Evans’s (2008) calibrations.

Andersen and Lindsley (1985) for 450 magnetite–ilmenite pairs from the literature following the Bacon and Hirschmann’s (1988) Mg/Mn exchange test. Similarly, by selecting the second option from the pull-down menu of Oxygen barometer in the Start-up Screen window (Fig. 1e), WinMIgob calculates the ΔNNO values with a high correlation ($r = 0.95$) through a linear regression equation $[\Delta NNO_{GE08} = 0.99157 \times \Delta NNO_{AL85} - 0.04250]$ using the Andersen and Lindsley’s (1985) and Ghiorso and Evans’s (2008) calibrations.

Fig. 1 Screenshots showing the WinMIgob’s pull-down menu options for magnetite–ilmenite geothermometer and oxygen barometer estimations. a – Selecting stoichiometric ferric and ferrous iron calculation procedure. b – Selecting input pressure (bars) value for relative oxygen fugacity (the nickel–nickel oxide buffer, ΔNNO) estimation. c – Selecting calibration model to display $T(°C)$–log $fO_2$ graph.
WinMIgob allows the user to test the coexistence of analyzed magnetite–ilmenite pairs by clicking the *Use Bacon and Hirschmann (1988) test for geothermometer and oxygen barometer* option from the pull-down menu.
of Test in the Data Entry Screen window (Fig. 1f). If coexisting oxides successfully pass the test, the program warns the user in column number 133 of the Calculation Screen window with “Passed”, otherwise “Failed” statements. If the Bacon–Hirschmann test option is clicked (see Fig. 1f), but “Failed” statement is encountered for any sample, then WinMigob does not list the calculated Fe–Ti oxide geothermometers and oxygen barometers in the Calculation Screen. Bacon and Hirschmann (1988) proposed that partitioning of Mg and Mn between titanomagnetite and ferrian ilmenite of volcanic rocks can be used as a test for equilibrium between coexisting phases. According to Bacon and Hirschmann (1988), the Mg/Mn magnetite–ilmenite partitioning test appears to be valid for fresh volcanic rocks but inapplicable to pairs in metamorphic, plutonic, and altered volcanic rocks due to these minerals typically have oxidized or exsolved at subsolidus temperatures. The logic of test, in a plot of ilmenite log (Mg/Mn) versus magnetite log (Mg/Mn) plot (Fig. 2), is based on to define the quality of analytical data and whether Fe–Ti oxide pairs have had their compositions altered by post-eruptive processes. Departures from the Bacon–Hirschmann line \[ \log (\text{Mg/Mn})_{\text{mag}} = 0.9317 \times \log (\text{Mg/Mn})_{\text{ilm}} - 0.0909 \] within two standard deviations of the equilibrium line (± 2σ) provide an empirical evaluation of the extent to which Fe–Ti oxide pairs are out of Mg/Mn exchange equilibrium. Thus, we can assume that if the Fe–Ti oxides are in Mg/Mn exchange equilibrium, then it is more likely that their bulk compositions reflect equilibration under the pre-eruptive temperature and oxygen fugacity conditions (Ghiorso and Evans 2008).

### 3. Worked examples

Using the selected dataset from literature (see Electronic Supplementary Material, ESM 1), the following examples show how WinMigob can be used for magnetite and ilmenite calculations, molecular ulvöspinel–magnetite and ilmenite–hematite amounts by different approaches, magnetite–ilmenite geothermometers, log oxygen fugacity, as well as in estimation of ΔNNO (Carmichael 1967; Anderson 1968; Powell and Powell 1977; Spencer and Lindsley 1981; Lindsley and Spencer 1982; Stormer 1983; Andersen and Lindsley 1985; Sauerzapf et al. 2008). Once the typed or loaded magnetite–ilmenite pairs are processed by clicking the Calculate icon (i.e., Σ) in the Data Entry Section window of program, all output parameters are displayed in columns 1–133 (see Tab. 1 of the Calculation Screen and in an output Excel file. 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 “.mi”. Representative Fe–Ti oxides with their stoichiometric Fe$_2$O$_3$ and FeO contents (wt. %), structural formulae (apfu), the sum of atomic molecular proportions, as well as molecular ulvöspinel, magnetite, ilmenite and hematite amounts by WinMigob program are given in Tab. 2 (see Fig. 3). By clicking the Send results to Excel file icon in the Calculation Screen, all outputs can be stored in an Excel file (Output.xlsx) and then displayed by clicking the Open and edit Excel file option. Fig. 2 An application of Mg/Mn exchange test (Bacon and Hirschmann 1988) for magnetite–ilmenite pairs selected from the literature (Ghiorso 2008; Blundy et al. 2008; Jolles and Lange 2019). Only 450 magnetite–ilmenite compositions that passed the test are displayed. Heavy (middle) and other two lines represent the mean linear regression and error envelope (± 2σ), respectively.
Tab. 2a Selected magnetite analyses (wt. %) with their stoichiometric FeO\_calculated and FeO contents (wt. %), structural formulae (apfu), sum of atomic molecular proportions and molecular ulvöspinel and magnetite amounts by WinMIgob program

| Row | Magnetite | Mt1 | Mt2 | Mt3 | Mt4 | Mt5 | Mt6 | Mt7 | Mt8 | Mt9 | Mt10 |
|-----|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 1   | SiO\_2    | 0.10| 0.02| 0.30| 0.00| 0.06| 0.07| 0.14| 0.18| 0.12| 0.09 |
| 2   | TiO\_2    | 12.80| 9.09| 12.44| 8.80| 11.38| 5.62| 6.32| 11.89| 8.76| 8.61 |
| 3   | Al\_2O\_3 | 0.92| 0.85| 0.59| 3.48| 1.83| 2.23| 2.69| 1.23| 1.17| 1.28 |
| 4   | V\_2O\_5  | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.56| 0.17| 0.13| 0.23 |
| 5   | Cr\_2O\_3 | 0.00| 0.01| 0.00| 0.00| 0.00| 0.00| 0.03| 0.04| 0.02| 0.02 |
| 6   | FeO\_2    | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 50.53| 50.66 |
| 7   | FeO\_calculated | 80.80| 82.60| 77.68| 79.60| 78.67| 85.27| 82.94| 78.24| 37.97| 37.68 |
| 8   | MnO       | 0.85| 0.90| 2.77| 0.40| 0.98| 0.43| 0.25| 0.41| 0.57| 0.48 |
| 9   | NiO       | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.02| 0.00| 0.00 |
| 10  | ZnO       | 0.18| 0.20| 0.00| 0.07| 0.00| 0.00| 0.15| 0.50| 0.00| 0.00 |
| 11  | MgO       | 0.16| 0.25| 1.77| 2.97| 0.68| 1.13| 0.92| 1.23| 0.59| 0.71 |
| 12  | CaO       | 0.01| 0.00| 0.00| 0.00| 0.00| 0.00| 0.21| 0.02| 0.01| 0.02 |
| 13  | Na\_2O    | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.03| 0.04| 0.00| 0.00 |
| 14  | K\_2O     | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.03| 0.00| 0.00 |
| 15  | Σ (wt. %) | 95.82| 93.92| 95.55| 95.32| 93.60| 94.75| 94.24| 94.00| 99.87| 99.78 |
| 16  | Fe\_2O\_3(calculated) | 43.120| 49.733| 44.545| 49.695| 43.687| 56.210| 52.926| 43.502| 0.000| 0.000 |
| 17  | FeO(calculated) | 41.999| 37.848| 37.596| 34.882| 39.358| 34.690| 35.315| 39.095| 0.000| 0.000 |

| Row | Usp\_apfu | 3.00| 3.00| 3.00| 3.00| 3.00| 3.00| 3.00| 3.00| 3.00|
|-----|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 33  | Usp (mol. %) | 36.72| 26.30| 36.08| 24.19| 32.98| 16.06| 18.39| 34.73| 25.37| 24.81 |
| 34  | Mag (mol. %) | 63.28| 73.70| 63.92| 75.81| 67.02| 83.94| 81.61| 65.27| 74.63| 75.19 |
| 35  | X\_Usp | 0.37| 0.27| 0.36| 0.26| 0.34| 0.17| 0.19| 0.35| 0.26| 0.25 |
| 36  | X\_Mag | 0.63| 0.73| 0.64| 0.74| 0.66| 0.83| 0.81| 0.65| 0.74| 0.75 |

Magnetic analyses (wt. %) with their stoichiometric FeO\_calculated and FeO contents (wt. %), structural formulae (apfu), sum of atomic molecular proportions and molecular ulvöspinel and magnetite amounts by WinMIgob program.

Only 450 of the total 689 magnetite and ilmenite compositions passed the Bacon and Hirschmann (1988) equilibrium test (Fig. 2).

3.1. Magnetite–ilmenite geothermometer calibrations and oxygen barometers

Buddington and Lindsay (1964) presented a graphical solution for the Fe–Ti oxide geothermometer and oxygen barometer using the earlier experimental studies carried out on cubic and rhombohedral Fe–Ti oxides. The technique takes into account the compositions of coexisting mag-
The geothermometer and oxygen barometer within the concept of a graphical solution later have been re-formulated on a thermodynamic basis using the earlier experimental data of Buddington and Lindsley (1964). For example, Powell and Powell (1977) used equilibrium thermodynamic methods to develop an independent Fe–Ti oxide geothermometer and oxygen barometer (Fig. 4), differently, based on the experimental data of Buddington and Lindsley (1964). They presented Fe–Ti geothermometer and oxygen barometer both as graphically and with defined equations for coexisting magnetite and ilmenite solid solutions in FeO–Fe₂O₃–TiO₂ system.

Tab. 2b Selected ilmenite analyses (wt. %) with their stoichiometric Fe₂O₃ and FeO contents (wt. %), structural formulae (apfu), sum of atomic molecular proportions and molecular ilmenite and hematite amounts by WinMIgob program

| Ilmenite | I1  | I11 | I12 | I13 | I14 | I15 | I16 | I17 | I18 | I19 | I20 |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| SiO₂     | 0.02| 0.03| 0.31| 0.00| 0.00| 0.04| 0.01| 0.03| 0.05| 0.03| 0.04|
| TiO₂     | 48.30| 49.34| 47.22| 38.50| 48.49| 41.35| 46.40| 43.12| 45.84| 45.27|
| Al₂O₃    | 0.04| 0.06| 0.00| 0.50| 0.11| 0.24| 0.24| 0.15| 0.08| 0.12|
| V₂O₅     | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.37| 0.08| 0.12| 0.28|
| Cr₂O₃    | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.02| 0.01| 0.01| 0.01|
| Fe₂O₃    | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 13.77| 15.20|
| MnO      | 1.50| 1.84| 3.81| 0.37| 1.59| 0.60| 0.39| 0.54| 1.10| 0.86|
| NiO      | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00|
| ZnO      | 0.00| 0.10| 0.00| 0.00| 0.00| 0.00| 0.07| 0.40| 0.00| 0.00|
| MgO      | 0.40| 0.63| 3.02| 3.61| 1.31| 1.86| 1.76| 2.21| 1.31| 1.51|
| CaO      | 0.02| 0.01| 0.00| 0.00| 0.00| 0.00| 0.04| 0.03| 0.07| 0.02|
| Na₂O     | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.02| 0.00| 0.00|
| K₂O      | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.01| 0.03| 0.00| 0.00|

Σ (wt. %) 99.46 100.44 99.05 96.58 98.63 97.86 96.77 96.76 99.34 99.16

53 Fe₂O₃ (calculated) 8.853 7.887 12.318 28.645 8.188 22.798 10.363 18.049 0.000 0.000
54 FeO (calculated) 41.134 41.333 33.606 27.823 39.722 33.286 38.115 33.879 0.000 0.000
55 Si      0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
56 Ti      0.915 0.924 0.878 0.723 0.920 0.781 0.892 0.824 0.873 0.863
57 V       0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.034
58 Cr      0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
59 As      0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
60 FeTi+   0.168 0.148 0.229 0.538 0.155 0.431 0.199 0.345 0.262 0.290
61 FeTi+   0.866 0.861 0.694 0.581 0.838 0.699 0.815 0.719 0.784 0.760
62 Mn      0.034 0.039 0.080 0.008 0.034 0.131 0.034 0.012 0.024 0.018
63 Ni      0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
64 Zn      0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
65 Mg      0.015 0.023 0.111 0.134 0.049 0.070 0.067 0.084 0.049 0.057
66 Ca      0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
67 Na      0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
68 K       0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
69 Σ (apfu) 2.000 2.000 2.000 2.000 2.000 2.000 2.000 2.000 2.000 2.000

Mt1–I11 to Mt6–I16 pairs from Ghiroso (2008); Mt7–I17 and Mt8–I18 from Blundy et al. (2008); Mt9–I19 and Mt10–I110 from Jolles and Lange (2019); Usp – ulvöspinel, Mag – magnetite, Ilm – ilmenite, Hem – hematite (molecular ulvöspinel, magnetite, ilmenite and hematite amounts by the method of Carmichael 1967); SAMP – sum of atomic molecular proportion (from Lepage 2003); X‘+ mol fraction amount of i (formulation from Sauerzapf et al. 2008)

Nettite–ulvöspinel (spinell phase) and ilmenite–hematite solid solution (rhombohedral phase) phases, defined as a mole fraction of ulvöspinel and a mole fraction of hematite, respectively. The magnetite–ilmenite geothermometer is based on the temperature-dependent exchange of Fe²⁺+Ti⁴⁺ for 2Fe³⁺ between magnetite–ulvöspinel and ilmenite–hematite endmembers, whereas the oxygen barometer considers an iron redox equilibrium, which may be formulated by the magnetite–hematite oxygen buffer equilibrium or by an equilibrium involving the Ti-rich endmembers of the two Fe–Ti oxide series (Sauerzapf et al. 2008).
Although their model may fit for the NNO and the fayalite–magnetite–quartz (FMQ) buffer assemblages, it does not predict the results of experiments reflecting the more reducing buffer conditions such as the cobalt–co-

Fig. 3 Screenshots of an output Excel file (Output.xlsx) created by WinMigob program showing all input and output parameters of magnetite–ilmenite compositions. a – Magnetite analyses with stoichiometric estimation of Fe$_2$O$_3$ and FeO (wt. %) contents. b – Recalculated cations of magnetite mineral analyses (apfu). c – Ilmenite analyses with stoichiometric estimation of Fe$_2$O$_3$ and FeO (wt. %) contents. d – Recalculated cations of ilmenite mineral analyses (apfu). e and f – Molecular ulvöspinel, magnetite, ilmenite and hematite amounts calculated by different methods (Carmichael 1967; Anderson 1968; Lindsley and Spencer 1982; Stormer 1983).
balt oxide (Co–CoO) and the wustite–magnetite (WM) at low temperatures (~600–800 °C) due to the increasing non-ideality of the solutions. Hence, Powell and Powell’s (1977) calibration is only valid for a limited range of temperature and oxygen fugacity conditions (Spencer and Lindsley 1981). Powell and Powell (1977) also pointed out that significant departures in composition from the system FeO–Fe₂O₃–TiO₂ may show large uncertainties in the calculated temperature and activity of oxygen.

Spencer and Lindsley (1981) developed a solution model for coexisting magnetite–ulvöspinel and ilmenite–hematite solid solutions based on a least-squares fit of thermodynamic parameters to experimental data obtained at temperatures from 550 to 1200 °C. They applied their solution approach to Buddington and Lindsley’s (1964) geothermometer and oxygen barometer model for coexisting magnetite–ilmenite pairs in a temperature–oxygen fugacity (T–fO₂) grid (Fig. 4). According to Spencer and Lindsley (1981), uncertainties in their model are approximately 40–80  °C and 0.5–1.0 log units fO₂ in ulvöspinel and ilmenite compositions. Taking into account the most analyses of natural Fe–Ti oxides that include small but significant amounts of minor components, Stormer (1983) proposed a new recalculation scheme, apart from the Carmichael’s (1967) and Anderson’s (1968) approach, based on the models of ionic substitution which is consistent with a thermodynamic model for the pure Fe–Ti system recommended by Spencer and Lindsley (1981). However, the Stormer’s (1983) scheme is more consistent with the model used by Spencer and Lindsley (1981) for fitting the experimental data and gives temperature and oxygen fugacity values falling in the middle of the range of variation with respect to the Carmichael’s (1967) and Anderson’s (1968) models.

Considering the inconsistent results, in addition to the compositional departures from the system Fe–Ti–O, Andersen and Lindsley (1988) presented new experimental data on the compositions of coexisting magnetite–ilmenite pairs to revise the solution model for magnetite and ilmenite solid solutions by including the effects of Mg and Mn, as well as examining the effects of order-disorder on the solution properties of spinels. An internally consistent solution model by Andersen and Lindsley (1988) applies the linear programming based on a multicomponent Margules-type solution for ilmenite and an assumed Akimoto-type and available cation-distribution for magnetite solid solutions. They reported that in terms of the system Fe–Ti–O, T (°C) between 600 and 1200 °C and fO₂ between the NNO and WM buffers, there is little difference between these two models in calculated temperature and oxygen fugacity values.

Ghiorso and Sack (1991) developed a new thermodynamic formulation for the Fe–Ti oxides which is calibrated models for spinel solid–solutions in the quinary system (Fe²⁺, Mg)(Al, Fe³⁺, Cr)₂O₄–(Fe²⁺, Mg)₂TiO₄ and rhombohedral oxides in the quaternary system (Fe²⁺,
Mg, Mn)TiO$_3$–Fe$_2$O$_3$ that can be applied to the estimation of temperature and oxygen fugacity values for intermediate to silicic volcanic rocks to investigate the systematic of T–log fO$_2$ trends for various magmatic ferromagnesian–silicate assemblages. However, application of both the Andersen and Lindsley (1988) and Ghiorso and Sack (1991) formulations to Fe–Ti oxides in more oxidized magmas, such as in magmatic arcs, may give too high estimates of oxygen fugacity and temperatures, both too high and too low values depending on the range of log fO$_2$ (Evans and Scaillet 1997; Evans et al. 2006).

For example, Lindsley and Frost (1992) noticed the users for Andersen and Lindsley’s (1988) formulation at oxygen fugacities higher than two log bar units above those of the FMQ (i.e., at ΔFMQ>2 or ΔNNO>1.3). Lattard et al. (2005) synthesized assemblages of titanomagnetite–ilmenite, ilmenite–pseudobrookite and single-phase samples under a wide range of fO$_2$ (in the range ΔNNO= -5 to +5) in sub–solids conditions, at 1 bar and at temperatures between 1000 and 1300°C, in the Fe–Ti–O system.

Considering unsatisfactory results of previous calibrations, especially at high temperature and low to moderate oxygen fugacity conditions that point out the crystallization of basic and intermediate rocks, Sauerzapf et al. (2008) presented a new version of magnetite–ilmenite geothermometer and oxygen barometer (Fig. 4) based on the numerical fits of a large experimental dataset, nearly 200, in the Fe–Ti–Al–Mg–O system and those of literature studies. Sauerzapf et al. (2008) recognized that their subsolidus experimental results at temperatures in the range 1100–1300°C and under low to moderate fO$_2$, (i.e., -4 < ΔNNO < 2) conditions with the addition of Mg and/or Al in the concentration ranges can be accommodated by simple projections. Thus, by applying numerical fits to those cited projections, they generated empirical formulations to retrieve temperature values from X$_{usp}$ and X$_{ilm}$ (i.e., projected mole fractions) of titanomagnetite–ilmenite solid solution pairs and oxygen fugacity values from X$_{usp}$ and T (°C) relationship. According to Sauerzapf et al. (2008), tests carried on the independent experimental results indicate that their model reproduces the experimental temperatures generally within ±70°C, and in most cases within ±50°C, as well as the oxygen fugacity values usually within ±0.4 log units. When compared to the Andersen and Lindsley (1988) and Ghiorso and Sack (1991) models, their formulations yield substantial temperature underestimates for assemblages equilibrated at temperatures > 950°C under moderate to low fO$_2$ values (i.e., ΔNNO ≤0). Thus, the Sauerzapf et al. (2008) formulations may give reliable results in estimating the magmatic temperature and oxygen fugacity conditions for rapidly cooled intermediate to basic igneous systems.

WinMIgob calculates the temperatures of Sauerzapf et al. (2008) model ($X_{ilm} = f(X_{usp}, T)$) through least–squares method using a series of third–order polynomial functions (Fig. 5a). Formulations used in the program’s structure indicate that the calculated temperature values, in the range 700–1300°C, by WinMIgob reproduce the Sauerzapf et al. (2008) model within ±19°C for 450 magnetite–ilmenite pairs reported in the literature from volcanic rocks that are primarily dacitic and rhyolitic composition. Consequently, WinMIgob calculates the Fe–Ti oxide geothermometer of Sauerzapf et al. (2008) model with a high correlation ($r = 0.99$) coefficient (Fig. 5b). On the other hand, the estimates of oxygen fugacity relative to the NNO (ΔNNO) by program are mostly within ±0.06 units (Fig. 5c), and there also exists a high correlation coefficient ($r = 0.99$) between the Sauerzapf et al. (2008) calibration and WinMIgob outputs (Fig. 5d).

Because of the magnetite–ilmenite geothermobarometer of Ghiorso and Sack (1991) has been found to overestimate the temperature and oxygen fugacity in most moderate– to highly–oxidized calc–alkaline magma series (e.g., Mt. Pinatubo dacitic magma), as well as collected high–quality cation–ordering data for hematite–ilmenite solid solutions along the Fe–O–FeTiO$_3$ join since then, a new thermodynamic model for rhombohedral oxide solid solutions in the system Fe$_2$O$_3$–FeTiO$_3$–MgTiO$_3$–MnTiO$_3$ containing minor amounts of Al$_2$O$_3$ was developed by Ghiorso and Evans (2008) to revise and correct the earlier Fe–Ti oxides geothermometer and oxygen barometer calibration. The model was applied by Ghiorso and Evans (2008) to a newly compiled dataset of natural Fe–Ti oxide pairs from silicic volcanic rocks, and results were compared to previous formulations. The general conclusion is that their current model gives a better estimate of the oxidation state for magmas that equilibrated under conditions more oxidizing than the NNO buffer. On the other hand, temperatures obtained from the Ghiorso and Evans (2008) model are also found to be consistent with experimental phase relations for the stability of cummingtonite in silicic volcanic rocks. According to Ghiorso and Evans (2008), the results of their geothermometer and oxygen barometer differ from previously calibrated Fe–Ti oxide pairs formulations (e.g., Andersen and Lindsley 1988; Ghiorso and Sack 1991), most notably in the estimation of oxidation state under relatively oxidized conditions (> NNO + 1).

WinMIgob provides the users to estimate Ghiorso and Evans (2008) Fe–Ti oxides geothermometer by using a linear regression equation $[T_{geob}$(°C) = 1.098258692 × $T_{seis}$ - 67.18937519] correlating the Sauerzapf et al. (2008) and Ghiorso and Evans (2008) calibrations (Fig. 6a). Although a high correlation ($r = 0.99$) exists between these two calibrations, the users should be careful when using
WinMIgob’s output for the Ghiorso and Evans (2008) geothermometer in their own studies especially for temperatures <700 °C and >950 °C. When compared to the magnetite–ilmenite geothermometer, the ΔNNO values in these two calibrations show much more variations, with a lower correlation ($r = 0.83$) coefficient (Fig. 6b) and should also be used with caution by the WinMIgob’s users. In terms of the ΔNNO values, there is a high correlation coefficient ($r = 0.95$) between the Andersen and Lindsley (1985) and Ghiorso and Evans (2008) calibrations (Fig. 6c). Thus, by selecting the second option from the pull-down menu of Oxygen barometer (see Fig. 1e) this relationship may be used by the program’s users in the estimation of the ΔNNO values by Ghiorso and Evans (2008). The current version of WinMIgop provides the users to display ten diagrams by using the Grapher program for coexisting magnetite–ilmenite compositions. Some of selected diagram types from the pull-down menu of Graph in the Calculation Screen are given in Fig. 7.

In this study, magnetite–ilmenite analyses that present both Fe$_2$O$_3$ and FeO (wt. %) were tested with FeO$_{tot}$ (wt. %) contents, estimated from FeO + 0.8998Fe$_2$O$_3$, to obtain $T$ (°C) and $f$O$_2$ values using different calibrations. Magnetite–ilmenite analyses with Fe$_2$O$_3$ and FeO (wt. %)

![Image](image-url)
compositions from the literature (Himmelberg and Ford 1977; Stormer (1983); Honjo et al. 1992; Venezky and Rutherford 1999; Mullen and McCallum 2013; Ondrejka et al. 2015) were first checked for the Bacon–Hirschmann equilibrium test by WinMIgop program. Then magnetite–ilmenite pairs that passed the test were subjected to both ferric and ferrous and total iron calculations to estimate $T$ (°C) and $fO_2$ values for different calibration methods (e.g., Anderson and Lindsley (1985); Sauerzapf et al. 2008). Finally, a comparison indicates that the resultant values of $T$ (°C) and $fO_2$ show no important variations, at least selected for magnetite–ilmenite analyses from the literature, in terms of allocation of ferric and ferrous electron-probe data in which total iron content is available (ESM 2).

4. Summary and availability of the program

WinMIgob is a user-friendly package for compositions of magnetite–ilmenite pairs, which is developed for personal computers running in the Windows operating system. The program calculates structural formulae of multiple magnetite and ilmenite analyses, obtained both from wet-chemical and electron-microprobe techniques, based on different ferric iron estimation methods. WinMIgob generates two main windows. The first window (i.e., Data Entry Screen) appears on the screen with several pull-down menus and equivalent shortcuts. By selecting options or clicking buttons on the start-up screen, the user can enter or load magnetite and ilmenite analyses into the data entry section and make necessary arrangements for a
desired calculation scheme on the toolbar. By clicking the Calculate icon (i.e., Σ) on the toolbar in the Data Entry Screen window, all calculated parameters are displayed in the second window. The second window (i.e., Calculation Screen) allows the user to display all the input and results of cations (apfu) with stoichiometric ferric and ferrous iron contents, molecular magnetite–ulvöspinel and ilmenite–hematite amounts, magnetite–ilmenite geothermometers, oxygen barometers, oxygen fugacities relative to the NNO buffer and Bacon–Hirschmann equilibrium test. WinMIgob reports the output in a tabulated form with columns numbered from 1 to 133 in the Calculation Screen window, as well as in an Excel file. All the estimated magnetite and ilmenite data in the Calculation Screen can be sent to a Microsoft Excel file (i.e., Output.xlsx) and then this file can be used for further data manipulation, graphing and preparing a quick table for publication and presentation purposes. WinMIgob displays calculated magnetite and ilmenite compositions in binary and ternary diagrams, which can be viewed.
and printed by the Grapher, available from the Golden software. These plots appear on the screen by selecting desired diagram type from the pull-down menu of Graph in the Calculation Screen window.

WinMigob is a compiled program that consists of a self-extracting setup file including all the necessary support files (i.e., with the extension of “.dll” and “.ocx” files) for the 32-bit system. If the Microsoft® Visual Studio package is not installed on the computer, all these support files are used by the program for proper execution. During the setup procedure, the program and its associated files (i.e., support files, help file, data files with the extensions of “.mil”, “.xls”, “.x1sx” and plot files with the extension of “.grf”) are installed into the personal computer’s “C:\ Program Files\WinMigob” folder with the Windows XP or later operating system.
WinMigob: A Windows program for magnetite–ilmenite geothermometer and oxygen barometer

Tab. 3 Notes:

M1–H1 to M6–I6 pairs from Ghiorso (2008); M7–I7 and M8–I8 from Blundy et al. (2008); M9–I9 and M10–I10 from Jolles and Lange (2019); Magnetite-ilmenite geothermometers of $T_{\text{PTOT}}$, (row 1) from Powell and Powell (1977) using the Carmichael (1967) method, $T_{\text{PTOT}}$, (row 2) from Powell and Powell (1977) using the Anderson (1968) method, $T_{\text{PTOT}}$, (row 3) from Powell and Powell (1977) using the Lindsley and Spencer (1982) method, $T_{\text{PTOT}}$, (row 4) from Powell and Powell (1977) using the Stormer (1983) method, $T_{\text{PTOT}}$, (row 5) from Spencer and Lindsley (1981) using the Carmichael (1967) method, $T_{\text{PTOT}}$, (row 6) from Spencer and Lindsley (1981) using the Anderson (1968) method, $T_{\text{PTOT}}$, (row 7) from Spencer and Lindsley (1981) using the Lindsley and Spencer (1982) method, $T_{\text{PTOT}}$, (row 8) from Spencer and Lindsley (1981) using the Stormer (1983) method, $T_{\text{PTOT}}$, (row 9) from Andersen and Lindsley (1985) using the Carmichael (1967) method, $T_{\text{PTOT}}$, (row 10) from Andersen and Lindsley (1985) using the Anderson (1968) method, $T_{\text{PTOT}}$, (row 11) from Andersen and Lindsley (1985) using the Lindsley and Spencer (1982) method, $T_{\text{PTOT}}$, (row 12) from Andersen and Lindsley (1985) using the Stormer (1983) method, $T_{\text{PTOT}}$, (row 13) from Sauerzapf et al. (2008) calculated by WinMigop, $T_{\text{DeltaNNO}}$, (row 14) from Ghiorso and Evans (2008) based on the linear regression equation $T_{\text{DeltaNNO}} = 1.098258692 - 67.18937519$ between Sauerzapf et al. (2008) and Ghiorso and Evans (2008) calibrations calculated by WinMigop, $T_{\text{DeltaNNO}}$, (row 15) from Sauerzapf et al. (2008) by selecting Sauerzapf et al. (2008) thermometer through least-squares using model by Andersen and Lindsley (1985) option from the pull-down-menu of Geothermometer. Option to select models for Fe–Mg–Mn–Ti oxides. Fe–Ti oxides.

DeltaNNO (Ghioro and Evans, 2008) through least-squares using model by Andersen and Lindsley (1985) option from the pull-down-menu of Oxygen barometer in the Start-up Screen window of program, $T_{\text{ΔNNO}}$, (row 16) from Ghiorso and Evans (2008) by selecting Ghiorso and Evans (2008) thermobarometer through least-squares using model by Andersen and Lindsley (1985) option from the pull-down-menu of Oxygen barometer in the Start-up Screen window of program, $T_{\text{ΔNNO}}$, (row 17) from Excel spreadsheet estimation developed by Sauerzapf et al. (2008), $T_{\text{ΔNNO}}$, (row 18) from Ghiorso and Evans (2008) calculated by online link [http://melts.ofm-research.org/CORBA_CTServer/OxideGeothrm/OxideGeothrm.php]; Magnetite-ilmenite oxygen barometers of $O_2$, (row 19) from Powell and Powell (1977) using the Carmichael (1967) method, $O_2$, (row 20) from Powell and Powell (1977) using the Anderson (1968) method, $O_2$, (row 21) from Powell and Powell (1977) using the Lindsley and Spencer (1982) method, $O_2$, (row 22) from Powell and Powell (1977) using the Stormer (1983) method, $O_2$, (row 23) from Spencer and Lindsley (1981) using the Carmichael (1967) method, $O_2$, (row 24) from Spencer and Lindsley (1981) using the Anderson (1968) method, $O_2$, (row 25) from Spencer and Lindsley (1981) using the Lindsley and Spencer (1982) method, $O_2$, (row 26) from Spencer and Lindsley (1981) using the Stormer (1983) method, $O_2$, (row 27) from Andersen and Lindsley (1985) using the Carmichael (1967) method, $O_2$, (row 28) from Andersen and Lindsley (1985) using the Anderson (1968) method, $O_2$, (row 29) from Andersen and Lindsley (1985) using the Lindsley and Spencer (1982) method, $O_2$, (row 30) from Andersen and Lindsley (1985) using the Stormer (1983) method, $O_2$, (row 31) from Sauerzapf et al. (2008) calculated by WinMigop, $O_2$, (row 32) from Sauerzapf et al. (2008) by selecting log $O_2$ (Sauerzapf et al., 2008) through least-squares using model by Andersen and Lindsley (1985) option from the pull-down-menu of Oxygen barometer in the Start-up Screen window of program, $O_2$, (row 33) from Excel spreadsheet estimation developed by Sauerzapf et al. (2008). Log oxygen fugacity values relative to nickel–nickel oxide buffer of $O_2$, (row 34) from Andersen and Lindsley (1985) using the Carmichael (1967) method, $O_2$, (row 35) from Andersen and Lindsley (1985) using the Anderson (1968) method, $O_2$, (row 36) from Andersen and Lindsley (1985) using the Stormer (1983) method, $O_2$, (row 37) from Andersen and Lindsley (1985) using the Anderson (1968) method, $O_2$, (row 38) from Sauerzapf et al. (2008) calculated by WinMigop, $O_2$, (row 39) from Ghiorso and Evans (2008) based on the polynomial equation $\Delta\text{NNO}_{\text{S08}} = -0.580629664 + 1.083216766 \times \Delta\text{NNO}_{\text{S08}} - 0.1011931202 \times \Delta\text{NNO}_{\text{G08}}^2$ between Sauerzapf et al. (2008) and Ghiorso and Evans (2008) calibrations calculated by WinMigop, $O_2$, (row 40) from Sauerzapf et al. (2008) by selecting $\Delta\text{NNO}$ (Sauerzapf et al., 2008) through least-squares using model by Andersen and Lindsley (1985) option from the pull-down-menu of Oxygen barometer in the Start-up Screen window of program, $O_2$, (row 41) from Ghiorso and Evans (2008) by selecting $\Delta\text{NNO}$ (Ghiorso and Evans, 2008) through least-squares using model by Andersen and Lindsley (1985) option from the pull-down-menu of Oxygen barometer in the Start-up Screen window of program, $O_2$, (row 42) from Excel spreadsheet estimation developed by Sauerzapf et al. (2008), $O_2$, (row 43) from Ghiorso and Evans (2008) calculated by online link [http://melts.ofm-research.org/CORBA_CTServer/OxideGeothrm/OxideGeothrm.php]

Systems. However, an installation of the program into a personal computer with the 64-bit operating system may require the mslexgrrd adjustment. This procedure is explained in detail in Electronic Supplementary Material (ESM 3) for the users. The self-extracting setup file is approximately 20 Mb and may be downloaded from the journal server.

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Electronic supplementary material. Examples of magnetite–ilmenite data recalculated and plotted by the WinMigop program (ESM 1), comparison of FeO, and FeO (wt. %) input (e.g., wet-chemical) with FeO (wt. %) contents (e.g., electron-microprobe) in the estimation of temperature (°C) and oxygen fugacity ($f(O_2)$) values (ESM 2), the steps for WinMigop program execution (ESM 3) and self-extracting WinMigop.exe setup file are available online at the Journal web site (http://dx.doi.org/10.3190/jgeosci.319).

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