Melting Behavior of Simplified Lherzolite in the System CaO-MgO-Al₂O₃-SiO₂-Na₂O from 7 to 35 kbar

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(Received 28 December 1992; revised typescript accepted 18 May 1993)

ABSTRACT

Phase equilibrium data have been collected for isobarically univariant melting of simplified lherzolite compositions in the system CaO-MgO-Al₂O₃-SiO₂-Na₂O over a pressure range of 7-35 kbar. These data permit the melting behavior of a wide variety of model lherzolite compositions to be determined quantitatively by algebraic methods. Two P-T univariant melting reactions, corresponding to plagioclase to spinel lherzolite and spinel to garnet lherzolite, are identified as peritectic-type transitions and have positive Clapeyron slopes. The univariant curves move to higher pressures and temperatures with increasing Na₂O in the liquid. The effect of the univariant curves on melting is to produce low-temperature regions and isobarically invariant melting intervals along herzolite solidi. In the plagioclase lherzolite stability field, melting of four-phase model lherzolite is pseudo-invariant, occurring over small temperature intervals ($\sim 5 \,^{\circ}$ C) and producing liquids that are quartz tholeiites at < 8 kbar and olivine tholeiites at > 8 kbar. Calculated equilibrium constants for plagioclase-liquid equilibria show both temperature and pressure dependence. Plagioclase with anorthite content (AN) >90 mol%, as observed in some oceanic basalts, can crystallize from liquids with <1% Na₂O. Melting of spinel lherzolite is not pseudo-invariant but occurs over large temperature intervals (15-60 °C), producing a wide range in liquid compositions, from alkali basalts and alkali picrites at low to moderate degrees of melting (<1-10%) to olivine tholei tes and picrites at higher degrees of melting (> 10%). On the basis of limited data in the garnet lherzolite field, melts from garnet lherzolite are more silica rich for a given degree of melting than melts from spinel lherzolite, and liquid compositions trend toward enstatite with increase in pressure. Source fertility (especially Na2O content) has a strong control on the temperature of melting and liquid composition. Less fertile sources produce smaller amounts of liquids richer in normative silica. For certain bulk compositions (high SiO₂ and low Al_2O_3), spinel is not a stable phase along the lherzolite solidus.

INTRODUCTION

Two approaches have been used to study the generation of basaltic magmas from a peridotite upper mantle. In one, experiments have been performed on a variety of natural lherzolite compositions (e.g., Mysen & Kushiro, 1977; Jaques & Green, 1980), on lherzolite plus basalt mixtures (Takahashi & Kushiro, 1983; Fujii & Scarfe, 1985; Falloon & Green, 1987), and on basaltic liquids saturated with a lherzolite assemblage (e.g., Stolper, 1980; Elthon & Scarfe, 1984; Kinzler & Grove, 1992a). Recent parameterizations of what is now a large body of experimental data have brought us closer than ever to a rigorous quantitative description of melting (Klein & Langmuir, 1987; McKenzie & Bickle, 1988; Niu & Batiza, 1991; Kinzler & Grove, 1992b). An alternative approach has been to determine phase

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equilibrium relationships in simple analog systems of low variance (e.g., Kushiro, 1969; Presnall *et al.*, 1979). In this paper we extend this second approach and present phase equilibrium data for melting of simplified lherzolite in the five-component system CaO-MgO-Al₂O₃-SiO₂-Na₂O (CMASN) from 7 to 35 kbar. Isobarically univariant and invariant melting of lherzolite in this system offers a close approximation to the natural system, as CMASN makes up ~93% of proposed upper-mantle compositions. This system was chosen for study because the addition of Na₂O to the existing data in the CMAS system is critical to an understanding of the compositional variations of basaltic magmas.

Here, we present the experimental data set, together with an examination of the methods of data acquisition and processing. These data are a redetermination and refinement of the data on which the diagrams of Presnall & Hoover (1987) are based and an extension of these data to 35 kbar. We show how the data for isobarically univariant and invariant melting can be used to determine the melting behavior of a wide variety of bulk compositions, allowing any number of melting scenarios for basalt generation to be developed. Finally, data are used for a discussion of the melting behavior of a number of simplified lherzolite compositions, and the results are compared and contrasted with the melting behavior of model natural lherzolite as presented by Kinzler & Grove (1992a, 1992b). In a forthcoming paper, the data set will be used to construct polybaric melting models for the generation of mid-ocean ridge basalt (MORB).

EXPERIMENTAL DESIGN AND PROCEDURES

We have collected phase equilibrium data along isobarically univariant melting curves involving forsterite, orthopyroxene, clinopyroxene, an alumina-rich phase (plagioclase, spinel, or garnet), and liquid over a pressure range of 7–35 kbar in the CMASN system. All coexisting phase compositions were analyzed, and these data have been interpolated and extrapolated over a pressure range of 5–35 kbar and from 0 (CMAS solidus) to 6 wt.% Na₂O in the liquid phase. We have used these data to investigate the melting behavior of simplified lherzolite over much of the plagioclase lherzolite stability field, the entire spinel lherzolite stability field, and a small portion of the garnet lherzolite stability field.

An advantage of investigating isobarically univariant melting of lherzolite is that once the compositions of all coexisting phases along a melting curve are known, it is possible, using the algebraic techniques described by Presnall (1986), to determine the melting behavior of a wide variety of model lherzolite bulk compositions. Also, liquid compositions for arbitrarily small amounts of melting of a model lherzolite can be known rigorously because the liquid compositions are determined in experiments that have large amounts of easily analyzed glass. This can be illustrated by considering the system diopside-albite-anorthite at 1 atm (Fig. 1), which, for purposes of illustration, will be treated as a strictly ternary system. Shown in this diagram is a liquidus univariant boundary line along which liquid (1), diopside (Di), and plagioclase solid solution (pl) are in equilibrium. For an experiment using bulk composition x, liquid of composition I would be in equilibrium with Di and plagioclase of composition pl. The proportions of the phases in the experiment are 50% l + 40% pl + 10%Di. The compositions of the coexisting phases could then be used to determine the phase proportions during melting of any bulk composition lying within the three-phase triangle l-Di-pl. For example, if bulk composition y were a model mantle composition, 2% of liquid l would coexist with 28% pl and 70% Di. By making experiments that define a range of threephase triangles along the univariant boundary line, the melting behavior of a wide range of



FIG. 1. The system diopside-albite-anorthite at 1 atm (after Bowen, 1915; Kushiro, 1973). The three-phase triangle shows the compositions of coexisting liquid (l), plagioclase solid solution (pl), and diopside, at 1225 °C. The point labeled x is a hypothetical starting mixture, and y is a simplified mantle composition.

compositions can be determined as long as plagioclase and diopside are both present. Thus, the composition of a very small amount of liquid for the model mantle can be defined from an experiment at the same pressure and temperature on an entirely different bulk composition chosen for its large proportion of liquid. This treatment is exactly analogous to our approach to studying the melting of model lherzolite compositions in the CMASN system, except that algebraic analysis is necessary.

Experiments were made in solid-media, piston-cylinder presses (Boyd & England, 1960). The 'hot' piston-out technique was used in all runs with no pressure correction (Presnall et al., 1978). The furnace cell assembly is the same as that described by Presnall et al. (1973), except that Pyrex glass sleeves were used instead of boron nitride. All assembly parts, except talc and glass sleeves, were dried under nitrogen flow at 1050 °C for 1 h just before experiments to ensure that the assembly parts were free of water. The samples were contained in platinum capsules of 2.5-mm diameter and either 2.5 or 4 mm in length. On the basis of a calibration of the temperature profile surrounding the furnace hot-spot, the thermal gradient across the diameter of a capsule is estimated to be 5 °C, and across the length is estimated to be 10 °C for 2.5-mm capsules and 15 °C for 4-mm capsules. Run temperatures were monitored by either W3Re/W25Re or W5Re/W26Re thermocouples with no pressure correction applied to e.m.f. values. Nominal temperatures were measured to a precision of \pm 1°C, and were held by automated temperature controllers to within \pm 3°C of the nominal temperature. All temperatures were calibrated according to the International Practical Temperature Scale of 1968 (Anonymous, 1969). Pressure is estimated to be accurate to within ± 0.5 kbar on the basis of the reproducibility of reactions used in calibration.

Thermocouple oxidation was a problem in runs made at lower pressures (<11 kbar). The oxidation resulted in a high thermocouple failure rate and/or anomalous e.m.f. values, resulting in power drift. It was determined that the reason for thermocouple oxidation was that the ceramic insulator was strong enough at lower pressures and temperatures to maintain a conduit for air down a significant portion of its length. The problem was overcome by maintaining a nitrogen flow down the thermocouple insulator throughout the run.

Starting materials

A disadvantage of working in systems with more than four components is the inability to represent compositions graphically. This made the initial task of determining suitable bulk compositions difficult because the compositions had to yield a four-phase lherzolite + liquid assemblage at the pressure of interest, and also had to yield enough glass (generally > 30%) and pyroxenes to facilitate microprobe analysis. A method that worked well was to estimate the compositions of phases expected at a given pressure from data in the CMAS system (Presnall *et al.*, 1979; Gasparik, 1984), and from data in the CMASN system as they became available. These estimated phase compositions were then added in desired proportions (e.g., 40% liquid + 20% Cpx + 20% Opx + ...) to calculate a bulk composition. A given bulk composition was generally useful over a range of 5–10 kbar. The compositions of the eight starting mixtures used in this study are listed in Table 1. A mixture of 10 g of each bulk

S	Starting composi	tio <mark>n</mark> s used i	n this study	(in wt.%)*	
	CaO	MgO	Al ₂ O ₃	SiO ₂	Na ₂ O
CMASN.03	6.53	30-29	16-68	45.30	1.20
CMASN.04	7.16	29 ·93	16.34	4 5·75	0.82
CMASN.06	8.90	26.14	18.94	45·57	0.45
CMASN.07	8.30	27·94	20-29	43·11	0-36
CMASN.10	11.40	20-41	15.17	51.52	1.50
CMASN.11	8.04	30-14	12.56	48.91	0.35
CMASN.12	9-26	21.21	12.82	54.35	2.26

TABLE I

*Based on the measured weights of oxides and carbonate used in mixtures, corrected for CO_2 and Na loss during firing.

composition was prepared from desired amounts of high-purity powdered oxides and carbonate (CaCO₃), with sodium added as Na₂O·2SiO₂ to reduce Na volatilization during firing. Each mixture was ground in alcohol to a fine powder, fired for 2 h at 1600 °C, and quenched to a glass. Na₂O volatilization during firing (0.001 g/h at 1600 °C, on average) was monitored and the bulk composition was recalculated accordingly. Each mixture was fired twice and ground three times. Glass powders were used as starting materials in all experiments.

Attainment of equilibrium

Equilibrium cannot be proved in the experiments in this study because the experiments were not reversed. However, it has been shown, on the basis of reversal data from experiments in the CMAS system (Presnall *et al.*, 1978; Sen & Presnall, 1984; Liu & Presnall, 1990), that for the phases observed in the experiments reported here, a period of several hours is adequate to establish reversals of phase boundaries at liquidus temperatures. All experiments in this study were of a minimum duration of 48 h.

A more rigorous assessment of equilibrium in an experiment is a measure of the compositional homogeneity of phases that exhibit variable composition. In the experiments reported here, glass and garnet compositions are homogeneous, whereas pyroxenes and feldspar exhibit variable degrees of heterogeneity. At the outset of this study, experiments were made for 24 h. Pyroxenes in runs of this duration exhibited severe heterogeneity, with

standard deviations (2σ) for Al_2O_3 , the most heterogeneous component, often >2 wt.%. Run times of 48, 72, and 120 h were tried, with a marked improvement in pyroxene homogeneity between 24 and 48 h (e.g., standard deviations for $Al_2O_3 < 0.5$ wt.%). However, no improvement was noticed for run times longer than 48 h. Temperature is also an important factor in attaining homogeneous phases. Pyroxenes in experiments at less than ~1400 °C were consistently more heterogeneous in all components than those at higher temperatures.

ANALYTICAL TECHNIQUES

Coexisting phases in all run products were identified by back-scattered electron imaging (BEI) and energy-dispersive spectrometry (EDS) with a JEOL model 8600 Superprobe. Wavelength-dispersive spectrometry (WDS) was used for quantitative analysis of phase compositions. On the basis of replicate analyses of standards as unknowns before each analytical session, all elements are reproduced to within a minimum precision of 1% relative deviation. Analytical working conditions for WDS analyses and special problems associated with the analyses are discussed below for all phases.

Glass

Glass analyses were made only if glass was present in an area > 10 μ m in diameter, and at least 10–15 μ m from quench crystals. These criteria were set to minimize the chances of interference with crystals beneath the sample surface and to minimize the effects of quench crystallization. A quench form of a high-calcium pyroxene was present in nearly all experiments as overgrowths on other phases, as feathery crystallites, or as discrete grains. These were readily identifiable by BEI and/or analysis because their compositions are significantly different from equilibrium clinopyroxene (Al₂O₃>14 wt.%). The effect of quench crystallization on glass composition was determined empirically in an experiment that displayed large quench-free regions at one end of the charge and regions of abundant quench crystallization at the other. The composition of glass > 10–15 μ m from the quench crystals was unaffected by quench crystallization. Most analyses were made in glass areas well in excess of this minimum standard.

A 10-nA beam current with a 15-kV accelerating voltage was used in all glass analyses. A broad beam spot of 10-30 μ m was used wherever possible to minimize sodium migration during analysis, although it was often necessary to use a 1-5 μ m spot size. Data were acquired for 30-40 s for all elements, with Na analyzed first. The theoretical quantification procedure, Phi-Rho-Z (Heinrich, 1986), was found to reproduce a set of synthetic glass standards used as unknowns better than other quantification procedures. Generally, 8-10 spots from different parts of a run could be analyzed to determine the average glass composition. Glass compositions were found to be homogeneous in all runs, with typical standard deviations (2σ) on the order of 0.05 wt.% for Na₂O to 0.50 wt.% for SiO₂, with all other oxides falling within this range.

Plagioclase

Because plagioclase in this study contains up to 5 wt.% Na₂O, steps were taken to minimize sodium migration. A 10-nA beam current with a 15-kV accelerating potential was used in all plagioclase analyses. A spot size of 5–10 μ m was used wherever possible, although a 1- μ m spot was often necessary. Data were acquired for 30–40 s for all elements, with Na

analyzed first. An analysis was accepted if the total was between 99 and 101%. Generally, 8–10 analyses of different crystals were used to determine the average plagioclase composition in a run. Data were corrected with the Bence-Albee correction procedure, using the alpha coefficients of Albee & Ray (1970).

Pyroxenes

All pyroxenes were analyzed with a $1-\mu m$ spot size, 20-nA beam current, and 15-kV accelerating potential. Data for all elements were acquired for 40 s and were corrected using the Bence-Albee correction procedure. An analysis was accepted if the total was between 99 and 101% and if the structural formula was within $3\cdot96-4\cdot04$ cations per six oxygen atoms.

Pyroxenes presented a special analytical problem because they were observed to be the most heterogeneous phase. The heterogeneity was not systematic. Although some sector zoning was observed, zoning tended to be patchy and irregular. Furthermore, within a given run, crystal cores were not consistently of similar composition relative to crystal rims, except at the lower run temperaures in the plagioclase stability field where the cores were often highly aluminous. Because of this variation, 10–30 spots, each from a separate crystal, were analyzed in a given run. Crystals in the 10–20 μ m range were preferred for analysis because they generally displayed less heterogeneity than larger crystals. In large crystals (> 30 μ m), margins were analyzed rather than cores, as the margins should have had the best chance of achieving compositional equilibrium with the liquid. Highly aluminous cores in pyroxenes from the plagioclase field were avoided and not included in averages. Pyroxenes in runs made at < 1400 °C displayed the highest degree of heterogeneity, with standard deviations (2σ) generally between 0·3 and 1·0 wt.% for all elements except Na. At higher temperatures standard deviations for these elements were generally on the order of 0·1–0·5 wt.%.

Other phases

Forsterite, garnet, and spinel were homogeneous and presented no special analytical problems. A $1-\mu m$ beam size and a 20-nA beam current with a 15-kV accelerating potential were used in all analyses. Data were acquired for 40 s for all elements and were corrected with the Bence-Albee correction procedure.

DATA

Run conditions and phase compositions for all experiments used in this study are presented in Table 2. Analytical uncertainty, reported as two standard deviations, is also listed for each oxide in each phase. Experiments for melting along the lherzolite solidus in the CMAS system from 1 atm to 14 kbar are from Presnall *et al.* (1979), and at 20 kbar are from J. D. Hoover (unpublished experiment). Phase compositions were reanalyzed for this study, and are included in Table 2. Milholland & Presnall (1989), also working in the CMAS system, located a six-phase (fo + opx + cpx + sp + gt + liq) P-T invariant point at 30 kbar and 1575 °C, and the observed phase compositions are also included in Table 2. We have used the data from the CMAS system in conjunction with our new data in the CMASN system to regress smoothed P-T-X surfaces to each oxide in each phase to determine the compositions of all coexisting phases at a chosen pressure and temperature within the range (interpolation), and to some degree outside the range (extrapolation), of the experimental data.

Figure 2 shows interpolated and extrapolated molecular normative liquid compositions projected from diopside onto the complementary ternaries FO-SD-PL and FO-PL-SX

[where FO is forsterite, SD is silica deficiency (2Ne), PL is plagioclase, and SX is silica excess]. This plotting method, developed by Chayes (1985), has the advantage that the SD and SX apices are antithetic so that variations in Na ,O and SiO, contents of liquids in either ternary produce essentially proportional shifts on the diagram. There is some deflection of projected traces of liquid composition across the plane of critical silica undersaturation, but they are minor for compositions near the central portion of the diagram. This plotting method is utilized throughout the remainder of this study. The solid circles in Fig. 2 are experimentally determined liquid compositions. Shown as narrow lines are the traces of selected isobarically univariant melting curves, and contours for percent Na₂O in the liquid. as determined in the regression procedure. The thick lines represent the traces of liquid compositions along the plagioclase to spinel and spinel to garnet lherzolite P-T univariant curves. For any liquid composition within the domain of the model data set, the compositions of the four coexisting phases are known. Therefore, the model data set encompasses melting in a large portion of the plagioclase lherzolite field, and the entire pressure range of the spinel lherzolite field applicable to model upper-mantle lherzolite. With the resultant model data set we quantitatively determine the melting behavior of simplified lherzolite

Data interpolation and extrapolation

A second-degree polynomial of the form

$$X_{i}^{i} = \alpha + \beta P + \chi P^{2} + \delta P T + \varepsilon T + \phi T^{2}$$
⁽¹⁾

		CaO	MgO	Al ₂ O ₃	SiO2	Na ₂ O	Total
			1 Atmospher	re			
1-9†	Glass (8)	15-6 (0-3)‡	12.4 (0.3)	158 (0-4)	55.5 (0.7)		99-3 (0-6)
1242 °C, 48 h	Cpx (20)	19-7 (2-2)	22.5 (2-0)	2.53 (0.4)	54.9 (0-6)	—	99-6 (0-5)
fo + en + di + pl + hq	Pig (15)	4.27 (0.7)	35-9 (1-0)	1.08 (0.4)	58 3 (0-3)		99-6 (0-5)
			7 kbar				
701-12	Glass (10)	11.1 (0.2)	98 (0-3)	17.3 (0-3)	56-5 (0-6)	4.27 (0-1)	99-0 (0-4)
1225 °C, 50 h	Cpx (20)	19.2 (1.2)	22.0 (18)	3.56 (0.7)	54.9 (0.9)	0-28 (0-04)	100-0 (0-6)
fo + en + di + pl + liq	Opx (15)	2.61 (0.6)	368 (05)	2.16 (0.3)	58-2 (0-5)	0-05 (0-01)	99.8 (0.8)
	Plag (8)	114 (0-6)	044 (0-2)	28.6 (0.4)	55-0 (0-5)	4.80 (0-3)	100-2 (0-5)
702.10	Glass (8)	12.2 (0.3)	107 (03)	18-0 (0-1)	54.8 (0-4)	3-08 (0-2)	98.8 (0-3)
1245 °C, 48 h	Cpx (20)	19-0 (0-9)	21.8 (0.7)	3.57 (0.7)	548 (0-8)	0-23 (0-05)	99.4 (0-5)
fo + en + di + pl + liq	Opx (16)	2.57 (0-4)	36-1 (0-6)	2.60 (0.6)	58-1 (0-4)	0-03 (0-01)	99-4 (0-6)
	Plag (8)	14-0 (0-5)	043 (01)	30-5 (0-4)	52.2 (0.7)	3.54 (0-3)	100-6 (0-5)
122-9†	Glass (8)	15-1 (0-1)	14.5 (0.2)	19-1 (0-3)	50-5 (0-3)		992(03)
1285 °C, 48 h	Cpx (16)	18.8 (1-0)	22.4 (0.9)	4.88 (0-8)	53.5 (0.9)		99.6 (0.6)
fo + en + di + pl + liq	Opx (16)	2.49 (0.3)	36-0 (0-7)	4.68 (1-0)	56.4 (1.4)	-	99-6 (0-6)
			9 kbar				
901-12	Glass (8)	10-7 (0-2)	10-1 (0-3)	18.9 (0-5)	53.8 (0.3)	5-15 (0-2)	98-7 (0-3)
1240 °C, 50 h	Cpx (16)	191 (0-8)	216 (0-8)	3.82 (0.6)	54-6 (0-5)	0-45 (0-1)	99-6 (0-6)
fo + en + di + pl + liq	Opx (16)	2 66 (0-3)	36-5 (1-3)	3-07 (0-6)	57.4 (0-8)	0.10 (0.02)	99-8 (0-9)
	Plag (8)	11.3 (0.4)	045 (0-2)	28.7 (0.5)	55.1 (0.6)	4-98 (0-3)	100 5 (0.8)
911-10	Glass (8)	12.7 (0-1)	11.8 (0.5)	18-9 (0-5)	52-9 (0-5)	2.63 (0-1)	98.9 (0.4)
1265 °C, 50 h	Cpx (20)	19-1 (1-4)	21.7 (1.1)	3-96 (0-7)	54.7 (0-8)	0.27 (0.05)	99-8 (0-5)
fo + en + di + pl + liq	Opx (16)	2-64 (0-4)	35-8 (0-7)	3.26 (0-6)	58-0 (0-6)	0-05 (0-01)	99-7 (0-6)
	Plag (8)	14.6 (0.5)	041 (0-2)	30-7 (0-6)	51.3 (0-7)	3·49 (0·4)	100-4 (1-2)
122-1, 9-3 kbar	Glass (6)	15-0 (0-4)	14.6 (0-1)	20-2 (0-4)	49-4 (0-3)		99·2 (0·3)
1302 °C, 48 h	Cpx (16)	19-7 (0-5)	20-2 (0-8)	8-52 (0-9)	51.4 (0.8)	—	99.8 (0-6)
fo + en + di + pl + sp + liq	Opx (16)	2-03 (0-2)	35-0 (0-4)	8-57 (0-9)	54.3 (0.7)		99-9 (0-6)

 TABLE 2

 Experimental conditions, run products, and phase compositions*

TABLE 2—continued

		CaO	MgO	Al ₂ O ₃	SiO ₂	Na ₂ O	Total
			10 kbar				
1002-10	Glass (10)	12.1 (0-3)	11.6 (0.2)	19-5 (0-3)	53.4 (0.5)	3.47 (0.1)	100-1 (0-7)
1280°C, 60 h	Cpx (12)	17.9 (0.9)	21.3 (0.6)	577 (05)	54·3 (0·5)	037 (01)	99.7 (0.6)
10 + en + al + pl + liq	Plag (8)	13.2 (0.7)	019 (01)	306 (06)	52-0 (0-8)	3.74 (0.3)	99·8 (03) 99·7 (0-6)
1101-12	Glass (8)	10-3 (0-2)	11 kbar 10-2 (0-4)	19-7 (0-4)	54-0 (0-6)	5.54 (0.2)	998(0-7)
1255 °C, 50 h	Cpx (20)	16-8 (1-9)	22.9 (1.9)	4.94 (0.9)	54 5 (0-8)	0-55 (0-1)	99.7 (0-7)
fo + en + di + pl + liq	Opx (16) Plag (8)	2·83 (0·4) 11·1 (0·5)	35·8 (0·6) 0·31 (0·2)	3·81 (0·4) 28·7 (0·5)	57·4 (0·3) 55·1 (0·4)	0·10 (0·01) 5 26 (0·3)	99-9 (0-6) 100-5 (0-6)
116-3+	Glass (8)	14-9 (0-2)	16-8 (0-2)	19-2 (0-2)	49-3 (0-2)		100-2 (0-3)
1350°C. 48 h	Cpx (20)	19-3 (0-5)	20-2 (1-0)	9.5 (1.3)	51.4 (0.8)	_	100-4 (0-4)
fo + en + di + sp + liq	Opx (20)	2.17 (0-2)	34.6 (0.5)	9·49 (1·3)	53.9 (1.3)	—	100-2 (1-3)
1203-10	Glass (12)	12.2 (0.1)	12 kbar 12.2 (0.5)	21.5 (0.3)	50-3 (0-4)	1.50 (0-1)	00.8 (0-6)
1205 10 1295°C 60 h	$C_{DX}(20)$	17.5 (1.8)	20-9 (1-6)	$\frac{213}{7.73}(0.3)$	50-5 (0-4)	D49 (01)	100-0 (0-8)
$f_0 + e_0 + d_1 + n_1 + h_0$	Opt (20)	2.41 (0.5)	34.1 (0.5)	7.11 (0.6)	56-1 (0-5)	0.08 (0.02)	99.8 (0-6)
	Plag (10)	13.4 (0-7)	018 (01)	31.1 (0.9)	517(1.1)	3-98 (0-4)	100-4 (0-8)
1201-06	Glass (12)	13.9 (0.2)	13-9 (0-4)	20-9 (0-3)	49.7 (0-2)	1-69 (0-1)	100-1 (0-5)
1345°C, 60 h	Cpx (30)	17.3 (1.7)	20-7 (1-8)	9.33 (1.5)	52.1 (1.1)	0-26 (0-04)	99.7 (0-8)
fo + en + di + sp + liq	Opx (30)	2.17 (0.5)	33.3 (0.8)	9-36 (1-2)	54-6 (0-8)	0-04 (0-01)	99-5 (0-7)
1202.10	Class (10)	11.4 (0.2)	13 kbar	21.0 (0.5)	61.1 (0.7)	4.22 (0.1)	100.2 (0.8)
1302°10	$C_{\text{DIASS}}(10)$	16-9 (1-7)	214 (1.4)	7.86 (0-9)	53.6 (0.8)	4-23 (0-1) 0-49 (0-1)	100-2 (0-8)
$f_0 + e_1 + d_1 + p_1 + h_0$	Opt (16)	2.68 (0.4)	339 (0.5)	7.47 (0.6)	561 (04)	0.09 (0.01)	100-3 (0-5)
io ; •ii ; •ii ; pi ; iiq	Plag (16)	13.1 (0.8)	013 (01)	30-5 (0-6)	52.4 (1 2)	4-08 (0-5)	100-3 (1-0)
	a (0)		14 kbar			1 22 (2.1)	
1400-04	Glass (8)	11-0 (0-2)	118 (0-3)	21.5 (0.2)	51-5 (0-0)	4-39 (0-1)	100-2 (0-7)
$f_{0} \pm e_{0} \pm d_{1} \pm s_{0} \pm lia$	Opt (14)	2.36 (0.6)	33.6 (1.4)	9-62 (0-8)	524 (02)	0-09 (0-01)	100-1 (0-3)
	Chara (9)	120 (00)	120 (10)	20.8 (0.5)	54 5 (0 6)	266 (0.1)	100 4 (1 1)
1365°C 90 h	Cor (16)	12.9 (0.2)	21-0 (1-6)	20°8 (0°3) 9°52 (0°8)	51.9 (0.6)	0-40 (0-05)	99-8 (0-9)
$f_0 + e_1 + d_1 + s_2 + h_2$	Opx(10)	2.37 (0.4)	33.7 (0.6)	9.59 (0-6)	54.2 (1-0)	0-07 (0-01)	100-0 (0-7)
1401-06	Glass (6)	136 (0-2)	15.2 (0-2)	20-7 (0-4)	49-4 (0-6)	145 (0-1)	100-4 (1 1)
1370 °C. 54 h	Cnx (14)	171(11)	21.1 (1.1)	9.58 (0-7)	52-0 (0-7)	0.27 (0.05)	100-1 (0-7)
fo + en + di + sp + liq	Opx (14)	2.32 (0.3)	33.7 (0.5)	9-55 (0-7)	54.4 (0.7)	0-05 (0-01)	100-1 (0-7)
44 17 66		0.0 (0.2)	17 kbar	216 (0.6)	510(0.6)	5.22 (0.2)	100 2 (0.8)
1390°C 45 h	Glass (8)	9-9 (0-3) 15-0 (1-6)	12-0 (0-5) 21-1 (1-4)	21.2 (0.2)	51.9 (0°0) 52.7 (0-6)	5-52 (0-2) 0-97 (0-1)	99-6 (0-5)
$f_0 + e_0 + d_1 + s_0 + liq$	Opx (16)	2.49 (0-6)	33.1 (0.6)	9.71 (0.6)	54.2 (0.3)	019 (0-01)	99·7 (0·5)
1701-06	Glass (6)	13-0 (0-1)	16.7 (0-2)	19-9 (0-2)	49-6 (0-3)	1.36 (0.1)	100-6 (0-4)
1420 °C. 50 h	Cnx (20)	163 (10)	21.6 (0.9)	971 (08)	51.8 (0.6)	0.28(0.03)	99·7 (0·5)
fo + en + di + sp + liq	Орх (16)	2.39 (0.3)	33.6 (0.5)	9-71 (0-5)	54-0 (0-5)	0-05 (0-01)	998 (0-7)
2008.03		10.2 (0.1)	20 kbar	20 ((0.1)	60 L (0 C)	106 (0.1)	100.2 (0.5)
2008/03 1424 °C 120 h	Glass (8)	10-2 (0-1)	14.4 (0.2)	20-6 (0-1)	50-1 (0-6)	490 (01)	100-2 (0-5)
$f_{424} = C_1 + I_2 + I_1 + $	$O_{\text{D}x}(15)$	2.29 (0.4)	33.6 (0.6)	10-0 (0-9)	53.7 (0-9)	0.92(0.1) 0.17(0.02)	99·8 (0·8)
2002-04	Glass (7)	11.0 (0.3)	163 (06)	20-0 (0-1)	49.2 (0.6)	2.70 (D-1)	100-1 (0-4)
1440°C 48 h	Cnx(12)	147 (1.2)	$22 \cdot 3$ (1.1)	10-0 (0-4)	52.7 (0.6)	0-63 (0-02)	100-3 (0-6)
fo + en + di + sp + liq	Opx (12)	2 27 (0-3)	33.5 (0.3)	9-83 (0-6)	54 6 (0-4)	013 (001)	100-3 (0-5)
2001-06	Glass (8)	13.2 (0.2)	17.7 (0.5)	19.5 (0-3)	48-4 (0-6)	1.15 (0.1)	100-0 (0-6)
1455°C, 72 h	$C_{DX}(14)$	15-8 (0-7)	22-0 (0-6)	10-0 (0-4)	52.4 (0.5)	0-31 (0-05)	100-5 (0-5)
fo + en + di + sp + liq	Opx (12)	2.38 (0-1)	33-6 (0-6)	9.72 (1.2)	54.5 (0-8)	0-05 (0-01)	100-3 (0-8)
66-20-38	Glass (6)	14.2 (0-2)	19-4 (0-4)	18-4 (0-3)	48.3 (0-3)		100-3 (0-4)
1470 °C, 48 h	Cpx (15)	16-4 (0-6)	22.4 (0.7)	10-0 (0-9)	51-3 (0-5)		100-1 (0-5)
fo + en + di + sp + liq	Opx (16)	2.58 (0.2)	34-1 (0-5)	987 (07)	53-6 (0-5)		100-2 (0-6)
2202.04	0	110 (0.0)	23 kbar	10 6 10 11	10 5 15 5	A # / / · · ·	100 6 10 -
2303-04	Glass (8)	14.2 (0-3)	181 (0-6)	19.5 (0.4)	48 5 (U6) 53.2 (0.5)	2.26 (0-1)	100-5 (0-7)
1400 C, 14 B fo⊥en+di⊥en+lie	Opt (15)	1472 (U8) 2.26 (0-1)	22"4 (0"0) 33.6 (0-3)	10-1 (0-3) 10-0 (0-6)	52.2 (U.S) 53.8 (D.S)	071 (01) 015 (0-01)	ንን ሀርዓ 00-0 (በ-4)
o ren tertertertig		120 (01)					100 4 (0 4)
2311-07 1490 °C 70 h	Cox (15)	13-0 (0-2)	18'4 (U·2) 22.4 (0-5)	19+2 (0·2) 10-2 (0-5)	48·4 (UJ) 57.1 (AP)	1.37 (0-1) 0-36 (0-05)	100-4 (0-6) 00-0 (0-6)
$f_0 + e_0 + d_i + s_0 + lio$	Opx (15)	2.36 (0-1)	33.5 (0.3)	9-94 (0-5)	53.7 (0-4)	0-07 (0-01)	99-6 (0-5)
	~P~ (12)				55. (0 -)		

		CaO	MgO	Al ₂ O ₃	SiO 2	Na ₂ O	Total
			27 kbar				
2702-03 1507 °C, 72 h fo + en + di + sp + liq	Glass (6) Cpx (11) Opx (10)	9·80 (0·2) 11 1 (0·5) 2·15 (0·1)	17·6 (0·3) 22.8 (0·5) 33·1 (0·3)	19-1 (0-2) 10-5 (0-2) 10-3 (0-3)	48 9 (0·2) 53·7 (0·3) 54·3 (0·3)	4-63 (0-2) 1-21 (0-1) 0-31 (0-02)	100-0 (0-5) 100-3 (0-4) 100-2 (0-4)
2701-04 1518°C, 72 h fo+en+di+sp+lug	Glass (8) Cpx (12) Opx (16)	11-0 (0-2) 12-2 (0-9) 2-33 (0-1)	18·7 (0·1) 23·7 (1·0) 33·0 (0·4)	18·8 (0·2) 10·5 (0·7) 10·3 (0·6)	48·5 (0·3) 53·2 (0 ·6) 54·3 (0 · 6)	3·30 (0·2) 0·86 (0·1) 0·19 (0·02)	100-3 (0-6) 100-5 (0-5) 100-1 (0-5)
2701-07 1535 °C, 72 h fo + en + di + sp + liq	Glass (8) Cpx (10) Opx (10)	12·5 (0·1) 13·1 (0·7) 2 45 (0·1)	20·8 (0·2) 23·7 (0·7) 33·1 (0·4)	18·3 (0·2) 10·5 (0·4) 10·4 (0·5)	47 6 (0-5) 52·4 (0-6) 54·0 (0-5)	1·24 (0·1) 0·39 (0·05) 0·09 (0·01)	100-4 (0-7) 100-1 (0-4) 100-1 (0-7)
	• • •		30 kbar				
3002-03 1531 °C, 72 h fo + en + di + sp + liq	Glass (6) Cpx (20) Opx (20)	9-81 (0-1) 10-1 (0-9) 2-14 (0-4)	18·7 (0·2) 24·6 (1·0) 32·9 (0·7)	185 (0-3) 107 (0-5) 106 (1-0)	49-1 (0-7) 53-3 (0-5) 53-8 (1-0)	4·25 (0·2) 1·20 (0·2) 0·27 (0·05)	100-4 (1-3) 99-9 (0-5) 99-7 (0-6)
562-11 1575°C, 72 h fo + en + dı + sp + gt + lıq	Glas (11) Cpx (15) Opx (10) Garnet (14)	13.5 (0-2) 13.8 (0-6) 2.83 (0-1) 5.43 (0-1)	22 1 (0·2) 23·7 (0·6) 32·9 (0·3) 25·2 (0·4)	17-0 (0-2) 10-9 (0-9) 10-6 (0-3) 25-2 (0-2)	47·3 (0·5) 51·4 (0·8) 53·6 (0·3) 44 2 (0·3)	 	99-9 (0-3) 99-8 (0-3) 99-9 (0-3) 100-0 (0-4)
			32 kbar				
$3202 \cdot 11$ 1580 °C, 50 h fo + en + di + sp + liq	Glass (8) Cpx (16) Opx (16)	11·4 (0·1) 11·1 (0·6) 2 37 (0·2)	22-0 (0-3) 24-3 (0-6) 33-0 (0-4)	174 (03) 108 (04) 106 (04)	47-5 (0-5) 52-7 (0-4) 53-7 (0-6)	2-00 (0-1) 0-81 (0-1) 0-23 (0-03)	100-3 (0-9) 99 7 (0-8) 99-9 (0-6)
			34 kbar				
3403-11 1580 °C, 50 h fo + en + d1 + gt + sp + liq	Glass (8) Cpx (12) Opx (12) Garnet (8)	11.4 (0-1) 10-9 (0-7) 2.29 (0-1) 5.08 (0-3)	22-0 (0-3) 24-7 (0-5) 33-4 (0-5) 25-5 (0-3)	16-5 (0-2) 10-7 (0-2) 9 76 (0-5) 24-9 (0-3)	48-0 (0-4) 52-6 (0-4) 53-9 (0-5) 44-1 (0-2)	2·18 (0·1) 0·84 (0·1) 0·20 (0·03)	100-1 (0-6) 99-7 (0-5) 99-6 (0-6) 99-6 (0-5)
3402·11 1585 °C, 52 h fo + en + di + gt + qu	Quench (20) Cpx (16) Opx (16) Garnet (10)	11.6 (1.1) 10.5 (0.9) 2 42 (0.2) 4 59 (0.5)	23·1 (13) 26·2 (1·1) 34·7 (0·7) 25·8 (0·6)	15·1 (0·5) 8·42 (0·6) 7·20 (0·9) 25·2 (0·3)	48 4 (0-7) 54·2 (0-5) 55 8 (0 -9) 44·6 (0-3)	1 18 (05) 085 (01) 023 (003)	99-4 (1·1) 100-2 (0-6) 100-3 (0-9) 100-2 (0-6)
			35 kbar				
3503-11 1594 °C, 50 h fo + en + di + gt + sp + liq	Glass (8) Cpx (14) Opx (14) Garnet (8)	10-9 (0-2) 10-7 (0-8) 2-37 (0-1) 4-90 (0-1)	22·2 (0·3) 25·0 (0·6) 33 1 (0·6) 25·8 (0·3)	16·2 (0·3) 10·3 (0·8) 10·0 (0·5) 24·9 (0·1)	48·4 (0·5) 53·0 (0·5) 53·9 (0·6) 44·4 (0·3)	2 70 (01) 086 (01) 024 (003)	100-4 (0-5) 99-9 (0-7) 99-6 (0-9) 100-0 (0-5)

TABLE 2-continued

* Information listed for each pressure is run number, temperature, duration, and assemblage where fo is forsterite, opx is orthopyroxene, cpx is clinopyroxene, pig is pigeonite, plag is plagioclase, sp is spinel, gt is garnet, liq is liquid, and qu is quench. † Reanalyzed experiments from Presnall *et al* (1979).

Numbers in parentheses are analytical uncertainties reported as two standard deviations.

§ Reanalyzed experiments from J.D. Hoover (unpublished experiments, 1982).

Data from Milholland & Presnall (1989).

with pressure (P) in kbar and temperature (T) as $T/10\ 000$ in °C, was fitted empirically to each dependent oxide variable (i) in each phase (j) as a function of the independent variables of P and T. Regression coefficients (α , β , etc.) were calculated using least-squares multiple linear regression. Data from each stability field were treated independently with the exception that phase compositions along the plagioclase-spinel and spinel-garnet univariant curves were used as fixed boundaries for adjacent stability fields (i.e., phase compositions from adjacent stability fields must change continuously toward, and meet at, the transition curves). These curves emanate from P-T invariant points in CMAS at 9.3 kbar [plagioclase-spinel transition; Presnall *et al.* (1979)] and 30 kbar [spinel-garnet transition; Milholland & Presnall (1989)].

The P-T slope of the spinel-garnet univariant curve was determined by a linear regression of experiments along the boundary at 30, 34, and 35 kbar. No experiments lay directly on the



FIG 2. Molecular normative diagram showing the field of interpolated and extrapolated liquid compositions from 5 to 35 kbar, as projected from DI onto the complementary ternaries FO-SD-PL and FO-PL-SX [see text and Chayes (1985) for explanation of this type of diagram]. Solid circles show the compositions of experimentally produced glasses. Also shown are the traces of liquid compositions along selected isobars and traces of the plagioclase-spinel lherzolite and spinel-garnet lherzolite univariant curves (thick lines). At any point within the range of the data shown, the compositions of phases coexisting with the liquid are also known.

plagioclase-spinel univariant curve, so the slope was estimated from the 9·3-kbar invariant point in CMAS, together with experiments that bracket the boundary at 10, 11, 12, and 13 kbar in CMASN. Both the plagioclase-spinel and spinel-garnet univariant curves extend to higher pressures and temperatures with increasing Na₂O in the liquid phase (i.e., have positive Clapeyron slopes). Next, the compositions of phases from the plagioclase field were regressed, and were extrapolated to the plagioclase-spinel univariant curve. Phase compositions along the spinel-garnet univariant curve were determined by regression of phase compositions in experiments on the phase boundary at 30, 34, and 35 kbar. These calculated phase compositions along the plagioclase-spinel and spinel-garnet univariant curves were then used as fixed boundary compositions for adjacent stability fields. Phase compositions from the spinel field, together with the calculated phase compositions along the univariant curves, were then regressed.

After the first iteration using this approach, it became apparent that phase compositions can change greatly near the univariant curves, and that in most cases, the equation used in the regressions could not reproduce known phase compositions accurately. We therefore divided the spinel stability field into regions. Figure 3 is a P-T plot that shows our chosen divisions and also the positions of the plagioclase-spinel and spinel-garnet univariant curves. Phase compositions from each region were treated separately, with the exception that in the transitional regions (B and D) some of the results from regions A and C were included. For example, solutions were first determined for all of the phase compositions from 17 to 30 kbar. Next, calculated phase compositions at 15 and 30 kbar from region C were used as upper and lower fixed boundary compositions for regions B and D, respectively. This approach resulted in regressions that reproduced all the data more accurately, although there are some minor compositional discontinuities between each region. Because of



FIG. 3. Pressure-temperature plot showing the regions used in the regression procedure. Also shown are the positions of the plagioclase-spinel and spinel-garnet lherzolite univariant curves. Regression coefficients for each oxide in each phase are listed on a region-to-region basis in Table 3.

insufficient data, phase compositions from experiments in the garnet lherzolite stability field were not regressed.

In Table 3 regression coefficients are presented for each oxide in each phase for all regions, together with the average differences (in wt.%) between calculated and measured concentrations for each solution. Also listed are the P-T equations for the two univariant curves. Figure 4 is a projection from Na₂O in the liquid onto the P-T plane, illustrating the results of the regression procedure. Contours of 0, 3, and 6 wt.% Na₂O lie on a surface in P-T-X space that has been regressed to the experimental data (solid diamonds). The data points are shown with error bars representing approximate experimental uncertainties in pressure and temperature. Because no attempt at including the effects of uncertainties in pressure, temperature, or phase compositions was made in the regression procedure, the average differences listed in Table 3 reflect the sum of all analytical uncertainties.

A noteworthy feature in Fig. 4 is that the regression of the data results in concave-up contours of constant Na_2O and of the CMAS solidus in the plagioclase lherzolite stability field. Presnall *et al.* (1979) drew the plagioclase lherzolite solidus in CMAS as a concave-down curve, consistent with the shape of the spinel lherzolite solidus, and with other silicate melting curves. Because errors in pressure and temperature are not considered in the regression, the fit is non-unique and the shapes of the contours may be an artifact of the procedure. Rather than forcing the regression to produce contours with a preconceived shape, we have chosen to acknowledge that the fit results in unlikely contour shapes. Although this does result in a slightly concave-up shape to the solidus of model lherzolite in the CMAS and CMASN systems (see the section 'Melting behavior of simplified lherzolite' and Fig. 7), it affects none of the conclusions on the melting behavior of model lherzolite in subsequent sections.

The regression procedure described above was used to interpolate and extrapolate data for phases of variable composition (opx, cpx, plag, and liquid). On the basis of selected microprobe analyses from several experiments over a range of pressures (not included in Table 2), it was determined that spinel and forsterite have near-endmember compositions over a range of experimental conditions, with the exception of 0.05% CaO and 0.20% SiO_2 in spinel, and 0.35% CaO in forsterite.

VARIATIONS IN PHASE COMPOSITIONS DURING LHERZOLITE MELTING

Compositional variation in phases is independent of the bulk composition being melted as long as all the crystalline phases of lherzolite are present (forsterite, orthopyroxene, clinopyroxene, and one of plagioclase, spinel or garnet).

	α	β	x	δ	З	φ	σ†
			Region A (7–15 kbar)‡			
Melt							
CaO	- 46-0886	3-61665	-0-015	- 32.2104	83-1121	3336.47	0-17
MgO	713-166	19.8105	0-027434	-163·543	-13091·7	60000-7	0-25
Al ₂ O ₃	199-041	5.6314	0-011539	43·4408	- 3505-29	16343 7	0.27
SiŌ,	- 73-9413	-17.7391	-0-037893	144·8	3994-18	-23746.1	0-40
Na ₂ O	- 97.7664	- 3·57945	0-028673	31-0356	2543.55	- 14141	0-21
Plagioclase §							
CaŎ	1467-33	34.8	0.11052	- 300-316	- 26565.6	120398	0-38
Al ₂ O ₂	1850-6	40-301	0-18305	-352.132	- 32617·5	145558	0.68
SiÔ,	-2161.3	- 52.2601	-0-20253	453.85	40186.7	-181245	0.86
Na ₂ O	-1030-26	-20.5347	-0-065356	176.788	18354-2	-81187	0-18
Clinopyroxen	е						
CaO	- 69·698	- 4.94824	-0-047	42.2652	-458-056	440-344	0-31
MgO	383.727	11.6337	0-047225	-97.7516	-6442.51	28469.1	0-30
ALO.	1089.47	1.45313	-0.062884	-0-292283	-17722.4	71836	0.40
SIQ.	-1124.4	-9.40092	-0-010447	76.269	19602-8	-81368.1	0-30
Na ₂ O	- 100-387	-0-602857	0-005	4.84105	1682.76	- 7039.91	0-02
Orthonyroxer	10						
CaO	59-0844	1-51915	0-017588	- 14.2045	- 955-064	4083.50	0.10
MaO	507.729	9.51127	0-048549		- 7886.32	33186-3	010
ALO	1188.56	3-80524	-0.077703	- 17.2244	- 10586.8	80306.5	0.12
SiO.	- 1185-21	- 16.2099	-0-013482	130-656	21165.2	- 89790	0.30
Na.O	-10-5632	-0.012221	0-0011	0.097067	180-207	- 766.225	0-01
			Perion R (10 15 khar)			
Melt			Region D (10–13 koar)			
CaO	896-56	5-82936	-0-009579	-49-1172	14026	56077-1	0.40
MeO	935-502	5.4572	0-029026	- 53.7498	- 14881.2	60675	0.58
ALO.	-137.438	3.74379	0-021385	- 29.9198	2192-09	-7533.7	0.36
SiQ.	- 475.774	-7.30911	-0-032525	63-6429	8830-37	- 37158.4	0.42
Na ₂ O	-962.143	-12.9863	0-017239	103.771	16113.9	-67365.8	0.75
Clinonwoxan			•••••		10110 /	0,0000	
Can	688.507	5.761		- 14.6774	- 10670-0	42158.6	0-32
MaO	49.4002	2.05021	-0010030	10.7652	- 10020 9	42130.0	0.32
AL O	-40,4775	4.21472	0.003163	20.4672	129557	- 538011	0.18
SO SO	297.259	4.21473	0.061357	- 304072	- 1240.19	24957.7	0.16
$N_2 O$	- 363-336	- 1.09979	-0-001337	101.333	781991	- 34632'2	0.00
Na ₂ O	- 205-99	- 5 78828	-000405	32.0075	44104	-18239'3	0.03
Orthopyroxer	1e 224.027	3 333((0.007051	20 5701	2007.00	16620 7	0.16
	234.837	3.11/00	0-007051	- 29.3/81	- 3807.89	12239.1	013
MgU	5-04064	2 (0250	-0014524	42.2254	922-163	- 5181.96	0.22
AI ₂ U ₃	- 304.405	- 3.00339	-0026185	33.0024	4918.80	- 19390-9	0.26
SIU_2	24.422	12.1803	0.004146	- 94.8425	- 9393.09	39433.3	0.01
	- 34.423	-0135448	0-004146	048338	530-384	- 2070-5	001

TABLE 3

Regression coefficients for phases of variable composition*

			Region C (15–30 kbar)			
Melt			- 5 - V	- ,			
CaO	575·294	8.34909	0-050795	- 79 ·9923	- 9679-3	42106.75	0-23
MgO	1028-51	23.8731	0-153631	-214.545	- 18295.7	82026	0-32
ALO,	-405.444	-9.93017	-0-067131	89-8585	7643.16	- 34165	0-11
SiÓ	-470-533	-12·3489	-0-076294	109-643	9321-03	-41500-2	0-34
Na ₂ O	- 606-387	-9-32633	-0-056696	89.546	10626-2	-46746.8	0-20
Clinopvroxene							
CaO	779-931	11.4164	0-053741	-100-76	-12582.9	52421.6	0-28
MgO	108-198	2.40638	0-015271	- 19-8811	- 1578·74	6956-31	0-22
ALO,	15-0359	0-037045	-0-001931	0-732718	- 89.5347	277.798	0-06
SiÓ	-448.1735	-9-32378	-0-051652	82.064	8482·71	- 36171.6	0-18
Na ₂ O	- 243·389	-3-07466	-0-013131	26.9841	3994-25	-16495-3	0.05
Orthopyroxene							
CaO	48.9859	0-761731	0-003916	- 6.75031	- 789·336	3358-16	0-08
MgO	199.647	3.85785	0-022382	- 34·3408	- 2942-05	13032.7	0-14
ALO,	78·376	1.40387	0-006981	-11.3816	-1162.52	4861.64	0-07
SiÓ,	-85·2681	- 3·28624	-0-021918	29.8983	2506.29	-11236.71	017
Na ₂ O	-47·2815	-0-524386	-0.002127	4.66156	768.505	-3150-28	0-01
			Region D (.	30–35 kbar)			
Melt			5	,			
CaO	437.739	9.56613	0-086819	101-954	- 8144·48	39313.8	0-30
MgO	1006-65	25-0415	0.124438	-211.156	-18237	81537·2	0-27
Al,O,	- 352-377	-10-7254	-0-084191	101.666	7112·88	- 33606-6	0-08
SiÔ,	- 449.548	- 14-0344	-0-020584	99.5084	9364 22	-40673.8	0-36
Na ₂ O	-854.605	-1.215	-0-01344	19.41	12301.6	-45399.7	0-57
Clinopyroxene							
CaO	681-214	11-2628	0113516	-122.734	-11291.4	50405-7	0.10
MgO	- 28-033	1.74307	-0-001711	- 10-4699	314.519	-71.2612	0-23
Al ₂ O ₃	13-5439	-0-204202	-0-021252	9.68177	-21.7329	- 804 348	0-06
SiÔ,	-421-023	-9-61248	-0-060438	87.3473	8190-41	- 35749.4	0-03
Na ₂ O	-156-351	- 3.68031	-0-027029	36.3549	2983	-14137-8	0-04
Orthopyroxene							
CaO	64-003	0-838088	0-007195	8·48998	999-646	4208-41	0.10
MgO	198.632	3.1615	0-035018	- 34 ·5781	2799-5	12597.77	0-08
Al ₂ O ₃	-27.7026	1.60454	-0-007637	- 7·29796	175.334	153-503	0-06
SiŌ	103-012	-3·8213	-0-0138149	30-3172	2837·67	-12352.6	0-05
Na ₂ O	- 17·1686	-0988154	-0.00542	8.97503	467·437	- 2593·91	0-01

TABLE 3—continued

Plagioclase-spinel lherzolite univariant curve: $T = 1366 \cdot 44 - 12 \cdot 78P + 0 \cdot 69P^2$.

Spinel-garnet lherzolite univariant curve: T = 1494 + 2.67P.

* Regression coefficients for second-order polynomial equation of the form:

$$X_{I}^{i} = \alpha + \beta P + \chi P^{2} + \delta PT + \varepsilon T + \phi T^{2}$$

where X_i^i is concentration in weight percent of oxide *i* in phase *j*, *P* is pressure (in kbar), and *T* is temperature/10 000 (in °C).

†Average difference between regressed and observed values.

[‡] See Fig. 2 for pressure-temperature regions.

§Average MgO content of plagioclase is 03 wt.%.

Liquid

Figure 5 shows how each oxide varies as a function of Na₂O content in the liquid at representative pressures in the plagioclase (7 kbar) and spinel (20 kbar) fields, and over a small portion of the melting curve in the garnet field at 40 kbar (estimated from experiments at 40 kbar not included in this study). (For brevity, the terms plagioclase field, spinel field, and garnet field will be used to indicate lherzolite assemblages containing olivine,



FIG. 4. Pressure-temperature plot showing contours of weight percent Na₂O in the liquid as determined in the regression procedure. Diamonds represent experimental data points with representative error bars for pressure and temperature. Thick lines are the plagioclase-spinel and spinel-garnet lherzolite univariant curves.

orthopyroxene, clinopyroxene, and one of the aluminous phases.) Na_2O was chosen as the independent variable in these diagrams rather than temperature, to facilitate comparison between fields. In all cases, decreasing Na_2O reflects increasing temperature and degree of melting along lherzolite melting curves. With increasing temperature at constant pressure, CaO increases in the plagioclase and spinel fields, and decreases in the garnet field. MgO increases in all fields, whereas Al_2O_3 decreases in the spinel and garnet fields, but increases in the plagioclase field. In the plagioclase and spinel fields, SiO_2 decreases with temperature, whereas in the garnet field it increases. At constant Na_2O in the liquid, an increase in pressure results in a decrease in CaO and an increase in MgO across all fields. SiO_2 decreases with pressure throughout the plagioclase and spinel stability fields, but increases in the garnet field. Al_2O_3 increases moderately from the plagioclase to spinel fields (except in liquids with low Na_2O), but decreases from the spinel to garnet fields.

Decreasing SiO_2 with increasing temperature is counter-intuitive on normative projections such as Fig. 2, because increasing temperature produces a shift toward the silica apex along all melting curves. In the CMAS system, movement of a point toward the silica apex in the normative tholeiitic basalt tetrahedron (forsterite-diopside-anorthite-silica) obviously corresponds to increasing SiO₂. However, if Na₂O is added to the system, movement of a point toward the silica apex can result in a decrease in SiO₂ if Na₂O simultaneously decreases sufficiently. This occurs because the anorthite has a much lower SiO₂ content than albite. Let us consider the case of a point in the fo-di-pl-qz tetrahedron in which the plagioclase is pure albite. A second composition at the same location in which the plagioclase component is pure anorthite would have a lower SiO₂ content. The example can be extended to show that a certain amount of movement of a point toward the silica apex can cocur even though the SiO₂ content decreases.

Plagioclase

We have used the expressions listed in Table 3 to calculate an equilibrium expression for plagioclase coexisting with liquid between 7 and 13 kbar. Liquid compositions have been



FIG. 5. Variation diagram showing oxide trends (in wt.%) for liquids along lherzolite melting curves in CMASN at selected pressures in the plagioclase field (7 kbar), spinel field (20 kbar), and garnet field (40 kbar—estimated from experiments not included in Table 2). Decreasing Na₂O corresponds to increasing temperature along all melting curves.

speciated into the molecular components CaO, $CaAl_2O_4$, MgO, SiO₂, and NaAlO₂, based on the procedure of Bottinga & Weill (1972). Sisson & Grove (1993) have shown that these components work well for describing olivine–liquid equilibrium in natural basaltic liquids. With these components, the plagioclase–liquid equilibrium reaction is written as

$$Ab_{plag} + CaAl_2O_{4 \ lig} = An_{plag} + SiO_{2 \ lig} + NaAlO_{2 \ lig}.$$
 (2)

For an ideal solution model, this reaction has an equilibrium constant given by

$$K_{eq} = (X_{An} \times X_{SiO_2} \times X_{NaAIO_2}) / (X_{Ab} \times X_{CaAI_2O_4}).$$
(3)

For a thermodynamically based expression relating K_{eq} , P, and T, multiple regression of calculated equilibrium constants between 7 and 13 kbar gives

$$\log_{10} K_{eo} = -6.605 + (9629.57/T) + [0.058(P-1)/T]$$
(4)

where T is in degrees Kelvin and P is in bars. The weighted sum of the deviations squared for the regression was 0.003. The good fit of equation (4) to the calculated equilibrium constants suggests that an ideal solution model gives a good approximation for plagioclase-liquid equilibria, at least for the chosen components.

Figure 6 is a temperature-pressure plot that shows contours of K_{eq} calculated from equation (4), at pressures between 7 and 13 kbar. Also shown are two contours of CaO/Na₂O in the liquid that correspond to a range that encompasses liquids generated along the



FIG. 6. Pressure-temperature plot showing contours of plagioclase-liquid equilibrium constants as determined from the equation $\log_{10} K_{eq} = -6.605 + (9629.57/T) + [0.058(P-1)/T]$ where P is in bars and T is in K. Contours of constant CaO/Na₂O in the liquid are shown as dashed lines.

lherzolite solidus in CMASN at these pressures, and, in general, most natural basaltic compositions. This diagram illustrates that plagioclase-liquid equilibrium is sensitive to both temperature and pressure. At constant pressure, an increase in temperature leads to an increase in the CaO/Na₂O in the liquid and a more anorthite-rich plagioclase. However, an increase in pressure at constant temperature leads to lower CaO/Na₂O in the liquid and to a more albite-rich plagioclase. An additional relationship not evident from Fig. 6 is the correspondence, for a given CaO/Na₂O in the liquid, of a higher value of K_{eq} to a more anorthite-rich coexisting plagioclase. Thus, for a given liquid CaO/Na₂O, coexisting plagioclase compositions become more albite rich with increasing pressure and temperature.

These data are consistent with phase relationships in the albite-anorthite system at pressures up to 20 kbar (Lindsley, 1968) and with the results of melting studies of basalt at high pressure. For example, Bender *et al.* (1978) found that the composition of the first plagioclase on the liquidus of FAMOUS basalt 527-1-1 was more albite rich at 8 kbar (An₇₃, 1250 °C) than at 6 kbar (An₇₈, 1240 °C). In CMASN, plagioclase coexisting with liquid + lherzolite at 9 kbar and 1270 °C has a composition of An₇₅, whereas at 7 kbar and 1260 °C plagioclase has a composition of An₈₀.

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Anorthite-rich plagioclase (>An₉₀) has been observed as megacrysts in oceanic basalts (e.g., Donaldson & Brown, 1977). Our data at 7 and 9 kbar suggest that liquids with Na₂O contents of less than ~1%, and SiO₂ content >52%, would coexist with anorthite-rich plagioclase (>An₉₀). Such 'depleted' liquids could occur at shallow levels (< 30 km) beneath mid-ocean ridges or ocean islands, and if isolated from other liquids would fractionate very An-rich plagioclase (Duncan & Green, 1980a, 1980b). The existence of liquids of such a depleted nature has been postulated by several workers (Duncan & Green, 1980b; Sen, 1982; Elthon & Casey, 1985; Johnson *et al.*, 1990).

Pyroxene

Silica-undersaturated pyroxenes in the CMASN system are quaternary solid solutions involving the diopside component (Di—CaMgSi₂O₆), the enstatite component (En—Mg₂Si₂O₆), the jadeite component (Jd—NaAlSi₂O₆), and the Ca-Tschermak component (CaTs—CaAl₂SiO₆) in clinopyroxene or the Mg-Tschermak component (MgTs—MgAl₂SiO₆) in orthopyroxene. Mole fraction end-member components are calculated from structural formulae on the basis of cations per 6 oxygens using the following expressions:

CPX:
$$X_{En} = 1 - Ca - Na$$

 $X_{Jd} = Na$
 $X_{CaTs} = (Al - Na)/2$
 $X_{Di} = 1 - X_{En} - X_{Jd} - X_{CaTs}$
OPX: $X_{Di} = Ca$
 $X_{Jd} = Na$
 $X_{MgTs} = (Al - Na)/2$
 $X_{En} = 1 - X_{Di} - X_{Jd} - X_{MgTs}$.

The variations in these components in both clinopyroxene and orthopyroxene as a function of temperature and pressure during melting of lherzolite are described briefly below.

Clinopyroxene

In both the plagioclase and spinel fields an increase in temperature (degree of melting) at constant pressure produces a decrease in the Jd component, and an increase in the CaTs component. In the spinel field, within the uncertainty of our data, the Al_2O_3 content remains essentially constant as temperature increases. However, in the plagioclase field, the CaTs component increases rapidly relative to the decrease in the Jd component, so that the net effect is an increase in Al_2O_3 as temperature increases. For example, at 9 kbar the Al_2O_3 content increases from 4.3 to 8.2 wt.% with an increase in temperature from 1252 °C to 1302 °C. In both fields, at constant temperature, the Jd component increases in clinopyroxene with an increase in pressure, whereas the CaTs component decreases.

In the plagioclase field, an increase in temperature at constant pressure results in a decrease in the Di component and an increase in the En component. Conversely, in the spinel field, Di increases and En decreases with an increase in temperature at constant pressure. An increase in pressure at constant temperature results in an increase in the Di component and a decrease in the En component in the plagioclase field, and again, the opposite is the case in the spinel field.

Orthopyroxene

The Jd component is much less soluble in orthopyroxene than in clinopyroxene but behaves similarly with respect to pressure and temperature. An increase in temperature at constant pressure results in a decrease in the Jd component, and an increase in the MgTs component in both the plagioclase and spinel fields. The Al_2O_3 content of orthopyroxene in the spinel field is constant with increase in temperature and has nearly the same concentration as in clinopyroxene. In the plagioclase field, the MgTs component shows a rapid increase with temperature, comparable with that of CaTs in clinopyroxene. With increase in pressure at constant temperature the Jd component increases in orthopyroxene in both fields. The MgTs component increases in the plagioclase field, and decreases in the spinel field, with an increase in pressure at constant temperature.

In the plagioclase field, both the Di and En components decrease with increasing temperature at constant pressure, whereas in the spinel field Di increases and En decreases. An increase in pressure at constant temperature results in an increase in the Di component and a decrease in the En component in the plagioclase field, and a decrease in both components in the spinel field.

Our results for both clinopyroxene and orthopyroxene compositions along the lherzolite solidus in CMAS (0% Na_2O) are within experimental uncertainty of the values predicted from the calculated CaTs, MgTs, and En isopleths of Gasparik (1984) from 1 atm to 20 kbar.

MELTING BEHAVIOR OF SIMPLIFIED LHERZOLITE

Simplified model lherzolite

To discuss the melting behavior of mantle peridotite, a model mantle composition in the CMASN system must be chosen; however, no unique method exists for transforming a natural composition into CMASN components. We have constructed model lherzolite compositions that we feel are suitable CMASN analogs for 'depleted' to 'fertile' sub-oceanic mantle. First, the average mode of 128 abyssal peridotites was determined (the residues of melting to produce MORB) based on data presented by Dick et al. (1984), Dick (1989), and Johnson et al. (1990). This yielded a mode of 73.4% ol, 20.6% opx, 5.2% cpx, 0.75% sp, and 0.05% pl. We selected a liquid at 11 kbar on the plagioclase-spinel univariant curve as a reasonable CMASN equivalent of a liquid parental to average primitive MORB. Mineral compositions in equilibrium with this liquid and the mode listed above were then used to calculate a CMASN depleted mantle composition. Next, this depleted mantle composition was mixed with the 11-kbar liquid composition in the proportions 80:20, 90:10, and 95:5 to produce a set of model lherzolite compositions ranging from fertile to relatively depleted. This method is nearly the same as that used by Presnall & Hoover (1987), and our model lherzolite A is similar to their model lherzolite B. These compositions are listed in Table 4, and are compared with the CMASN equivalent of the estimates of upper-mantle peridotite compositions of Ringwood (pyrolite 3, 1975) and Hart & Zindler (hereafter H&Z) (1986).

Algebraic methods

Melting involving five phases in a five-component system is isobarically univariant. At a given pressure, the coefficients of a chemical equation involving all phases (four solids + liquid) and a suitable lherzolite bulk composition can be determined at any temperature along the portion of the univariant curve constrained by the data set (e.g., 0-6

		Simplified model inerzoille compositions					
	₽B ⁺	DP*	A	В	С	Pyrolite 3†	H&Z†
CaO	13.6	1.8	4.2	3-0	2.4	3.15	3.25
MgO	13.3	50-4	43-0	46.7	48·5	44.30	44 · 4 0
Al ₂ O ₃	20-9	2.8	6-4	4.6	3.7	4.30	4.10
SiÔ,	50-6	45-0	46-1	45-5	45.3	47.85	47·90
Na,O	1.6	0-02	0-3	0-2	0-1	0.40	0-35
DP:PB‡	—	—	80:20	90:10	95:05	_	—

Table 4

Simplified model lherzolite compositions

* PB-Model primary basalt; DP-model depleted peridotite.

† CMASN equivalent to pyrolite 3 (Ringwood, 1975) and estimated primitive mantle of Hart & Zindler (1986). Natural compositions are recast into CMASN components by transforming into normative components and multiplying normative phase proportions by end-member CMASN compositions.

[‡] The ratio of model depleted peridotite (DP) to model primary basalt (PB) used to calculate model herzolite compositions.

wt.% Na_2O in the liquid). We use the determinant method of Korzhinskii (1959) for balancing chemical equations.

As discussed by Presnall (1986), the coefficients of a balanced equation involving all phases and a lherzolite bulk composition are physically meaningful only if the bulk composition can be described as a linear, positive combination of the five equilibrium phases (i.e., the bulk composition can be described as liquid + lherzolite). If the liquid has a negative coefficient in the determinant, then the selected temperature lies below the solidus for the chosen bulk composition, but the reaction coefficients do not represent sub-solidus phase proportions. If one or more solid phases have negative coefficients in the determinant, then at that temperature a solid phase(s) has been lost to melting, and the reaction coefficients, again, do not represent phase proportions. Thus, by observing the temperature at which the coefficient for the liquid becomes negative, or at which that for a solid phase becomes negative, the solidus and phase-out temperatures and phase proportions can be uniquely determined for that bulk composition. In the temperature interval between these two extremes, where the bulk composition can be described as liquid + four-phase lherzolite, the determinant gives the phase proportions during lherzolite melting. We use this quantitative method to assess the melting behavior of simplified lherzolite in CMASN. In a forthcoming paper, we present a method for accurately identifying the nature of the lherzolite melting reaction in multicomponent systems involving several solid solutions.

Equilibrium melting of model lherzolite

Figure 7 shows equilibrium phase fields in a pressure-temperature isopleth for model lherzolite A. Solid lines on the diagram are determined and dashed lines are schematic. In the CMAS system, the sub-solidus transitions between plagioclase and spinel lherzolite and between spinel and garnet lherzolite are each defined by a univariant curve in P-T space (Presnall et al., 1979; Gasparik, 1984). When Na₂O is added, these curves are broadened to divariant regions (Fig. 7), and the cusps on the CMAS lherzolite solidus at 9.3 kbar (Presnall et al., 1979) and 30 kbar (Milholland & Presnall, 1989) are broadened to univariant curves. The sub-solidus transition regions are drawn in accordance with available experimental data on the transitions from both the CMAS system and natural compositions (Kushiro & Yoder, 1966; Green & Ringwood, 1967; O'Hara et al., 1971; Jenkins & Newton, 1979; O'Neill, 1981;



FIG. 7. Pressure-temperature isopleth for equilibrium melting of model herzolite A. Solid lines are determined from data in CMASN and dashed lines are inferred. Sub-solidus transition boundaries are estimated on the basis of experimental data in the CMAS system and on natural compositions (Kushiro & Yoder, 1966; Green & Ringwood, 1967; O'Hara et al., 1971; Jenkins & Newton, 1979; O'Neill, 1981; Gasparik, 1984). Labels give the stable phase assemblages within each region.

Gasparik, 1984). The position of the spinel to garnet lherzolite transition along the solidus at 33-33-5 kbar in the CMASN system, and at 30 kbar in the CMAS system, is higher in pressure than estimated by Gasparik (1984) in the CMAS system (22 kbar). Our data, and those of Milholland & Presnall, are the first experimental determinations of this transition along the solidus in these systems, and are consistent with an extension of the data from the sub-solidus in the CMAS system if the P-T slope of the transition becomes shallower as it approaches the solidus. Such a change in slope has been noted experimentally by O'Hara et al. (1971) and Green & Ringwood (1967) for natural compositions. The location of the spinel to garnet lherzolite transition along the solidus of pyrolite has been located by Green & Ringwood at 30 kbar. Further, the data of Takahashi (1986) along the solidus of natural spinel lherzolite KLB-1 constrains the transition to be above 25 kbar. Our data show that the addition of Na₂O to the CMAS system moves the transition to higher pressures. O'Neill (1981) and Nickel (1986) showed experimentally that the addition of Cr₂O₃ to the CMAS system also moves the transition to higher pressures, even beyond 35 kbar for moderately depleted and depleted mantle bulk compositions. O'Neill also calculated the effect of FeO on the transition, and found that for every 10 mol % Fe in olivine, the transition is shifted to lower pressure by $\sim 2-3$ kbar. When the offsetting effects of Na, Cr, and Fe are considered, our data in the CMASN system compare favorably with data from natural compositions.

The shapes of the cusps along the lherzolite solidus in CMASN are changed and accentuated relative to the CMAS system because the solidus follows along the plagioclase-spinel and spinel-garnet univariant lines, fo + opx + cpx + pl + sp + liq and fo + opx + cpx + sp + gt + liq, for short pressure intervals. Phase compositions along the univariant lines change with pressure, and the equations in Table 3, together with the methods described by Presnall (1986), have been used to determine the defining equations at several points along the lines (Table 5). For the plagioclase-spinel univariant line, Table 5 shows that the reaction is fo + opx + pl = cpx + sp + liq at pressures < 109 kbar and fo + pl = opx + cpx + sp + liq above this pressure. A singular point occurs at 10.9 kbar,

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P (kbar)	T (°C)	Reaction
Plag/spinel		
10	1308	0.09 opx + 0.69 pl + 0.22 fo = 0.86 lig + 0.05 cpx + 0.09 sp
12	1313	0.72 pl + 0.28 fo = 0.78 lig + 0.10 opx + 0.04 cpx + 0.08 sp
14	1323	0.69 pl + 0.31 fo = 0.66 liq + 0.23 opx + 0.04 cpx + 0.07 sp
Spinel/garnet		
32	1580	0.58 opx + 0.26 cpx + 0.16 sp = 0.14 lig + 0.16 fo + 0.70 gt
34	1585	0.53 opx + 0.31 cpx + 0.16 sp = 0.16 lig + 0.14 fo + 0.70 gt

Reaction coefficients along the plagioclase-spinel lherzolite and spinel-garnet lherzolite P-T univariant transitions

1309 °C, which defines the starting point for the univariant curve fo + pl = cpx + sp + liq. The position of this curve has not been located and is not shown in Fig. 4. The defining equation for the spinel-garnet univariant line is opx + cpx + sp = fo + gt + liq.

Figure 8 shows the compositions of liquids along the solidus and for varying melt percentages as projected from DI onto FO-SD-PL-SX. At <10.5 kbar, melting of plagioclase lherzolite proceeds to the point of exhaustion of either clinopyroxene (12% at 5 kbar to 18% at 9 kbar) or plagioclase (22% at 10 kbar to 27% at 10.5 kbar) over a small temperature interval of, on average, $\sim 5^{\circ}$ C. As shown in Fig. 8, this produces only a small range of liquid compositions; therefore, as pointed out by Presnall & Hoover (1987), melting of plagioclase lherzolite in CMASN is isobarically pseudo-invariant. Liquid composition is most sensitive to changes in pressure, with liquids moving toward the SX apex with decrease in pressure. At pressures less than ~ 8 kbar, liquids are quartz tholeiites, and above this they



FIG. 8. Molecular normative diagram showing the composition of liquids along the solidus, percent melting contours, and phase-out contours during equilibrium melting of model herzolite A, as projected from DI onto FO-SD-PL-SX. Thick lines show the traces of the plagioclase-spinel and spinel-garnet herzolite univariant curves. Thin lines show the traces of melting curves at selected pressures. Dashed lines are best estimates for melting of garnet herzolite.

are olivine tholeiites, a result similar to that found by Jaques & Green (1980) for melting of a pyrolite composition.

Figure 9 shows an enlargement of the low-temperature region along the solidus that results from the plagioclase to spinel lherzolite transition. At pressures from 11.6 to 15 kbar, the



FIG. 9. Pressure-temperature plot showing the solidus and percent melting contours for equilibrium melting of model herzolite A at pressures around the plagioclase-spinel herzolite univariant curve. The sub-solidus region is divided according to the stable herzolite assemblage. Dashed lines separating sub-solidus regions estimated as in Fig. 7. Thick solid lines represent the solidus. Thin solid lines show percent melting contours and first phase-out contours. Dash-dot lines show the estimated positions of second phase-out contours.

plagioclase-spinel univariant line is the solidus and forms an upper temperature limit for a sub-solidus region in which both plagioclase and spinel coexist. First, let us consider melting at 15 kbar. The sub-solidus assemblage is $f_0 + op_x + cp_x + sp$ (spinel lherzolite), and this is the lowest pressure at which melting occurs entirely within the spinel lherzolite stability field. Melting proceeds until the exhaustion of spinel at $\sim 23\%$. At 13 kbar the sub-solidus assemblage is plagioclase + spinel lherzolite and the solidus is the plagioclase - spinel univariant curve. Isobaric melting takes place according to the univariant melting reaction at constant temperature, and proceeds until plagioclase is exhausted. The degree of melting at which this occurs is given by the intersection of the spinel field melt percent contour with the univariant curve, which in this case is $\sim 5\%$. Further increase in temperature results in melting of spinel lherzolite until spinel is exhausted at $\sim 24\%$ melting; 11.6 kbar is the lowest pressure at which the univariant curve is the solidus. At this pressure, invariant melting proceeds until plagioclase is exhausted at 10% melting, after which melting of spinel lherzolite proceeds until spinel is exhausted. Between 10.5 and 11.6 kbar the sub-solidus assemblage is plagioclase lherzolite. Melting proceeds with increasing temperature until the univariant curve is reached. For example, at 11 kbar this occurs at 10% melting. Invariant melting then occurs because an additional phase, spinel, crystallizes while plagioclase continues to dissolve. Plagioclase is completely eliminated at $\sim 15\%$ melting, and melting of spinel lherzolite continues with increasing temperature until $\sim 25\%$ melting. At 10.5 kbar, melting of lherzolite proceeds until the nearly simultaneous exhaustion of plagioclase and spinel at 25% melting. By comparison, Presnall & Hoover (1987), starting from their more fertile model lherzolite A, found nearly simultaneous elimination of cpx and spinel at 9.6 kbar over an entirely invariant melting interval.

Figure 8 shows with increasing pressure, the compositions of liquids along the solidus of model lherzolite A between 11.6 and 15 kbar become increasingly deficient in normative silica. The Na₂O content of these liquids varies from 2.2% at 11.6 kbar to just over 6% at 15 kbar, and this reflects the transition from melting in the plagioclase lherzolite field, where Na₂O is relatively compatible ($D_{Na} \sim 0.30$), to melting in the spinel lherzolite field, where Na₂O is relatively incompatible ($D_{Na} \sim 0.05$). Between 15 and 31.5 kbar, melting of spinel lherzolite proceeds until spinel is exhausted at between 22 and 25% melting. Extrapolation of our data suggests that clinopyroxene is exhausted shortly thereafter, at ~ 26–28% melting. Figure 10, a plot of melt percent vs. temperature at 9, 20, and 30 kbar, further illustrates differences in melting behavior between the plagioclase and spinel lherzolite fields. At 9 kbar



FIG. 10. Temperature vs. melt percent diagrams for equilibrium melting of model lherzolite A at 9 kbar in the plagioclase lherzolite stability field, and at 20 and 30 kbar in the spinel lherzolite stability field.

(plagioclase lherzolite field) the amount of liquid produced with increase in temperature is nearly constant at $\sim 4\%/^{\circ}$ C. In the spinel lherzolite field, melting occurs over larger temperature intervals compared with plagioclase lherzolite melting (60° at 15 kbar to 16° at 30 kbar; see Fig. 7), with the first several percent of melting making up about half the temperature interval. This type of melting behavior near the solidus is consistent with that observed by Mysen & Kushiro (1977) for melting of natural lherzolite compositions. They attributed this behavior to the depolymerization effects of alkalis. Because sodium is relatively more compatible in the residue than in liquids in equilibrium with plagioclase lherzolite, this effect should not be as substantial as it is for liquids in equilibrium with spinel lherzolite, and this is consistent with the melting behavior in CMASN.

In the spinel lherzolite field, a wide range of liquid compositions is produced over a large temperature interval (Fig. 8), with much of the temperature variation occurring over the first few percent of melting. Therefore, melting of spinel lherzolite is not pseudo-invariant (Jaques & Green, 1980; Stolper, 1980; Fujii & Scarfe, 1983; Presnall & Hoover, 1987; Kinzler & Grove, 1992b). With increasing pressure, the range of liquid compositions produced between the solidus and the phase-out contour narrows (as does the temperature interval) and liquids along the solidus become less silica depleted. This is a result of an increase in D_{Na} from ~0.05 at 15 kbar to ~ 0.10 at 30 kbar as pyroxenes become richer in the Jd component. Thus, although initial spinel lherzolite melts are silica undersaturated throughout the spinel field, in agreement with the results of Takahashi & Kushiro (1983), they become increasingly less silica undersaturated with increase in pressure up to the spinel-garnet univariant curve. For model lherzolite A in the spinel field, liquids produced by less than $\sim 10\%$ melting are silicaundersaturated alkali basalts and alkali picrites. Liquids produced by greater than $\sim 10\%$ melting are olivine tholeiites and picrites. This result is consistent with many previous melting studies on both natural and synthetic systems (see Basaltic Volcanism Study Project, 1981, pp. 549-553).

Silica-undersaturated liquids are produced by low to moderate degrees of melting throughout the spinel field, and for model lherzolite A can be produced along the plagioclase-spinel univariant curve at pressures as low as 12 kbar and $\sim 7\%$ melting. A pressure of 12 kbar for the minimum pressure of alkali-basalt generation is the same as that predicted by Presnall *et al.* (1978) based on data from the diopside-forsterite-anorthite system. For bulk compositions much richer in Na₂O than model lherzolite A, alkali basalts can be generated at pressures within the plagioclase field as low as ~ 9 kbar.

A second low-temperature region along the solidus occurs as a result of the spinel to garnet lherzolite transition. The topology of phase relationships at pressures around this transition is similar to that described for the plagioclase to spinel lherzolite transition, and Fig. 11 shows an enlargement of this region. At 31.2 kbar the phase-out contours from both stability



FIG. 11. Pressure-temperature diagram showing the solidus and melt percent contours for equilibrium melting of model lherzolite A at pressures around the spinel-garnet lherzolite univariant curve. Long-dashed lines separating sub-solidus regions are schematic. Short-dashed lines are estimated percent melting contours for garnet lherzolite. Thick lines represent the solidus. Solid and dash-dot lines as in Fig. 9.

fields converge and melting proceeds to 23%, where spinel, clinopyroxene, and garnet are exhausted. Between 33 and 33.5 kbar the univariant curve is the solidus and the sub-solidus assemblage is fo + opx + cpx + sp + gt. Above 33.5 kbar, garnet lherzolite is the sub-solidus assemblage. On the basis of our limited data in the garnet lherzolite field, melting proceeds to ~28% before clinopyroxene is exhausted at 34 kbar, and this melt is mildly silica undersaturated. In Fig. 8 we show liquids coexisting with garnet lherzolite as trending toward EN with increasing pressure. This is consistent with the limited data in the CMASN (including two experiments at 40 kbar not included in Table 2), and with data in the CMAS system for melting in the diopside-forsterite-pyrope join (Davis & Schairer, 1965) and along the garnet lherzolite solidus (Fujii *et al.*, 1989; Herzberg, 1992). Based on these limited data, we concur that as pressure increases in the garnet field, liquids produced by a constant degree of melting become increasingly rich in normative silica and eventually initial liquids become silica saturated, probably at a pressure of >40 kbar (O'Hara, 1965, 1968; Mysen & Kushiro, 1977).

Under the right conditions, silica-undersaturated basalts can be produced from spinel lherzolite at moderate degrees of melting whereas silica-saturated basalts may be produced by low to moderate degrees of melting of garnet lherzolite at higher pressures. On the basis of the phase relationships in several simplified systems, Kushiro (1968) predicted that silicaundersaturated basalts are produced by small degrees of melting at high pressures (e.g., > 30 kbar) and that silica-saturated basalts are generated by larger degrees of melting at lower pressures. The data in CMASN are consistent with this possibility, but also provide an alternative to this scenario. Indeed, it is interesting to note that the most silicaundersaturated liquid composition along the solidus of model lherzolite A occurs at 15 kbar.

Fractional melting of model lherzolite

Between the solidus and the temperature of disappearance of the first phase, isobaric fractional melting produces liquid compositions very similar to those produced by equilibrium melting. The total amount of melting before a phase is exhausted increases slightly for fractional melting (e.g., from 22 to 24% at 20 kbar), and the temperature interval between the solidus and elimination of the first phase is expanded as a result of the continuous depletion of the bulk composition. Although a wider range of liquid compositions is produced, the average composition of all liquids produced up to any particular melt percent contour is more silica deficient. For example, in Fig. 8, the 10% melting contour in the spinel lherzolite field at 20 kbar moves to the position of an 8% contour, whereas there is essentially no difference in the composition of liquids in the plagioclase lherzolite field. The characteristics of polybaric fractional melting vs. equilibrium melting will be dealt with in a subsequent paper on magma generation at mid-ocean ridges.

The effects of source composition

The composition of liquids produced in the spinel lherzolite field is most sensitive to the Na_2O content of the source (see also Kinzler & Grove, 1992b). Because the Na_2O content of the source is a good first-order indicator of the degree of depletion, it is appropriate to discuss the melting behavior of bulk compositions related by various degrees of melt extraction, such as model lherzolites A, B, and C (Table 4). With progressive source depletion, the solidus temperature increases and the amount of melt that can be produced before the elimination of a phase decreases. For example, relative to the solidus temperature of model lherzolite A, the solidus temperature of model lherzolite C is higher by ~40 °C at 15 kbar and ~10 °C at 30

kbar, and only 8% melt is produced before spinel is eliminated. Figure 12 shows the compositions of liquids along 5% melting contours for melting of model herzolites A, B, and C as projected from DI onto FO-SD-PL-SX. The effect of an increase in the temperature of melting is to produce more silica-rich liquids at a given degree of melting. Figure 12 shows that source fertility has a significant effect on liquid composition in the spinel herzolite field and a lesser effect in the plagioclase herzolite field. Also, depleted herzolite compositions produce primarily silica-saturated basalts, owing to their depleted alkali contents.



FIG. 12. Molecular normative diagram showing the compositions of liquids along 5% melting contours for equilibrium melting of model lherzolites A, B, and C. The projection is from DI onto FO-SD-PL-SX.

We compared the melting behavior of model lherzolite A with that of the H&Z composition in CMASN at 9 and 20 kbar. At 9 kbar, model lherzolite A and H&Z show similar melting behaviors. However, at 20 kbar, spinel is not a stable phase during melting of the H&Z composition but is stable in model lherzolite A. Aluminous spinel may not be a stable phase along the solidus of certain lherzolite compositions, as all the spinel may become dissolved into aluminous pyroxenes in the sub-solidus. This is consistent with phase relationships observed by Green & Ringwood (1967, 1970) for sub-solidus equilibration of pyrolite III composition (similar to the H&Z composition). At constant pressure in the sub-solidus portion of the spinel lherzolite field, increase in temperature produces an increase in the alumina content of pyroxenes according to the reaction

pyroxene + spinel ⇒ aluminous pyroxene + olivine

[see equations (2a) and (2b) of Green & Ringwood, (1970)]. On the basis of their experiments on pyrolite III composition, aluminous spinel is not predicted to be stable along the solidus.

This result, however, is inconsistent with that of Kinzler & Grove (1992a). Based on their parameterization of lherzolite melting, spinel is stable up to >30% melting for a composition nearly identical to H&Z. Further, Takahashi (1986) found spinel at the solidus of lherzolite KLB-1 up to pressures of 30 kbar. In nature, spinel is a complex solid solution between aluminous spinel, hercynitic spinel, and chromite. The ubiquitous occurrence of spinel in abyssal peridotites, and its co-variation with chemical parameters indicative of

degree of melting (e.g., mg-number of olivine; Dick & Bullen, 1984), suggests that some form of spinel is stable during lherzolite melting. Furthermore, the occurrence of spinel in plagioclase- and garnet-bearing peridotites from both sub-oceanic and sub-continental environments attests to the stability of spinel over a wide range of pressures. Our data in the CMASN system cannot adequately address the complicated stability behavior of spinel because of the absence of iron and chromium in our experiments.

Some general conclusions follow from the differences in the melting behavior between the two fertile compositions (A and H&Z). Bulk compositions with higher CaO/Al_2O_3 and SiO_2 than model lherzolite A produce less melt in the spinel field, and in some bulk compositions spinel will not be stable along the lherzolite solidus. Such compositions will still produce a significant amount of melting in the plagioclase field, and plagioclase is the first phase eliminated at all pressures within the field. Conversely, bulk compositions with higher Al_2O_3 and lower SiO_2 are more fertile in the spinel lherzolite field, and less fertile in the plagioclase lherzolite field. That is, a larger amount of melt is generated before the elimination of the first crystalline phase.

Comparison with the melting behavior of natural lherzolite compositions

Experiments reported for melting of natural lherzolite compositions have been performed using a variety of bulk compositions and techniques, are generally restricted to high degrees of melting, and are of varying quality. Rather than drawing general comparisons with a number of individual studies, we have made a more comprehensive comparison with the results of Kinzler & Grove (1992b), who presented equations that describe the compositions of liquids saturated with a four-phase lherzolite assemblage in the plagioclase and spinel lherzolite stability fields. We chose to compare our data with this study because the parameterizations of Kinzler & Grove are based on a set of critically evaluated experimental data for melting of natural and simplified lherzolite from the literature, and from their new experiments on basalt compositions saturated with lherzolite minerals. This study also provided a comprehensive treatment of the melting behavior of a model lherzolite composition (H&Z dep 1).

Figure 13 compares the trends of CMASN oxides as a function of melt percent for isobaric equilibrium melting of model lherzolite A and H&Z dep 1 at 8 kbar (plagioclase lherzolite field) and 20 kbar (spinel lherzolite field). Although these two model compositions may not be strictly analogous to each other (see above), they do have very similar Na₂O contents. As reported above, and by Kinzler & Grove, the Na, O content of the source has a large effect on the composition of liquids. Because isobaric equilibrium and near-fractional melting produce a similar melting behavior, our discussion will focus only on equilibrium melting. In terms of the direction of change of oxides during melting (i.e., increasing or decreasing) there is complete agreement between the two data sets. For melting at 20 kbar (Fig. 13b) the trends are remarkably similar, and differences in actual abundances can be attributed primarily to dilution of components in the CMASN system. These data sets confirm that SiO₂ decreases with increase in melting, a result different from previous parameterizations of lherzolite melting experiments (Klein & Langmuir, 1987; McKenzie & Bickle, 1988). Whereas the direction of change for all oxides is the same at 8 kbar (plagioclase field, Fig. 13a), the differences in abundances cannot be attributed totally to dilution, although they may result largely from differences in bulk composition. For example, at a given degree of melting, CMASN liquids appear more CaO and Al₂O₃ rich, and most evidently, are more Na₂O and SiO₂ poor (when the effects of dilution are considered). Another possibility is that these differences may result from the use by Kinzler & Grove of a constant value of 1.32 for a



FIG. 13. CMASN oxides (wt.%) vs. melt percent for equilibrium melting of model lherzolite A (solid lines; this study) compared with equilibrium melting of H&Zdep1 (dashed lines) as presented by Kinzler & Grove (1992b). Diagram (a) is for melting of plagioclase lherzolite at 8 kbar, and (b) is for melting of spinel lherzolite at 20 kbar.

plagioclase/liquid K_D^{Ca-Na} [where $K_D^{Ca-Na} = (CaO_{plag}/Na_2O_{plag}/(CaO_{liq}/Na_2O_{liq})]$. In CMASN, the K_D for plagioclase-liquid equilibria calculated in this way is close to 1.0 along the solidus of model lherzolite A. This explains the higher CaO and lower Na₂O in CMASN liquids. The expressions used to describe plagioclase-liquid equilibria used by Kinzler & Grove (1992a) may be too simplified to predict the effect of plagioclase-liquid equilibria on the Al₂O₃ and SiO₂ contents of liquids, and this could explain the differences in liquid composition between the two data sets for these components.

CONCLUDING STATEMENT

In this paper we have presented a data set for melting of simplified lherzolite in the CMASN system, and have shown how it can be used to determine quantitatively the phase equilibrium of melting for a wide variety of model lherzolite compositions. The conclusions we have reached apply only to melting of specific bulk compositions under specified conditions. However, the utility of this data set is that one can apply it to basalt generation in particular geologic environments (e.g., mid-ocean ridges, ocean islands, or continental rift zones) by constructing melting models (e.g., equilibrium or fractional melting under isobaric or polybaric conditions), and testing them to see if they are viable in light of independent data. In a forthcoming paper, we will apply this data set to basalt generation at mid-ocean ridges.

ACKNOWLEDGEMENTS

We thank Robert Gribble, Gudmunder Gudfinnson, Jock Keiller, Robert Luth, Cheney Milholland, Biswajit Mukhopadhyay, Gene Scott, Tom Sisson, Robert Stern, and Steven Talman for valuable assistance and discussions. We thank Tom Sisson for a helpful review of an early version of the manuscript, and for useful reviews from Connie Bertka and Rosamond Kinzler. This work was supported by National Science Foundation grant EAR-8816044 and by Texas Advanced Research Program grants 009741-007 and 3927. Support was also provided to M.J. W. during manuscript preparation from a Killam Foundation Post-Doctoral Fellowship and NSERC infrastructure and operating grants to Robert Luth.

REFERENCES

Albee, A. L., & Ray, L., 1970. Correction factors for electron-probe microanalysis of silicates, oxides, carbonates, and sulfates. Anal. Chem. 42, 1408-14.

Anonymous, 1969. The international practical temperature scale of 1968. Metrologia 5, 35-44.

Bender, J. F., Hodges, F. N., & Bence, A. E., 1978. Petrogenesis of basalts from the project FAMOUS area: experimental study from 0 to 15 kbars. *Earth Planet Sci. Lett.* **41**, 277–302.

Bottinga, Y., & Weill, D. F., 1972. The viscosity of magmatic silicate liquids: a model for calculation. Am. J. Sci. 272, 438-75.

Bowen, N. L., 1915. The crystallization of haplobasaltic, haplodioritic, and related magmas. *Ibid.* 40, 4th Series, 161-85.

Boyd, F. R., & England, J. L., 1960. Apparatus for phase equilibrium measurements at pressures up to 50 kilobars and temperatures up to 1750°C. J. Geophys. Res. 65, 741-8.

Chayes, F., 1985. Complementary ternaries as a means of characterizing silica saturation in rocks of basaltic composition. J. Geol. 93, 743-7.

Davis, B. T. C., & Schairer, J. F., 1965. Melting relations in the join diopside-forsterite-pyrope at 40 kilobars and a atmosphere. Carnegie Inst. Wash. Yearb. 64, 123-6.

Dick, H. J. B., 1989. Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism. In: Saunders, A. D., & Norry, M. J. (eds.) Magmatism in the Ocean Basins. Geol. Soc. Spec. Publ. 42, 71-105.

--- Bullen, T., 1984. Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. Contr. Miner. Petrol. 86, 54-76.

Basaltic Volcanism Study Project, 1981. Basaltic Volcanism on the Terrestrial Planets. New York: Pergamon, 1286 pp.

- —— Fisher, R. L., & Bryan, W. B., 1984. Mineralogic variability of the uppermost mantle along the mid-ocean ridges. Earth Planet. Sci. Lett. 69, 88-106.
- Donaldson, C. H., & Brown, R. W., 1977. Refractory megacrysts and magnesium-rich melt inclusions within spinel in oceanic tholeiites: indicators of magma mixing and parental liquid compositions. *Ibid.* 37, 81–9.
- Elthon, D., & Casey, J. F., 1985. The very depleted nature of certain primary mid-ocean ridge basalts. Geochim. Cosmochim. Acta 49, 289-98.
- ----- Scarfe, C. M., 1984. High pressure phase equilibria of a high-magnesia basalt and the genesis of primary oceanic basalts. Am. Miner. 69, 1-15.
- Falloon, T. J., & Green, D. H., 1987. Anhydrous partial melting of MORB pyrolite and other peridotitic compositions at 10 kbar: implications for the origin of primitive MORB glasses. *Miner. Petrol.* 37, 181–219.
- Fujii, T., & Scarfe, C. M., 1985. Composition of liquids coexisting with spinel lherzolite at 10 kb and the genesis of MORBs. Earth Planet. Sci. Lett. 90, 18-28.
- ----- Tachikara, M., & Kurita, K., 1989. Melting experiments in the system CaO-MgO-Al₂O₃-SiO₂ to 8 GPa: constraints to the origins of komatiites. EOS Trans. Am. Geophys. Union 70, 483.
- Gasparik, T., 1984. Two-pyroxene thermobarometry with new experimental data in the system CaO-MgO-Al₂O₃-SiO₃. Contr. Miner. Petrol. 87, 87-97.
- Green, D. H., & Ringwood, A. E., 1967. The genesis of basaltic magmas. Ibid. 15, 103-90.
- 1970. Mineralogy of peridotitic compositions under upper mantle conditions. Phys. Earth Planet. Inter. 3, 359-71.
- Hart, S. R., & Zindler, A. Z., 1986. In search of bulk earth composition. Chem. Geol. 57, 247-67.
- Heinrich, K. F. J., 1986. Comparisons of algorithms for X-ray mass absorption coefficients. *Microbeam Analysis* 279.
- Herzberg, C., 1992. Depth and degree of melting of komatuites. J. Geophys. Res. 97(B4), 4521-40.
- Jaques, A. L., & Green, D. H., 1980. Anhydrous melting of peridotite at 0-15 kbar pressure and the genesis of tholeiitic basalts. Contr. Miner. Petrol. 73, 287-310.
- Jenkins, D. M., & Newton, R. C., 1979. Experimental determination of the spinel peridotite to garnet peridotite inversion at 900°C and 1000°C in the system CaO-MgO-Al₂O₃-SiO₂ and at 900°C with natural garnet and olivine. *Ibid.* 68, 407-19.
- Johnson, K. T., Dick, H. J. B., & Shimizu, N., 1990. Melting in the oceanic upper mantle: an ion microprobe study of diopsides in abyssal peridotites. J. Geophys. Res. 95(B3), 2661–78.
- Kinzler, R. J., & Grove, T. L., 1992a. Primary magmas of mid-ocean ridge basalts 1. Experiments and methods. *Ibid.* 97(B5), 6885–906.
- ---- 1992b. Primary magmas of mid-ocean ridge basalts 2. Applications. Ibid. 97(B5), 6907-26.
- Klein, E. M., & Langmuir, C. H., 1987. Global correlations of mid-ocean ridge basalt chemistry with axial depth and crustal thickness. *Ibid.* 92(B8), 8089-115.
- Korzhinskii, D. S., 1959. Physicochemical Basis of the Analysis of the Paragenesis of Minerals. New York: Consultants Bureau.
- Kushiro, I., 1968. Compositions of magmas formed by partial zone melting of the Earth's upper mantle. J. Geophys. Res. 73, 619–34.
- ---- 1973. The system diopside-anorthite-albite: determination of compositions of coexisting phases. Carnegie Inst. Wash. Yearb. 72, 502-7.
- ---- Yoder, H. S., 1966. Anorthite-forsterite and Anorthite-enstatite reactions and their bearing on the basalt-eclogite transformation. J. Petrology 7, 337-62.
- Lindsley, D. H., 1968. Melting relations of plagioclase at high pressures NY State Mus. Sci. Serv. Mem. 18, 39-46. Liu, T. C., & Presnall, D. C., 1990. Liquidus phase relationships on the join anorthite-forsterite-quartz at 20 kbar
- with applications to basalt petrogenesis and igneous sapphirine. Contr. Miner. Petrol. 104, 735-42.
- McKenzie, D., & Bickle, M. J., 1988. The volume and composition of melt generated by extension of the lithosphere. J. Petrology 29, 625-79.
- Milholland, C. S., & Presnall, D. C., 1989. Liquidus phase relationships on the join anorthite-forsterite-quartz at 30 kbar: applications to the petrogenesis of basalt, and esite, and eclogite. EOS Trans. Am. Geophys. Union 70, 1394.
- Mysen, B. O., & Kushiro, I., 1977. Compositional variations of coexisting phases with degree of melting of peridotite in the upper mantle. Am. Miner. 62, 843-65.
- Nickel, K. G., 1986. Phase equilibria in the system SiO₂-MgO-Al₂O₃-CaO-Cr₂O₃ (SMACCR) and their bearing on spinel/garnet lherzolite relationships. *Neues Jahrb. Miner. Abh.* 155, 259-87.
- Niu, Y., & Batiza, R., 1991. An empirical method for calculating melt compositions produced beneath mid-ocean ridges: application for axis and off-axis (seamounts) melting. J. Geophys. Res. 96(21), 753-77.
- O'Hara, M. J., 1965. Primary magmas and the origin of basalts. Scott. J. Geol. 1, 19-40.
- ----- 1968. The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks. *Earth-Sci. Rev.* 4, 69–134.

- ---- Richardson, S. W., & Wilson, G., 1971. Garnet-peridotite stability and occurrence in crust and mantle. Contr. Miner. Petrol. 32, 48-67.
- O'Neill, H. St.C., 1981. The transition between spinel lherzolite and garnet lherzolite, and its use as a geobarometer. *Ibid.* 77, 185–94.
- Presnall, D. C., 1986. An algebraic method for determining equilibrium crystallization and fusion paths in multicomponent systems. Am. Miner. 71, 1061-70.
- Brenner, N. L., & O'Donnell, T. H., 1973. Drift of Pt/Pt10Rh and W3Re/W25Re thermocouples in single stage piston-cylinder apparatus. *Ibid.* 58, 771–7.
- Dixon, S. A., Dixon, J. R., O'Donnell, T. H., Brenner, N. L., Schrock, R. L., & Dycus, D. W., 1978. Liquidus phase relations on the joint diopside-forsterite-anorthite from 1 atm. to 20 kbar: their bearing on the generation and crystallization of basaltic magma. *Contr. Miner. Petrol.* 66, 203–20.
- Dixon, J. R., O'Donnell, T. H., & Dixon, S. A., 1979. Generation of mid-ocean ridge tholeiites. J. Petrology 20, 3–35.
- ---- Hoover, J. D., 1987. High pressure phase equilibrium constraints on the origin of mid-ocean ridge basalts. Magmatic processes: Physicochemical Principles. Geochem. Soc. Spec. Publ. 1, 75-89.
- Ringwood, A. E., 1975. Composition and Petrology of the Earth's Mantle. New York: McGraw-Hill, 618 pp.
- Sen, G., 1982. Composition of basaltic liquids generated from a partially depleted herzolite at 9 kbar pressure. Nature 299, 336-8.
- ----- Presnall, D. C., 1984. Liquidus phase relationships on the join anorthite-forsterite-quartz at 10 kbar with applications to basalt petrogenesis. *Contr. Miner. Petrol.* 85, 404-8.
- Sisson, T. W., & Grove, T. L., 1993. Temperature and H₂O contents of low-MgO high-alumina basalts. *Ibid.* 113, 167-84.
- Stolper, E., 1980. A phase diagram for mid-ocean ridge basalts: preliminary results and implications for petrogenesis. *Ibid.* 74, 13-27.
- Takahashi, E., 1986. Melting of a dry peridotite KLB-1 up to 14 GPa: implications on the origin of peridotitic upper mantle. J. Geophys. Res. 91(B9), 9367–82.
- ----- Kushiro, I., 1983. Melting of a dry peridotite at high pressures and basalt magma genesis. Am. Miner. 68, 859-79.