of olivine gabbro and granulite, and the uppermost mantle is composed of thick layers of banded perido- tite and pyroxenite underlaid by a zone of massive spinel lherzolite. The depth from which the host magmas have derived may be different among the erupt- ive units considering the variety and the systematics in the xenolith associations shown in Fig.1. The lavas which contain spinel lherzolites, however, must have derived from the deepest zone of the strata.

High pressure phase relations of a basalt taken from the unit KRB (which contains the largest amount of spinel lherzolites among the 10 units in Fig.1) have been determined (Fig.5) with a piston-cylinder apparatus under dry conditions (Takahashi, 1980). The lava KRB is considered to have last equilibrated with the spinel lherzolite upper mantle at about 40 to 50 km depth and may have ascended without chemical modi- fication, because it coexists with ol+opx+cpx on its liquidus at 14 kbar (Fig.5).

Fig. 6

Southwest Honshū Arc

Fig. 5

Fig. 7
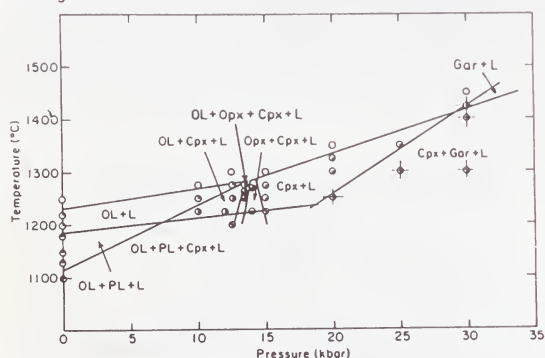
Spinel lherzolite is considered to be the major constituent of the earth's uppermost mantle and the xenoliths of that rock type predominate over other peridotite and pyroxenite in most of the alkali basalt localities in the world (Forbes & Kuno, 1967). How- ever, paucity of spinel lherzolite xenoliths and ex- istence of the large amount of cumulative peridotite and pyroxenite xenoliths are common natures in alkali basalt localities in the Sowthwest Japan (e.g. Yama- guchi,1964; Aoki,1968; Takahashi,1978). The upper- most part of the mantle beneath this area may be oc- cupied with a large amount of peridotite and pyroxe- nite cumulates (Fig.6).

According to Hashizume & Matsui (1979), no sharp reflections from the Moho discontinuity have been observed from this area, and their best fit velocity model (Fig.7)suggests that the crust/mantle boundary beneath this area comprises numerous alterations of mafic and ultramafic rocks such as in layered intru- sive bodies. The crust and upper mantle beneath the
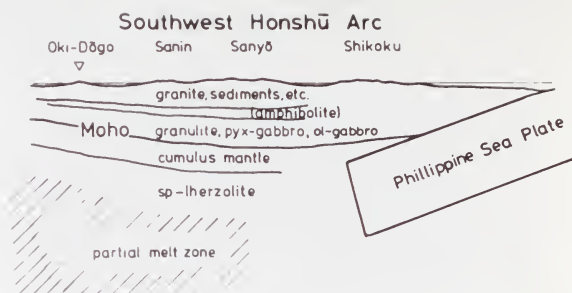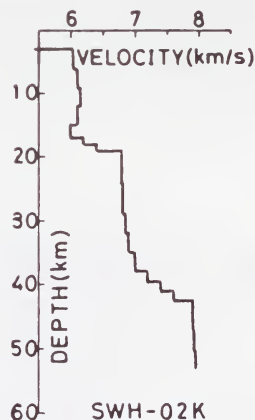
Southwest Japan may have been chemically differenti- ated due to a large flux of magmas during the last 100 Ma period, where and when extensive andesite vol- canisms and granitic batholith formation took place. The bulk chemical composition of the crust above the petrologic Moho (the boundary between the spinel lherzolite layer and the cumulative peridotite/pyro- xenite layer in Fig.4 and Fig.6) could be basaltic rather than andesitic.

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H18 THEORETICAL PREDICTION OF SUBSOLIDUS PHASE RELATIONSHIPS IN PERIDOTITES AND BASALTS
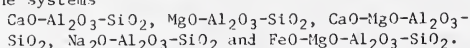
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A considerable amount of experimental and calorimetric data on the thermodynamic properties of pure minerals and solid solutions have been obtained in recent years. These data have been used to calibrate geothermometers and geobarometers (e.g. $CaMgSi_2O_6$ orthopyroxene-clinopyroxene) in an attempt to determine the physical conditions of formation of crustal and mantle rocks. Thus far, however, such approaches have used only a few of the possible components present in multiphase assemblages and, with the exception of the work of Nicholls (1977)

there has been no attempt to calculate the total compositions and stabilities of all possible phases. The object of this study is to predict both phase relationships and mineral compositions as functions of pressure, temperature, and bulk rock composition by integrating available thermodynamic and phase equilibrium data.

The method used to calculate equilibrium assemblages at given P, T and composition is that of free energy minimisation using steepest descent.

This has been employed to obtain an internally consistent thermodynamic data set based on calorimetric and phase equilibrium measurements in the systems $CaO-Al_2O_3-SiO_2$, $MgO-Al_2O_3-SiO_2$, $CaO-MgO-Al_2O_3-SiO_2$, $Na_2O-Al_2O_3-SiO_2$ and $FeO-MgO-Al_2O_3-SiO_2$.

Currently, the following data give good fits to enthalpy, entropy and phase equilibrium data in the CMAS System:

Phase	Component	H(1000K) cal	S(1000) cal K-1
clinopyroxene	$CaMgSi_2O_6$	-34 900	96.7
" "	$CaAl_2SiO_6$	-18 400	97.1
" "	$Mg_2Si_2O_6$	-15 180	94.17
" "	$NaAlSi_2O_6$	-18 100	92.12
orthopyroxene	$CaMgSi_2O_6$	-34 900	96.7
" "	$MgAl_2SiO_6$	+1 920	95.0
" "	$Mg_2Si_2O_6$	-16 820	93.51
spinel	$MgAl_2O_4$	-5 380	64.47
plagioclase	$CaAl_2Si_2O_8$	-24 250	127.8
olivine	Mg_2SiO_4	-14 980	66.23
garnet	$Ca_3Al_2Si_3O_{12}$	-77 510	187.2
"	$Mg_3Al_2Si_3O_{12}$	-20 450	185.9
quartz	SiO_2	0	27.62
corundum	Al_2O_3	0	43.0

Phase	Component	V(298K) c·c	$\alpha \cdot 10^5$	$\beta \cdot 10^6$
clinopyroxene	$CaMgSi_2O_6$	66.1	2.92	0.82
" "	$CaAl_2SiO_6$	63.62	2.7	0.8
" "	$Mg_2Si_2O_6$	62.64	2.92	1.01
" "	$NaAlSi_2O_6$	60.4	2.66	0.75
orthopyroxene	$CaMgSi_2O_6$	66.1	2.92	0.82
" "	$MgAl_2SiO_6$	58.93	2.92	1.01
" "	$Mg_2Si_2O_6$	62.64	2.92	1.01
spinel	$MgAl_2O_4$	39.71	2.75	0.49
plagioclase	$CaAl_2Si_2O_8$	100.79	1.48	1.1
olivine	Mg_2SiO_4	43.79	4.14	0.79
garnet	$Ca_3Al_2Si_3O_{12}$	125.24	2.34	0.54
"	$Mg_3Al_2Si_3O_{12}$	113.3	2.57	0.47
quartz	SiO_2	22.688	6.0	2.5
corundum	Al_2O_3	25.575	2.61	0.37

These data reproduce phase equilibrium measurements on the spinel-peridotite → garnet-peridotite reaction in the systems $MgO-Al_2O_3-SiO_3$ and $CaO-MgO-Al_2O_3-SiO_2$ assuming $\Delta Cp = 0$. In the former system, the reaction passes through the P-T points 20.2kbar/1100°C, 18.3kbar/900°C and 17.5kbar/600°C with the spinel-olivine-pyroxene assemblage being stable on the low pressure side. In the CMAS system, the reaction is calculated to be shifted to pass through points 14.5kbar/1100°C, 14.2kbar/900°C and 15.2kbar/600°C. The reaction: Forsterite + Anorthite = Spinel + Orthopyroxene + Clinopyroxene is calculated to take place at points 7.9kbar/1300°C, 7kbar/1100°C and 6.1kbar/800°C.
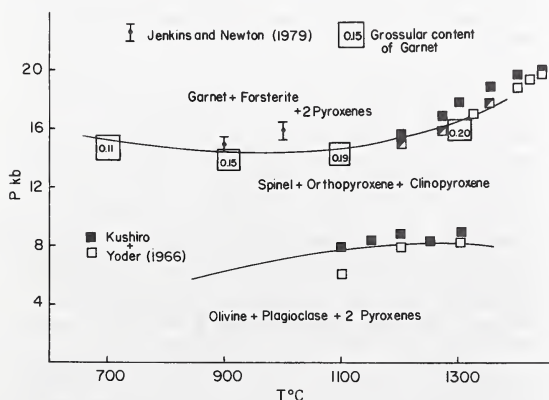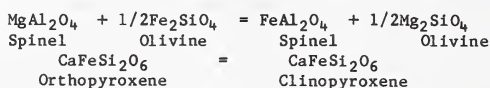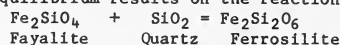

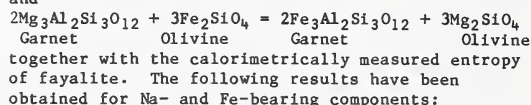The figure shows calculated positions of facies boundaries in the CMAS system, together with

available experimental data on the reactions of concern. Of particular interest is the shallow positive (~6bar/K) P-T slope of the garnet-spinel reaction at high temperatures and the negative slope at low temperatures. The changeover can be ascribed to the fact that the pyroxenes which are involved in the reaction have much more extensive mutual solubility and higher Al_2O_3 contents at high temperature than at low temperature. The decreasing extent of solid solution with lowering temperature lowers the entropies of the pyroxene phases sufficiently for the high pressure garnet-bearing assemblage to have a higher entropy than the low pressure spinel assemblage at temperatures below 950°C. A similar, but opposite effect can be seen at the plagioclase-spinel lherzolite boundary, the relevant reaction having pyroxene on the high pressure side. Uncertainties in the calculated boundaries mainly arise from uncertainties in the solid solution properties. For example, pyrope-grossular garnets appear, on the basis of calorimetric measurements (Haselton and Westrum, 1980) to have moderate excess entropies. The relatively flat, calculated P-T slope of the spinel-garnet reaction at high pressures is, in part, an artifact of this excess entropy term which stabilizes garnet progressively with increasing temperature. In order to fit the available unreversed data (Kushiro and Yoder, 1966; Herzberg, 1978) better, a steeper slope is required. This can only be achieved with excess entropies close to zero. In addition, the equilibrium garnet composition is calculated to change substantially along the spinel-garnet boundary whereas available data (Jenkins and Newton, 1979; Boyd, 1970) suggest that it should be constant at Ca/Ca+Mg of 0.15.

The effects of Na_2O on the lherzolite reactions may be calculated reasonably well using calorimetric and phase equilibrium data on jadeite and high albite together with activity-composition relations for diopside-jadeite and albite-anorthite solid solutions.

Constraints on the thermodynamic properties of Fe-bearing components ($Fe_2Si_2O_6$, $CaFeSi_2O_6$ etc.) are much poorer than those discussed earlier. Data for such components were dominantly based on phase equilibrium results on the reactions:

Fe_2SiO_4 + SiO_2 = $Fe_2Si_2O_6$
Fayalite   Quartz   Ferrosilite

$MgAl_2O_4$ + $1/2Fe_2SiO_4$ = $FeAl_2O_4$ + $1/2Mg_2SiO_4$
Spinel   Olivine   Spinel   Olivine
    $CaFeSi_2O_6$ = $CaFeSi_2O_6$
    Orthopyroxene   Clinopyroxene
and
$2Mg_3Al_2Si_3O_{12} + 3Fe_2SiO_4 = 2Fe_3Al_2Si_3O_{12} + 3Mg_2SiO_4$
Garnet   Olivine   Garnet   Olivine
together with the calorimetrically measured entropy of fayalite. The following results have been obtained for Na- and Fe-bearing components:

Phase	Component	H(1000K) cal	S(1000) cal K-1
clinopyroxene	$NaAlSi_2O_6$	-18 100	92.12
" "	$CaFeSi_2O_6$	-28 900	105.23
" "	$Fe_2Si_2O_6$	-6 790	110.44
orthopyroxene	$CaFeSi_2O_6$	-27 485	105.23
" "	$Fe_2Si_2O_6$	-7 220	109.94
spinel	$FeAl_2O_6$	-2 720	72.04
plagioclase	$NaAlSi_3O_8$	-15 700	130.11
olivine	Fe_2SiO_4	-6 850	83.47
garnet	$Fe_3Al_2Si_3O_{12}$	-12 780	209.17

Phase	Component	V(298K) c·c	$\alpha \cdot 10^5$	$\beta \cdot 10^6$
clinopyroxene	$NaAlSi_2O_6$	60.4	2.66	0.75
" "	$CaFeSi_2O_6$	67.88	3.9	0.82
" "	$Fe_2Si_2O_6$	65.98	3.9	1.0
orthopyroxene	$CaFeSi_2O_6$	67.88	3.9	0.82
" "	$Fe_2Si_2O_6$	65.98	3.9	1.0
spinel	$FeAl_2O_4$	40.75	2.54	0.49
plagioclase	$NaAlSi_3O_8$	100.43	3.44	1.6
olivine	Fe_2SiO_4	46.39	3.2	0.91
garnet	$Fe_3Al_2Si_3O_{12}$	115.3	2.44	0.53

Preliminary calculations on a model natural peridotite "pyrolite III" indicate that the spinel-garnet reaction is shifted downwards to about 10kbar at 900°C. This result is in good agreement with the experimental data of Jenkins and Newton (1979). Calculations on the gabbro-eclogite reaction in an Fe-rich bulk composition indicate that garnet should appear at 8kbar at 900°C. This is in good agreement with the experiments of Green and Ringwood (1967), bearing in mind the small overpressure (~ 2kbar) required to achieve nucleation of garnet.

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H19 KIMBERLITES OF SOUTHERN AFRICA - ARE THEY RELATED TO SUBDUCTION PROCESSES?

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Although proposed by Sharp (1974) that the Mesozoic kimberlites in Southern Africa originated from activity at the deep end of a subducted oceanic plate, a connection of kimberlites with subduction processes has not been generally accepted. Dawson (1980 p. 220) states that such "hypothesis is contrary to the observed random distribution of kimberlites in Southern Africa ..", and remarks further that " ... the confinement of kimberlite magmatism to the cratonic centers of continents well away from any major fold belts, together with the very limited amounts of kimberlite magma, appear to preclude any connection with classical subduction zones."

However, inspite of recent progress in our knowledge of kimberlite formation and emplacement, the " ... vexing problem of why kimberlites occur, and why they occur where they do has not been solved" (Meyer, 1979). Other plate-tectonic-related hypotheses of kimberlite distribution, such as transform fault models (Williams and Williams, 1977; Stracke et al., 1979) or hot spot models (Hastings and Sharp, 1979; Crough et al., 1980), do not explain the ultimate source of H_2O and CO_2 necessary for kimberlite formation, and we can only speculate whether these volatiles "come from deeper" or from "recycling via subduction" (Wyllie, 1979). While the hypothesis that the volatiles are juvenile gases from the deep mantle provides no means of predicting the location and timing of kimberlite eruptions, the possibility of a causal relationship to subduction can be tested because kimberlites should be localized above remnants of subducted plates. For such relationships to become obvious, the classical view that all subduction zones are steeply dipping and therefore cannot reach far enough under continents where most kimberlites originated must be abandoned. This is justified by the occurrence of fragments of subducted oceanic lithosphere as eclogite xenoliths in kimberlites from the Colorado plateau (Helmstaedt and Doig, 1975) as well as by the distribution of Tertiary magmatic rocks in the southwestern United States that suggest the former existence of a shallow-dipping subduction zone in this region (Dickinson and Snyder, 1978). The fact that a similar "flat-plate" subduction model was proposed by Lock (1980) for the formation of the Cape Fold belt warrants a new look at Sharp's original hypothesis.

Two independent questions are pursued:
1. Did such low-angle subduction occur under Southern Africa and if so, are the kimberlites related to it?

2. Do xenolith suites of these kimberlites include possible samples of subducted material?

1. Both Sharp and Lock relate the Permian to Middle Triassic Cape folding to subduction under Gondwanaland prior to its breakup, when according to Sharp " ... the oceanic plate associated with this orogeny dived to great depth and went hundreds of kilometers inland underneath the former continent". As folding in the Cape Fold belt was broadly contemporaneous with the opening of the Tethys ocean we suggest that spreading of the Tethys caused the increase in plate convergence rates necessary to initiate low-angle subduction along the southern margin of Gondwanaland.

A compilation on a map of the reconstructed Gondwana continent shows that the distribution of kimberlites is considerably less random than suggested by distribution maps using the present configuration of continents. A broad zone of kimberlites cuts numerous different geological provinces and lies parallel to the belt of Late Paleozoic igneous rocks stretching from South America past South Africa, through Antarctica to Australia (Samfrau geosyncline of DuToit, 1937). In South America and Southern Africa the southwestern boundary of this kimberlite belt lies between 1500-2000 km cratonwards from the assumed Late Paleozoic to Triassic continental margin. Although the timing of the kimberlite eruptions (between 79 and 133 m.y., Davis, 1977) approximately coincides with the break up of Gondwanaland, the southwestern margin of the belt shows no relationship to the orientaion of the South Atlantic rift. Similarily, a correlation with transform faults, as proposed by Williams and Williams (1977) for West African kimberlites, is not obvious. In a subduction model the time lag between subduction and kimberlite emplacement may be explained as a consequence of the emplacement mechanism. If kimberlites traverse the lithosphere along stress corrosion fractures (Anderson, 1979), emplacement was not possible until Gondwanaland became an extensional regime. Scatter in timing of kimberlite eruptions can be explained by differences in lag times following cessation of subduction that are a function of variations in thermal gradients within the sub-continental mantle as well as local structural conditions.

A subduction model for the Mesozoic kimberlites in Southern Africa must also account for the Karroo magmatism, as there is a common regional association of kimberlites with Karroo dykes and sills. Isotopic data appear to suggest that tholeiitic flood basalts are derived from continental