

Table 27–4a Some Useful Geothermobarometers in Petrology: Exchange and Solvus Equilibria

Exchange Thermometers		
Garnet-Biotite	Fe-Mg exchange	Thompson (1976), Goldman and Albee (1977), Ferry and Spear (1978), Perchuk and Lavrent'eva (1981), Hodges and Spear (1982), Pigage and Greenwood (1982), Ganguly and Saxena (1984), Indares and Martingole (1985), Chipera and Perkins (1988), Berman (1990), Perchuk (1991), Bhattacharya et al. (1992), Patiño-Douce et al. (1993), Kleemann and Reinhardt (1994), Kullerud (1995), Alcock (1996), Holdaway et al. (1997), Gessmann et al. (1997), Holdaway (2000, 2004) , Kaneko and Miyano (2003)
Garnet-Cordierite	Fe-Mg exchange	Currie (1971), Hensen and Green (1973), Thompson (1976), Holdaway and Lee (1977), Perchuk and Lavrent'eva (1981), Martignole and Sisi (1981), Bhattacharya et al. (1988), Perchuk (1991) , Kaneko and Miyano (2003)
Garnet-Clinopyroxene	Fe-Mg exchange	Råheim and Green (1974), Mori and Green (1973), Ellis and Green (1979), Saxena (1979), Ganguly (1979), Dahl (1980), Powell (1985), Pattison and Newton (1989), Krogh (1988), Carswell and Harley (1989), Brey and Köhler (1990), Perchuk (1991), Green and Adam (1991), Ai (1994), Nikitina and Ivanov (1995), Berman et al. (1995), Aranovich and Pattison (1995), Ravna (2000a)
Garnet-Orthopyroxene	Fe-Mg exchange	Mori and Green (1978), Harley (1984), Sen and Bhattacharya (1984), Lee and Ganguly (1988), Carswell and Harley (1989), Brey and Köhler (1990), Perchuk (1991), Bhattacharya et al. (1991), Lal (1993), Carson and Powell (1997), Aranovich and Berman (1997), Pattison et al. (2003)
Garnet-Hornblende	Fe-Mg exchange	Graham and Powell (1984), Perchuk (1991), Himmelberg et al. (1993), Ravna (2000b)
Garnet-Chlorite	Fe-Mg exchange	Dickenson and Hewitt (1986), Laird (1988), Grambling (1990), Perchuk (1991)

Garnet-Staurolite	Fe-Mg exchange	Perchuk (1991)
Chloritoid-(Garnet or Chlorite or Biotite)	Fe-Mg Exchange	Perchuk (1991), Vidal et al. (1999)
Garnet-Epidote	Fe-Mg Exchange	Perchuk (1991)
Garnet-Olivine	Fe-Mg exchange	Kawasaki (1977), O'Neil and Wood (1979, 1980), Smith and Wilson, (1985), Carswell and Harley (1989), Brey and Köhler (1990)
Garnet-Olivine	Ni-(Fe-Mg) exchange "Ni-in-garnet"	Griffin et al. (1989), Canil (1994), Griffin et al. (1996)
Garnet-Ilmenite	Fe-Mg and Fe-Mn exchange	Pownceby et al. (1987a,b), Feenstra and Engi (1998)
Garnet-Phengite	Fe-Mg exchange	Krogh and Råheim (1978), Green and Hellman (1982), Hynes and Forest (1988), Carswell and Harley (1989), Coggon and Holland (2002)
Olivine-Spinel	Fe-Mg exchange	Fabriès (1979), Roeder et al. (1979), Ozawa (1982), Engi (1983)
Olivine-Orthopyroxene	Fe-Mg exchange	Docka et al. (1986), Carswell and Harley (1989), Brey and Köhler (1990), Kock-Mueller et al. (1992)
Olivine-Clinopyroxene	Fe-Mg exchange	Powell and Powell (1974), Sengupta et al. (1989), Köhler and Brey (1990), Brey and Köhler (1990), Perkins and Vielzeuf (1992), Loucks (1996)
Orthopyroxene-Ilmenite	Fe-Mg exchange	Docka et al. (1986), Carswell and Harley (1989)
Clinopyroxene-Ilmenite	Fe-Mg exchange	Docka et al. (1986), Carswell and Harley (1989)

Olivine-Ilmenite	Fe-Mg exchange	Docka et al. (1986), Carswell and Harley (1989)
Orthopyroxene-Biotite	Fe-Mg exchange	Fonarev and Konilov (1986), Sengupta et al. (1990)
Orthopyroxene- Sapphirine	Fe-Mg exchange	Kawasaki and Sato (2002)
Cordierite-Spinel	Fe-Mg exchange	Vielzeuf (1983)
Cordierite-Orthopyroxene	Fe-Mg exchange	Sakai and Kawasaki (1997)
Nepheline-Feldspar	Na-K exchange	Perchuk et al. (1991)
Oxygen isotope thermometry	O ¹⁸ -O ¹⁶ Exchange	O'Neil and Clayton (1964), Bottinga and Javoy (1973, 1975, 1987), Javoy (1977), Clayton (1981), Valley et al. (1986), O'Neil and Pinkthorn (1988), Chiba et al. (1989), Bechtel and Hoernes (1990), Zheng and Simon (1991), Agrinier (1991), Clayton and Kieffer (1991), Eiler et al. (1993), Sharp et al. (1993), Farquahar et al. (1993, 1996), Matthews (1994), Krylov and Mineev (1994), Hoffbauer et al. (1994), Ghent and Valley (1998), Moecher and Sharp (1999), Valley (2001, 2004)
Carbon isotope thermometry	C ¹³ -C ¹² Exchange	Valley and O'Neil (1980), Wada and Suzuki (1983), Valley et al. (1986), Dunn and Valley (1992), Morrison and Barth (1993), Eiler et al. (1993), Kitchen and Valley (1995), Satish-Kumar (2000), Valley (2001)
Solvus Thermometers		
Two-Pyroxene	Ca-Mg-Fe exchange	David and Boyd (1966), Wood and Banno (1973), Warner and Luth (1974), Ross and Heubner (1975), Saxena and Nehru (1975), Saxena (1976), Nehru (1976), Lindsley and Dixon (1976), Wells (1977), Mori and Green (1978), Sachtleben and Seck (1981), Kretz (1982), Lindsley (1983), Lindsley and Andersen

		(1983), Finnerty and Boyd (1984), Nickel and Brey (1984), Nickel and Green (1985), Nickel et al. (1985), Carswell and Gibb (1987), Brey and Kohler (1990), Fonarev and Graphchikov (1991)
Two-Feldspar	Na-K exchange	Stormer (1975), Whitney and Stormer (1977), Powell and Powell (1977a), Brown and Parsons (1981, 1985), Ghiorso (1984), Green and Udansky (1986), Fuhrman and Lindsley (1988), Elkins and Grove (1990), Perchuk et al. (1991), Kroll et al. (1993), Voll et al. (1994)
Calcite-Dolomite	Ca-Mg exchange	Goldsmith and Heard (1961), Goldsmith and Newton (1969), Anovitz and Essene (1982, 1987a), Powell et al. (1984)
Muscovite-Paragonite	Na-K exchange	Eugster et al. (1972), Chatterjee and Flux (1986)
Monazite-Xenotime	Ce-Y Exchange in phosphates	Heinrich et al. (1997), Gratz and Heinrich (1997)

Table 27-4b Some Useful Geothermobarometers in Petrology: Continuous Net-Transfer and Miscellaneous Equilibria

Continuous Net-Transfer Equilibria

Garnet-Al ₂ SiO ₅ -Quartz-Plagioclase (GASP)	$3 \text{ An} = \text{Grs} + 2 \text{ Al}_2\text{SiO}_5 + \text{Qtz}$	Ghent (1976), Ghent et al. (1979), Newton and Haselton (1981), Hodges and Spear (1982), Ganguly and Saxena (1984), Hodges and Royden (1984), Powell and Holland (1988), McKenna and Hodges (1988), Koziol and Newton (1988), Koziol (1989), Dasgupta et al. (1991), Ganguly et al. (1996), Holdaway (2001, 2004)
Garnet-Rutile-Al ₂ SiO ₅ -Ilmenite-Quartz (GRAIL)	Several Reactions	Bohlen et al. (1983b), Ghent and Stout (1984, 1994), Bohlen and Liotta (1986), Essene and Bohlen (1985)

Garnet-Rutile-Ilmenite-Plagioclase- Quartz (GRIPS)	$\text{Grs} + 2 \text{ Alm} + 6 \text{ Rut} = 6 \text{ Ilm} + 3 \text{ An} + 3 \text{ Qtz}$	Bohlen and Liotta (1986), Anovitz and Essene (1987b)
Garnet-Plagioclase-Muscovite-Biotite	$\text{Bt} + \text{Grs} + \text{Mu} = 3 \text{ An} + \text{Bt}$	Ghent and Stout (1981), Hodges and Crowley (1985), Hoisch (1991), Powell and Holland (1988)
Garnet-Plagioclase-Muscovite-Quartz	$\text{Prp} + \text{Grs} + 3 (\text{Al-Al})\text{Mu} + 6 \text{ Qtz} = 6 \text{ An} + 3 (\text{Fe-Si})\text{Mu}$	Hodges and Crowley (1985), Hoisch (1991)
Garnet-Muscovite-Quartz- Al_2SiO_5	$\text{Prp} + 3 (\text{Al-Al})\text{Mu} + 4 \text{ Qtz} = 3 (\text{Fe-Si}) \text{ Mu} + 4 \text{ Al}_2\text{Si}_2\text{O}_5$	Hodges and Crowley (1985), Hoisch (1991)
Garnet-Muscovite-Biotite-Quartz- Al_2SiO_5	$\text{Prp} + \text{Mu} = \text{Bt} + 2 \text{ Al}_2\text{SiO}_5 + \text{Qtz}$	Hodges and Crowley (1985), Holdaway et al. (1988, 2004), Hoisch (1991)
Garnet-Biotite-Plagioclase-Quartz	> 1	Wu et al. (2004)
Garnet-Plagioclase-Hornblende-Quartz	Complex reactions involving Si-Al exchange in Hbl and Plag + Fe-Mg exchange	Kohn and Spear (1989, 1990), Dale et al. (2000)
Garnet-Plagioclase-Olivine	$3 \text{ Fo} + 3 \text{ An} = \text{Grs} + 2 \text{ Prp}$	Wood (1975), Johnson and Essene (1982), Bohlen et al. (1983a,c)
Garnet-Plagioclase-Orthopyroxene- Quartz (GAES-GAFS)	$3 \text{ Opx} + 3 \text{ An} = 2 \text{ Prp-Alm} + \text{Grs} + 3 \text{ Qtz}$	Wood (1975), Newton and Perkins (1982), Bohlen et al. (1983a), Perkins and Chipera (1985), Powell and Holland (1988), Bhattacharya et al. (1991), Eckert et al. (1991), Faulhaber and Raith (1991), Lal (1993)
Garnet-Plagioclase-Clinopyroxene-	$3 \text{ Cpx} + 3 \text{ An} = 2 \text{ Alm-Pry} + 2$	Newton and Perkins (1982), Perkins (1987), Powell and Holland (1988), Moecher

Quartz (GADS-GAHS)	Grs+ 3 Qtz	et al. (1988), Eckert et al. (1991)
Garnet-Plagioclase-Orthopyroxene- Clinopyroxene-Quartz	Prp-Alm + Di-Hd + Qtz = En- Fs + An	Paria et al. (1988)
Garnet-Cordierite-Sillimanite-Quartz	3 Cord = 2 Prp-Alm + 4 Al ₂ SiO ₅ + 5 Qtz	Currie (1971), Hensen and Green (1973), Weisbrod (1973), Thompson (1976), Tracy et al. (1976), Hensen (1977), Holdaway and Lee (1977), Newton and Wood (1979), Martignole and Sisi (1981), Lonker (1981), Aranovich and Podlesskii (1983), Perchuk (1991)
Biotite-Cordierite-Al ₂ SiO ₅ -Quartz	Several reactions	Patiño-Douce et al. (1993)
Garnet-Biotite-Al ₂ SiO ₅ -Quartz		
Garnet-Cordierite-Biotite-Quartz		
Garnet-Clinopyroxene	2 Grs + Prp = 3 Di + 3 CaTs	Mukhopadhyay (1991)
Garnet-Monazite	Y-Al-Grt + OH-Ap + Qtz = Grs + An + YPO ₄ -Mnz + H ₂ O	Pyle and Spear (2000), Pyle et al. (2001)
Garnet-Carbonate	3 Dol + Grs = 6 Cal + Pyr	Yaxley and Brey (2004)
Pyroxene-Plagioclase-Quartz	Jd + Qtz = Ab	Johannes et al. (1971), Holland (1980), Hemmingway et al. (1981), Carswell and Harley (1989), Perchuk (1994), Meyre et al. (1997)
Pyroxene-Plagioclase-Quartz	CaTs + Qtz = An	Gasparik and Lindsley (1980), Newton (1983), Gasparik (1984), McCarthy and Patiño-Douce (1998)
Pyroxene-Olivine-Quartz	2 Fs = Fo + Qtz	Bohlen et al. (1980), Bohlen and Boettcher (1981), Newton (1983), Carswell and

		Harley (1989)
Amphibole-Plagioclase	Several equilibria	Spear (1980, 1981), Plyusnina (1982), Blundy and Holland (1990), Fershtater (1991), Holland and Blundy (1994), Bhadra and Bhattacharya (2007)
Amphibole-Plagioclase-Clinopyroxene- Quartz	$Ts + Di + Qtz = Tr + An$	Liogys and Jenkins (2000)
Wollastonite-Plagioclase-Garnet- Quartz (WAGS)	$Grs + Qtz = An + 2 Wo$	Huckenholz et al. (1981)
Garnet-Clinopyroxene-Phengite- Kyanite-Quartz	Several	Waters and Martin (1993), Ravna and Terry (2004)
Garnet-Spinel-Sillimanite-Quartz	$Alm + 2 Sill = 3 Hc + 5 Qtz$	Bohlen et al. (1986)
Garnet-Spinel-Sillimanite-corundum	$Alm + 5 Crn = 3 Hc + 3 Sill$	Shulters and Bohlen (1989)
Orthopyroxene-Spinel-Olivine	$En + Sp = MgTs + Fo$	Fujii (1976), Gasparik and Newton (1984), Witt-Eickschen and Seck (1991), Ballhaus et al. (1991)
Spinel barometers	Several equilibria	Perchuk (1991)
Talc-Kyanite-Phengite-Coesite Garnet-Zoisite-Kyanite-Coesite Garnet-Omphacite-Kyanite-Coesite	Several equilibria	Massone and Schreyer (1989), Okay (1995), Nakamura and Banno (1997)
Titanite-Kyanite-Plagioclase-Rutile	$Ttn + Ky = An + Rt$	Manning and Bohlen (1991), Tropper and Manning (2008).
Other Geothermobarometers		

Phengite barometry	Phengite content of white mica	Powell and Evans (1983), Massone and Schreyer (1987), Bucher-Nurminen (1987)
Stilpnomelane-Chlorite-Phengite	> 1	Currie and Van Staal (1999).
Sphalerite-Pyrrhotite-Pyrite barometry	Fe content of sphalerite	Scott (1973, 1976), Lusk and Ford (1978), Jamieson and Craw (1987), Bryndzia et al. (1988, 1990), Toulmin (1991)
Magnetite-Ilmenite thermometry	$4 \text{ Mt} + \text{O}_2 = 6 \text{ Hem} \text{Fe}_2\text{TiO}_4 + \text{Fe}_2\text{O}_3 = \text{Fe}_3\text{O}_4 + \text{FeTiO}_3$	Buddington and Lindsley (1964), Powell and Powell (1977b), Spencer and Lindsley (1981), Ghiorso and Sack (1991), Lindsley and Frost (1992), Anderson et al. (1993), Sauerzapf et al. (2008)
Al-in-Hornblende thermometry	Al-content of hornblende in some igneous rocks	Hammarstrom and Zen (1986), Hollister et al. (1987), Johnson and Rutherford (1989), Vyhnal et al. (1991), Schmidt (1992), Anderson and Smith (1995)
Na-in-Cordierite thermometry	Na-content of cordierite coexisting with albite and NaOH	Kalt et al. (1998)
Chlorite thermometry	Al^{IV} in chlorite	Stoessel (1984), Cathelineau and Nieva (1985), Walshe (1986), Caritat et al. (1993), Xie et al. (1997), Vidal et al. (2001, 2005, 2006)
Rutile-(Ti-in-zircon)	$\text{Rt} + \text{Zr} = \text{Ti-Zr} + \text{Qtz}$	Zack and Luvizotto (2006), Fu et al. (2008)
Magmatic Epidote		Naney (1983), Vyhnal et al. (1991)
Fluid Inclusion thermometry		Hollister and Crawford (1981), Vityk et al. (1994)
Plagioclase-Liquid		Mathez (1973), Loomis (1979), Glazner (1984), Marsh et al. (1990), Ariskin and

		Barmina (1990), Housh and Luhr (1991), Sugawara (2001), Putirka (2005)
Basaltic glass	Wt. % MgO and CaO	Helz and Thorber (1987), Helz et al. (1995)
Piezothermobarometry	Elastic effects around inclusions	Rosenfeld and Chase (1961), Rosenfeld (1969), Adams et al. (1975a, b), Cohen and Rosenfeld (1979)
