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Primary melt inclusions in andalusite from anatectic graphitic metapelites: Implications for the position of the Al_2SiO_5 triple point

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ABSTRACT

Anatectic crustal xenoliths in the Miocene volcanic rocks of Mazarrón (southeast Spain) contain andalusite with melt inclusions, an unprecedented finding. Microstructures indicate that the melt inclusions were trapped during andalusite growth. The volatile content of the peraluminous inclusions is too low ($\text{Cl} < 0.4 \text{ wt\%}$, $\text{F} < 0.3 \text{ wt\%}$, $\text{P} \approx 1500 \text{ ppm}$, $\text{B} < 850 \text{ ppm}$) to have caused a significant reduction of the wet solidus temperature. Moreover, the presence of graphite, as observed, during partial melting is expected to have raised the temperature of the wet solidus. Melting temperatures for the inclusions—obtained from quartz-albite-orthoclase haplogranite system ($680\text{--}790^\circ\text{C}$), Zr ($620\text{--}705^\circ\text{C}$), and light rare earth element ($615\text{--}725^\circ\text{C}$) thermometry—indicate that the stability of andalusite + melt is incompatible with the position of the most commonly used andalusite = sillimanite equilibrium, and that the Al_2SiO_5 triple point must be placed at higher temperatures and pressures.

Keywords: andalusite, crustal melting, low-pressure metamorphism, melt inclusions, sillimanite, thermobarometry.

INTRODUCTION

The Al_2SiO_5 polymorphs constitute the backbone for the construction of phase relationships and thermobarometric methods in metapelitic rocks. Despite the general adoption of the triple point of Holdaway (1971), the pressure-temperature (P - T) location of the andalusite (And) = sillimanite (Sil) curve is still controversial, because it is extremely difficult to constrain experimentally. Triple points at higher P and T (e.g., Pattison, 1992) show better agreement with natural assemblages from low- P metapelites and are now increasingly used (Johnson et al., 2003, and references therein). In addition, a reaction of And = Sil at higher T would account for a stable P - T field for And + melt. The stability of And + melt does not by itself invalidate the Holdaway (1971) triple point. In fact, if andalusite stability is expanded by minor elements (e.g., Fe^{3+}) and/or if the haplogranite solidus is lowered by significant solution of Al_2O_3 and/or volatiles (e.g., B, F), a P - T field for And + melt can also be obtained with the And = Sil curve of Holdaway. Kerrick (1990) urged more attention to natural laboratories as the way to constrain the location of the And = Sil curve, but until now a definitive solution to this controversy has been hampered by the lack of precise data on the chemistry of And-bearing natural melts.

Here we characterize silicate melt inclusions in andalusite from crustal xenoliths in the Neogene volcanic province of southeast Spain. This is an exceptional finding, because melt inclusions in andalusite have never been reported until now. A detailed analysis of glass composition and volatile contents was used to evaluate the temperature of melt in the inclusions and to constrain the P - T locations of the And =

Sil curve and melt solidus. The results support a higher P - T triple point such as that of Pattison (1992) and highlight the role of graphite in low- P fluid-present melting.

GEOLOGIC SETTING AND PETROGRAPHY

The xenoliths in the Miocene high-K calc-alkaline volcanic rocks of the Neogene volcanic province (Fig. 1) represent restites after anatexis of crustal protoliths, which took place at 9.1 Ma in the context of lithospheric thinning that accompanied the opening of the Alborán Sea (Cesare and Gómez-Pugnaire, 2001).

Andalusite-bearing xenoliths occur in the Neogene volcanic province along a belt extending for $\sim 100 \text{ km}$ (Fig. 1) and are particularly abundant in the area of Mazarrón. Andalusite is observed in xenoliths that also contain sillimanite, hercynite ($X_{\text{Fe}} = 0.80$), cordierite ($X_{\text{Fe}} = 0.50\text{--}0.60$), biotite ($X_{\text{Fe}} = 0.70$, TiO_2 to 6.0 wt%), plagioclase ($\text{An}_{40\text{--}50}$), glass, and graphite. K-feldspar and quartz are present only as inclusions in other minerals. Glass occurs as interstitial films and as silicate melt inclusions in all minerals. Graphite is a ubiquitous phase of these xenoliths. Resorbed grain boundaries and variable replacement by sillimanite indicate that andalusite is a metastable relict and that the xenoliths finally equilibrated within the sillimanite stability field (Cesare et al., 2002). However, the initial stages of the partial melting history are preserved in andalusite, in the form of mineral, fluid, and melt inclusions.

Mineral inclusions in andalusite are quartz, plagioclase ($\text{An}_{20\text{--}40}$), K-feldspar, biotite, graphite, and hercynite. The increase of anorthite content from inclusions to matrix plagioclase is consistent with the progress of anatexis under increasing temperature. Fluid inclusions in

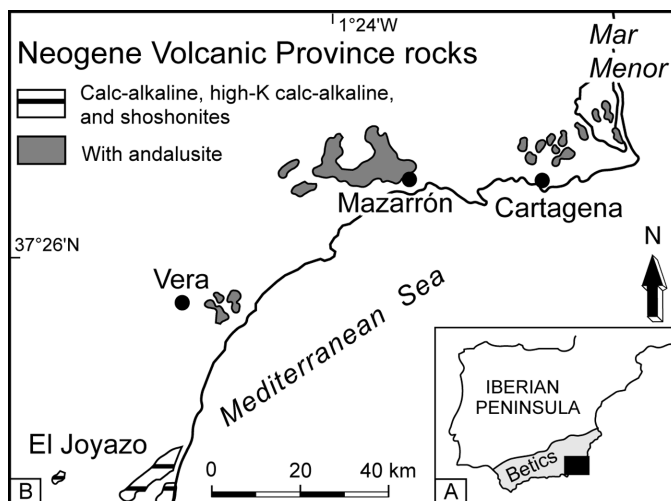


Figure 1. A: Geographic location of Neogene volcanic province of southeast Spain; black box indicates area enlarged in B. B: Main edifices of Miocene volcanic rocks.

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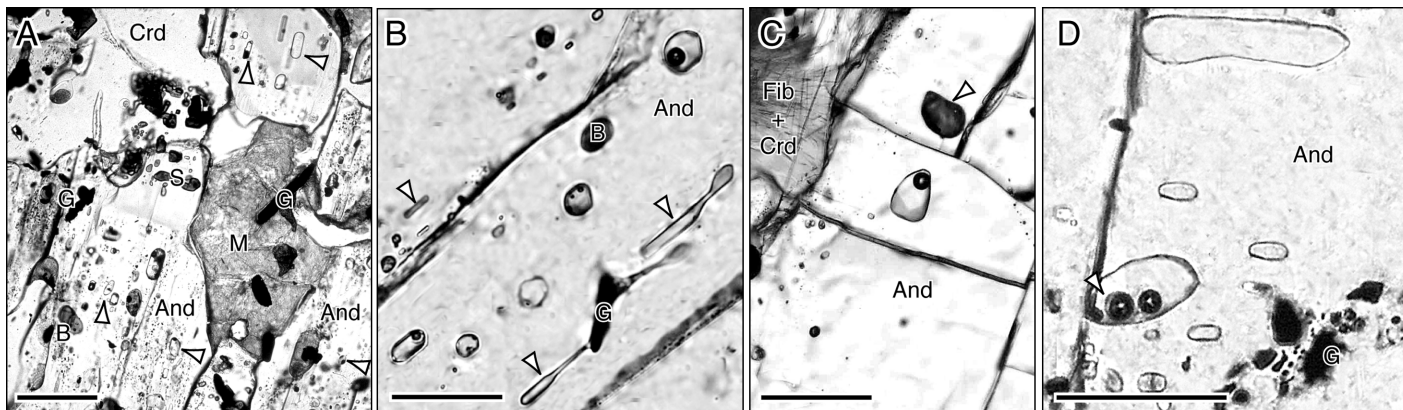


Figure 2. Main microstructural aspects of melt inclusions in andalusite from xenoliths of Mazarrón. **A:** General view of inclusion-rich andalusite (And) with resorbed grain boundaries, surrounded by cordierite (Crd) and interstitial devitrified glass (M). Inclusions consist of melt (arrows), biotite (B), hercynitic spinel (S), and graphite (G). **B:** Subspherical to tubular (arrows) melt inclusions. Walls of tubular inclusions are parallel to andalusite cleavage (top right to bottom left). **C:** Two adjacent melt inclusions; one is fresh, with clear glass and small shrinkage bubble, and other is devitrified (arrow). Fib is fibrolite. **D:** One melt inclusion with two shrinkage bubbles. Double meniscus in left-side bubble (arrow) attests to presence of fluid in it, determined as H₂O. Scale bars represent 100, 60, 150, and 50 μm , respectively.

andalusite consist of CO₂ + CH₄ mixtures rich in CO₂. Melt inclusions are common; they range from subspherical (approximate diameters < 40 μm) to irregular or tubular in shape (lengths to 150 μm). Subspherical inclusions are randomly distributed in the andalusite host and may form clusters associated with graphite, hercynite, or other solids (Fig. 2A). Tubular inclusions are often parallel to the crystallographic axes of andalusite (Fig. 2B). Microstructural evidence (further detailed in Fig. DR1¹) points to a primary trapping origin (i.e., during andalusite growth) for most melt inclusions.

The glass in the inclusions is in most cases clear and fresh (Fig.

¹GSA Data Repository item 2003082, Figure DR1, microstructural relationships between melt inclusions and host andalusite, and Appendix DR1, analytical methods, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

2C). Inclusions may contain a small shrinkage bubble. Some shrinkage bubbles display a double meniscus (Fig. 2D); in these bubbles, a low-density aqueous solution was detected.

ANDALUSITE AND MELT COMPOSITIONS

Table 1 reports representative analyses of andalusite and melt inclusions from two xenoliths. Details of electron microprobe (EMP) and laser-ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) techniques can be found in Appendix DR1 (see footnote 1). Andalusite is virtually stoichiometric Al₂SiO₅, with Fe₂O₃ < 0.4 wt% (average 0.2) and MgO and MnO < 0.04 wt%. The only measured trace elements present in significant quantities are P (80–200 ppm), Ti (60–230 ppm), and V (~45–83 ppm). B in andalusite ranges from 3.5 to 11 ppm.

Melts in inclusions are peraluminous (alumina saturation index = 1.2), felsic (FeO + MgO + TiO₂ < 1.6 wt%) rhyolites, with CaO < 1 wt%, and molar K₂O > Na₂O. On a CIPW-normative basis, the melts are corundum normative (~3%) and cluster around an average composition of Q₂₇Ab₂₅Or₃₃An₄. In the CIPW-normative Q-Ab-Or (quartz-albite-orthoclase) diagram for haplogranites (Fig. 3), melts plot below the cotectic curve on the Or-rich feldspar side of the thermal minima. Cl contents analyzed by EMP are <0.4 wt%. F was analyzed in only some melt inclusions, and its average content is <0.3 wt%. P analyzed by LA-ICP-MS is on average 1500 ppm (0.35 wt% P₂O₅), but occurs in maximum concentrations of 3800 ppm. B is highly variable; it av-

TABLE 1. REPRESENTATIVE ANALYSES OF MELT INCLUSIONS AND THEIR ANDALUSITE HOSTS IN XENOLITHS OF MAZARRÓN

Oxide	MA 2-2			MA 5-10		
	Melt (wt%)	Melt (wt%)	And (wt%)	Melt (wt%)	Melt (wt%)	And (wt%)
SiO ₂	68.41	68.98	36.57	71.21	70.35	36.59
Al ₂ O ₃	15.07	15.16	63.32	13.87	14.19	63.34
FeO*	1.61	1.34	0.15	1.46	1.69	0.23
MnO	0.03	0.00	0.00	0.15	0.04	0.04
MgO	0.09	0.11	0.03	0.12	0.10	0.02
CaO	1.05	0.79	0.00	0.61	0.63	0.01
Na ₂ O	2.65	3.55	0.00	2.72	2.64	0.01
K ₂ O	5.37	5.72	0.00	5.74	6.31	0.01
Cr ₂ O ₃	0.00	0.01	0.01	0.00	0.00	0.02
Cl	0.37	0.33	0.00	0.27	0.36	0.00
Total	94.65	96.01	100.08	96.15	96.31	100.27
Element	(ppm)			(ppm)		
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Li	118	bdl	0.8	22	224	bdl
Be	0.3	0.2	0.1	2.3	0.6	bdl
B	1430	972	9.6	934	1434	4.9
P	2227	1402	133	1063	2117	121
Ti	603	659	210	551	443	74
V	39	5.1	78	0.6	4.4	57
Zr	29	47	bdl	26	42	bdl
Sum LREEs	31	33	bdl	32	20	bdl

Note: Oxide components determined by electron microprobe; elements by laser-ablation inductively coupled plasma-mass spectrometry; bdl = below detection limit; And = andalusite; LREEs = light rare earth elements.

*Total iron as FeO.

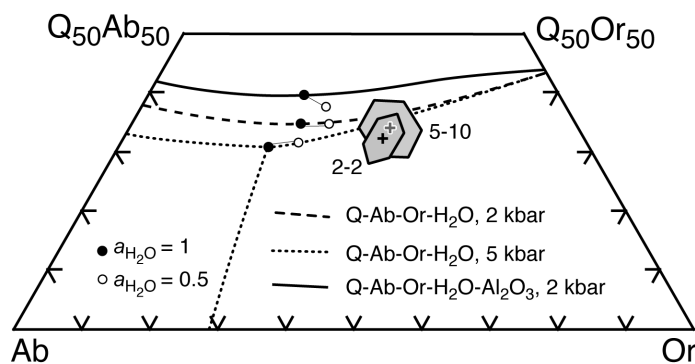


Figure 3. CIPW-normative Q-Ab-Or (quartz-albite-orthoclase) diagram reporting average compositions (crosses) and 1 σ contours (shaded fields) of melt inclusions in andalusite from two studied samples. Also reported are thermal minima or eutectics (dots) and cotectic curves at variable pressure and Al₂O₃ saturation.

erages <850 ppm, which corresponds to <0.27 wt% B₂O₃. Only 2 of 33 inclusions have B contents of ~3000 ppm (~1 wt% B₂O₃). Zr is between 10 and 50 ppm, whereas the sum of the light rare earth elements (LREEs) varies from 10 to 70 ppm. The variation in trace elements is far above the analytical uncertainties. Therefore, it appears that andalusite trapped melts with different compositions.

With the adopted EMP setup, the H₂O contents of the melts can be estimated (Devine et al., 1995) as the difference from 100% of the EMP totals (92.5–99.5 wt%) plus the other elements detected by LA-ICP-MS (~1 wt%). Therefore, the H₂O contents are 0–6.5 wt% (average 4.0 wt%). Because there is evidence that H₂O exsolution occurred in some inclusions (Fig. 2D), it is likely that the primary H₂O content was toward the higher side of the range (4.0–6.5 wt%).

DISCUSSION

Andalusite + Melt Equilibrium

The primary origin of melt inclusions is cogent evidence that andalusite was growing in the presence of a leucogranitic melt. Based on the rock type where andalusite is found, on the inferred *P-T* path of the xenoliths, and on the occurrence of quartz and K-feldspar only as anhedral inclusions in andalusite, we infer that andalusite did not crystallize from the melt, but with it, as a result of a peritectic melting reaction of the type quartz + K-feldspar + plagioclase + fluid + A = melt + andalusite + B, where fluid denotes a graphite-saturated C-O-H fluid, and A and B are additional reactants and products. The microstructural evidence of growth of andalusite in the presence of melt is a key observation supporting the equilibrium of And + melt. Although metastable growth of andalusite in the sillimanite stability field cannot be ruled out a priori, we consider this possibility untenable in the light of the high-temperature, melt-present conditions that favor reaction kinetics and the systematic distribution of the And + melt assemblage on a regional scale (>10² km).

Melt Temperatures

The compositions of melt inclusions provide thermobarometric constraints for the And + melt assemblage. The location of the melts in the Q-Ab-Or triangle (Fig. 3) indicates that their temperatures were higher than the eutectic minimum in the Al₂O₃-saturated haplogranite system (~660 °C at 2 kbar, Holtz et al., 1992). Extrapolation of the Al₂O₃-saturated phase relationships at reduced *a*_{H₂O} values compatible with the presence of graphite (see next section) would indicate melt temperatures, bracketed between liquidus and solidus, in the range 680–790 °C (average 735 °C). Zircon and monazite were present in the xenoliths during the entire partial melting process, so the variation of Zr (Watson and Harrison, 1983) and LREEs (Montel, 1993) can be expressed as a function of melt temperature. The two methods agree very well (Fig. 4). Sample MA 5-10 has generally lower temperatures, in the range 620–705 °C for Zr and 615–685 °C for LREEs. Sample MA 2-2 yields values of 670–695 °C for Zr and 675–725 °C for LREEs. The range of *T* determined with all methods strongly supports a prograde growth of andalusite in the presence of melt.

Location of And = Sil and the Wet Solidus

The position of the And = Sil phase boundary can shift in *P-T* space because of partitioning of minor elements between the two polymorphs. At Mazarrón, only Fe₂O₃ has the potential to enlarge the andalusite stability field, but its content (0.2 wt%) results in a shift of the equilibrium of <5 °C at 2 kbar (Kerrick and Speer, 1988). Therefore, andalusite was not stabilized to higher *T* by minor elements.

Because the melts in the inclusions coexist with andalusite, the Al₂O₃-saturated solidus must be considered. This is situated at ~30 °C lower *T* (at 2 kbar) than the haplogranite solidus (Holtz et al., 1992). Additional temperature-lowering effects of B (B₂O₃ < 0.3 wt%) and F (<0.3 wt%) are estimated to be <15 °C each (Pichavant and Man-

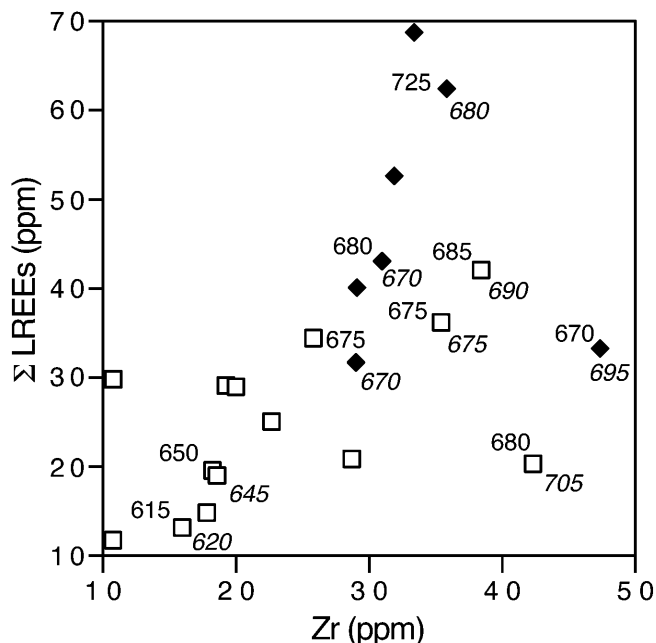


Figure 4. Trace element composition of melt inclusions in andalusite from sample MA 5-10 (squares) and MA 2-2 (diamonds). Light rare earth element (Σ LREE) label refers to sum from La to Gd, excluding Eu. Selected symbols are labeled with calculated temperatures obtained from LREEs and Zr (given in *italics*) thermometry.

ning, 1984). By contrast, CaO, FeO, and MgO in the melt result in a raising of the solidus temperature: CaO leads to an increase of ~10 °C (Johannes, 1984), whereas the effect of FeO + MgO is ~10–20 °C (Icenhower and London, 1995).

A drastic shift in solidus temperature is caused by graphite, which displaces fluid-present melting equilibria to higher *T*, owing to the lowering of *a*_{H₂O} in the fluid. This effect can be quantified by intersecting the isopleths of the maximum H₂O content of graphite-saturated fluids (*X*_{H₂O}^m, Connolly and Cesare, 1993) and those of *X*_{H₂O} values of fluids coexisting with haplogranitic melts (e.g., Ebadi and Johannes, 1991). The displacement (Fig. 5) is negligible for *P* > 7 kbar and increases with decreasing *P* (e.g., 35 °C at 2 kbar). Unlike in the cases of Al₂O₃, B, and F, such displacement is a minimum, because it is calculated for maximum *X*_{H₂O} values.

Implications for the Al₂SiO₅ Triple Point

Figure 5 depicts the *P-T* relationships between the herein-constrained graphitic, peraluminous, haplogranitic solidus and the And = Sil equilibria of Holdaway (1971) and Pattison (1992), along with the thermometric estimates provided by the melt inclusions. It is apparent that only with the And = Sil of Pattison (1992) is a field for And + melt + graphite possible. Additionally, the melts in the inclusions were generated over a temperature range of ~50–100 °C, indicating that a significant And + melt field must exist. The temperature range of 670–725 °C determined in sample MA 2-2 is remarkably consistent with the And + melt field that results from the herein-constrained solidus and the triple point of Pattison (1992). Temperatures from sample MA 5-10 are slightly lower (615–705 °C), but can be fully explained only using the triple point of Pattison (1992). The best fit for the And + melt field is obtained at *P* = 2.0–2.5 kbar; such a pressure is in good agreement with the estimated 4.0–6.5 wt% H₂O of the melts (Fig. 5) if compared with values reported by Johannes and Holtz (1996).

The confirmation of the Al₂SiO₅ triple point at higher *P-T* than generally assumed has far-reaching consequences for the understanding of low-*P*-high-*T* metamorphism and crustal melting. The And = Sil

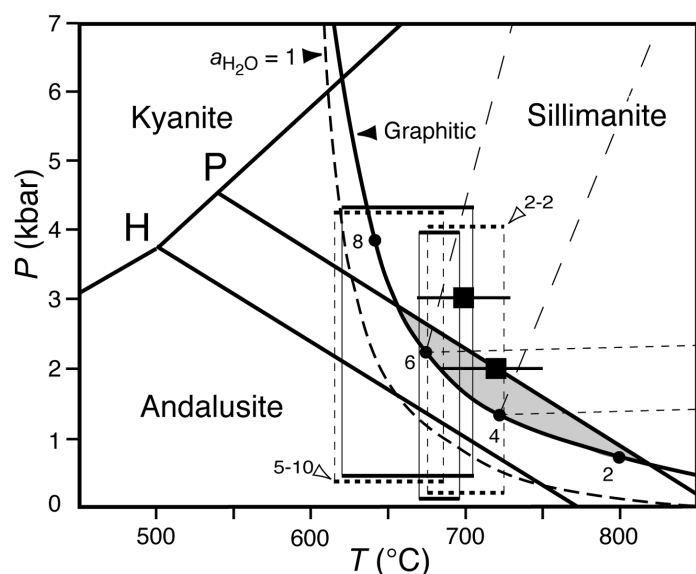


Figure 5. Pressure-temperature (P - T) diagram illustrating relationships between And = Sil (andalusite, sillimanite) and granitic solidi. Al_2SiO_5 triple points after (H) Holdaway (1971) and (P) Pattison (1992). Solidi for Al_2O_3 -saturated haplogranite with $a_{\text{H}_2\text{O}} = 1$ (dashed, after Johannes and Holtz, 1996) and coexisting with graphite (thick solid) are reported. Numbers along graphitic haplogranite indicate wt% H_2O in melt at solidus; long- and short-dashed thin lines represent minimum and maximum H_2O contents of melt, respectively. Vertical lines are minimum and maximum thermometric estimates from Zr (solid) and light rare earth element contents (dashed) of melt inclusions from two samples. Horizontal bars and small black squares are estimated ranges and averages of melt temperature based on compositions in Q-Ab-Or diagram at $P = 2$ and 3 kbar. Shaded area: field of And + melt stability for melts as in melt inclusions from this study.

transition is often used to calibrate T and P in contact aureoles, and is essential for the derivation of metamorphic bathozones (Carmichael, 1978). Our new results show that the T - P conditions of diagnostic mineral assemblages (e.g., the KASH invariant point $\text{Ms} + \text{Qtz} + \text{Kfs} + \text{And} + \text{Sil} + \text{H}_2\text{O}$) can be as much as 50 °C and 1 kbar higher, and that boundaries between bathozones can move to 1 kbar higher P (discussion in Pattison and Tracy, 1991). Moreover, the equilibrium And = Sil is crucial for thermodynamic modeling of metapelites, and its shift severely affects previously calculated petrogenetic grids. In internally consistent databases, which represent the basis of most published grids, the proposed shift must affect all equilibria involving And or Sil. Hence, equilibria used to constrain isograds in low- P metapelites (e.g., the breakdown of staurolite) will change positions. The established And + melt P - T field explains the occurrence of andalusite in peraluminous granites and anatectic metapelites without the necessity of a decrease in solidus temperature due to high contents of volatiles such as B and F. By using the analyzed B contents of andalusite and melt, a partition coefficient $D_B^{\text{And/melt}} = 0.005\text{--}0.008$ is determined, which can be used in future work to establish whether andalusite in migmatites was in equilibrium with a B-enriched, low- T melt.

CONCLUSIONS

Melt inclusions in andalusite, albeit rare, provide a natural laboratory to study the position of the And = Sil equilibrium, which is widely used to calibrate low- P metamorphic reactions. The compositions of the melt inclusions provide evidence that this equilibrium is situated at temperatures to 100 °C higher than commonly considered, and is therefore compatible with the Al_2SiO_5 triple point of Pattison (1992). Graphite drastically increases the temperature of the wet solidus at low P , and has proved to be one of the critical parameters for

discriminating between different triple points. Our data show that in low- P partial melting of metapelites, the coexistence of And + melt should be the rule rather than the exception. The conclusions of this research are relevant not only for melt-bearing equilibria, but more generally for thermodynamic modeling of metapelites at low P , which should be reconsidered in the light of a higher P - T Al_2SiO_5 triple point.

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REFERENCES CITED

- Carmichael, D.M., 1978, Metamorphic bathozones and bathograds: A measure of the depth of post-metamorphic uplift and erosion on the regional scale: *American Journal of Science*, v. 278, p. 769-797.
- Cesare, B., and Gómez-Pugnaire, M.T., 2001, Crustal melting in the Alborán domain: Constraints from the xenoliths of the Neogene Volcanic Province: *Physics and Chemistry of the Earth, Ser. A*, v. 26, p. 255-260.
- Cesare, B., Gómez-Pugnaire, M.T., Sanchez-Navas, A., and Grobety, B., 2002, Andalusite-sillimanite replacement (Mazarrón, southeast Spain): A microstructural and TEM study: *American Mineralogist*, v. 87, p. 433-444.
- Connolly, J.A.D., and Cesare, B., 1993, C-O-H-S fluid composition and oxygen fugacity in graphitic metapelites: *Journal of Metamorphic Geology*, v. 11, p. 379-388.
- Devine, J.D., Gardner, J.E., Brack, H.P., Layne, G.D., and Rutherford, M.J., 1995, Comparison of microanalytical methods for estimating H_2O contents of silicic volcanic glasses: *American Mineralogist*, v. 80, p. 319-328.
- Ebadi, A., and Johannes, W., 1991, Beginning of melting and composition of first melts in the system Qz-Ab-Or- H_2O - CO_2 : *Contributions to Mineralogy and Petrology*, v. 106, p. 286-295.
- Holdaway, M.J., 1971, Stability of andalusite and the aluminum silicate phase diagram: *American Journal of Science*, v. 271, p. 97-131.
- Holtz, F., Pichavant, M., Barbey, P., and Johannes, W., 1992, Effects of H_2O on liquidus phase relations in the haplogranite system at 2 and 5 kbar: *American Mineralogist*, v. 77, p. 1223-1241.
- Icenhower, J., and London, D., 1995, An experimental study of element partitioning among biotite, muscovite, and coexisting peraluminous silicic melt at 200 MPa (H_2O): *American Mineralogist*, v. 80, p. 1229-1251.
- Johannes, W., 1984, Beginning of melting in the granite system Qz-Or-Ab- H_2O : *Contributions to Mineralogy and Petrology*, v. 86, p. 264-273.
- Johannes, W., and Holtz, F., 1996, Petrogenesis and experimental petrology of granitic rocks: Berlin, Springer-Verlag, 335 p.
- Johnson, T.E., Brown, M., and Solar, G.S., 2003, Low-pressure subsolidus and suprasolidus phase equilibria in the MnNCKFMASH system: Constraints on conditions of regional metamorphism in western Maine, northern Appalachians: *American Mineralogist*, v. 88, p. 624-638.
- Kerrick, D.M., 1990, The Al_2SiO_5 polymorphs: *Mineralogical Society of America Reviews in Mineralogy*, v. 22, 406 p.
- Kerrick, D.M., and Speer, J.A., 1988, The role of minor element solid solution on the andalusite-sillimanite equilibrium in metapelites and peraluminous granulites: *American Journal of Science*, v. 288, p. 152-192.
- Montel, J.-M., 1993, A model for monazite/melt equilibrium and application to the generation of granitic magmas: *Chemical Geology*, v. 110, p. 127-146.
- Pattison, D.R.M., 1992, Stability of andalusite and sillimanite and the Al_2SiO_5 triple point: Constraints from the Ballachulish aureole, Scotland: *Journal of Geology*, v. 100, p. 423-446.
- Pattison, D.R.M., and Tracy, R.J., 1991, Phase equilibria and thermobarometry of metapelites, in Kerrick, D.M., ed., *Contact metamorphism: Mineralogical Society of America Reviews in Mineralogy*, v. 25, p. 105-206.
- Pichavant, M., and Manning, D.A.C., 1984, Petrogenesis of tourmaline granites and topaz granites: The contribution of experimental data: *Physics of the Earth and Planetary Interiors*, v. 35, p. 31-50.
- Watson, B.E., and Harrison, M.T., 1983, Zircon saturation revisited: Temperature and composition effects in a variety of crustal magma types: *Earth and Planetary Science Letters*, v. 64, p. 295-304.

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