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JADEITE, ANALCITE, NEPHELINE, AND ALBITE AT HIGH TEMPERATURES AND PRESSURES*

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ABSTRACT. The stability fields of the phases albite ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$), jadeite ($Na_2O \cdot Al_2O_3 \cdot 4SiO_2$), and analcite ($Na_2O \cdot Al_2O_3 \cdot 4SiO_2 \cdot H_2O$) have been investigated at high pressures and temperatures. The equilibrium pressure-temperature curves for the following reactions have been experimentally determined:

1. Albite = jadeite + quartz
2. Albite + nepheline = 2 jadeite
3. Analcite = jadeite + water

In addition the phase diagram for analcite has been approximately determined. All experimental work was done in a piston-cylinder high pressure apparatus. The results are:

1. The curve for the reaction albite = jadeite + quartz is represented by the equation P (bars) = 6800 + 18.6 T°C, and these results are in excellent agreement with previous experimental and thermochemical determinations.

2. The reaction albite + nepheline = 2 jadeite is shown by the curve P (bars) = —4000 + 25 T°C, and these results are in excellent agreement with the previous determinations of Birch's laboratory in the range 500 to 600°C, but our curve has substantially greater slope.

3. The curve for the reaction analcite = jadeite + H_2O has been reversibly located at temperatures of both 500° and 600°. The slope of the reaction is P (bars) = 9.5 T°C + 6000. The slope of this reaction is consistent with theoretical considerations.

4. The curve for the reaction analcite = albite + nepheline + water has been located to within ±3 kilobars at 600°.

INTRODUCTION

The sodic pyroxene, jadeite, has been intensely investigated both in the field and laboratory for the past decade. This preoccupation with what was formerly regarded as a rather obscure, interesting gem mineral, has followed the recognition that the origin of jadeite is a topic of major significance to geology and geophysics.

Yoder (1950) was the first writer to focus attention on the "jadeite problem". When he wrote his paper there were only two localities where jadeite, approaching the end member composition ($NaAlSi_2O_6$), was known to occur in situ, in spite of its being in great demand by primitive and modern man as a tool material and gem stone. These localities were in Burma and Niigata prefecture, Japan. Since that time jadeite has been discovered in situ in Guatemala and California.

Yoder's (1950) work discusses the paragenesis of jadeite in its known localities and deals at length with its probable pressure-temperature stability field, as deduced from thermochemical considerations and from existing experimental data.

The specific gravity of jadeite averages approximately 3.34, which is a value well in excess of any of its chemically equivalent minerals. Thus, postulated reactions for the formation of jadeite at high pressures which lead to a reduction in volume are:

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1. albite = jadeite + quartz ($\Delta V = -17.8$ cm^3/mole)
2. nepheline + albite = 2 jadeite ($\Delta V = -34.9$ cm^3/mole)
3. analcite = jadeite + water ($\Delta V = -18.8$ cm^3/mole)

Chemical reactions involving reduction in volume of the products are favored by high pressure, thus jadeite was widely considered to be a high pressure phase. This view was supported by the rarity of jadeite and by the failure of investigators to synthesize the mineral even at pressures up to 4000 bars. Thus, the "jadeite problem" is that of the necessary PT conditions for jadeite stability and the question of how these PT requirements were met in naturally occurring jadeite bearing rocks. Adams (1953) calculated the PT stability field of jadeite formed by the reaction of nepheline + albite. His calculated univariant curve showed jadeite to be truly a high pressure mineral that had not been synthesized because the requisite pressure had not been achieved. Adams also considered the formation of jadeite from the reaction

analcite = jadeite + water ($\Delta V = -18.8$ cm^3/mole)

de Roever (1955) was among the several field geologists who agreed that jadeite was a product of a rather special kind of low-grade metamorphism. It is associated with rocks of the glaucophane schist facies characterized by minerals such as lawsonite, pumpellyite, and glaucophane. These minerals are presumed to indicate conditions of both high pressures and relatively low temperatures. de Roever showed that the Celebese jadeite deposit was a product of glaucophane schist type metamorphism formed by the breakdown of albite to jadeite + quartz according to reaction (1) of this paper.

Morey (1957) discussed the system nepheline–albite–water and outlined a variety of phases that might be expected in this system. He listed the possible configurations of univariant curves and inivariant points and noted that the combinations of phases coexisting in stable equilibrium could only be determined by experiment.

Robertson, Birch, and MacDonald. (1957) synthesized jadeite from albite and nepheline and from a glass of jadeite composition in nitrogen pressure medium apparatus. Robertson and his co-workers determined the approximate location of the P-T plane of the reaction

nepheline + albite = 2 jadeite

and his experimental results agreed with the position of the plane calculated by Kelley and others (1953) from the thermochemical data of Kracek, Neuvonen, and Burley (1951).

Fyfe and Valpy (1959) showed from thermochemical data that reaction (3), analcite = jadeite + water, should be a reaction with positive slope at least at low temperatures. They suggested a theoretical curve for this reaction. Birch and Le Comte (1960) experimentally determined the reaction albite = jadeite + quartz using essentially the same methods and apparatus of Robertson, Birch, and MacDonald (1957).

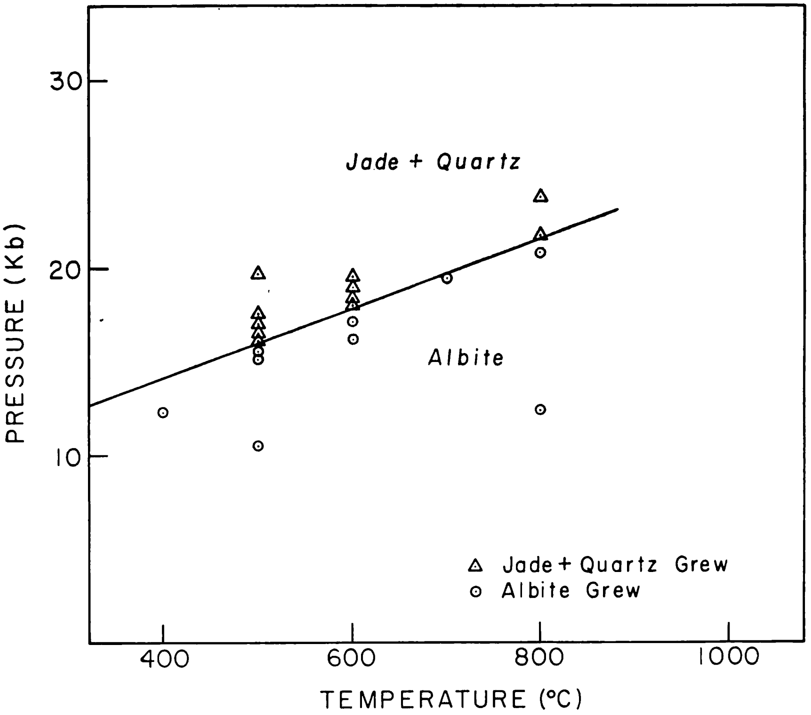

Fig. 1. Equilibrium curve for the reaction albite = jadeite + quartz.

They found satisfactory agreement between their experimental work on the slope of the reaction

albite = jadeite + quartz

compared with the computed reaction based on available thermochemical data.

Greenwood (1961) determined the P-T trajectory of another possible reaction in the plane jadeite-water. The reaction studied was albite + nepheline + 4 water = 2 analcite.

Edgar (ms) also examined the reaction albite + nepheline + 4 water = 2 analcite to water pressures of 1000 bars. Bell (1964) determined the melting relations of jadeite in a dry system at high pressures and temperatures. His experiments were made in apparatus identical to ours.

Kennedy (1961) published some reconnaissance data obtained in piston-anvil apparatus on the various reactions involving nepheline + albite, albite, and jadeite. Results obtained from this apparatus were sharply in contrast to those obtained by Birch and co-workers. Extensive subsequent work on both coesite-quartz, kyanite-sillimanite, et cetera, however, has shown the results in piston-anvil apparatus rarely represent equilibrium results. The difficulties of measuring pressure in piston-anvil apparatus and the possible effect of shear in displacing a transition

TABLE 1

Runs of albite composition. Starting material is jadeite + quartz + albite

Run	T°C	P Kb	Time (hours)	Result
1	400	12.3	5	Ab
2	500	10.5	7	Ab
3	500	15.2	5	Ab
4	500	15.7	15	Ab
5	500	15.8	4.5	Jade + Q
6	500	16.2	12	Jade + Q
7	500	16.3	5	Jade + Q
8	500	17.1	8	Jade + Q
9	500	17.6	4	Jade + Q
10	500	19.6	5	Jade + Q
11	600	16.2	5	Ab
12	600	17.1	7	Ab
13	600	18	12	Jade + Q
14	600	18.3	8	Jade + Q
15	600	19	5	Jade + Q
16	600	19.5	8	Jade + Q
17	700	19.5	7	Ab
18	800	12.4	5	Ab
19	800	20.9	14	Ab
20	800	21.8	14	Jade + Q
21	800	23.8	5	Jade + Q

make results from this apparatus unreliable. Consequently it was decided to reinvestigate the various equilibria in our solid pressure media apparatus.[1]

EXPERIMENTAL WORK

All the experimental results reported in this paper were obtained using piston-cylinder apparatus. This apparatus has been described many times before.

The various reactions were studied by using mixtures of natural minerals. Natural jadeite from Santa Rita peak, California, was kindly supplied us by Dr. R. G. Coleman of the U.S. Geological Survey. The jadeite was separated from its other associated minerals with heavy liquids of density grading to 3.31. The indices of refraction were the same as reported for pure end member jadeite. Amelia Courthouse albite was used. Wet chemical analysis by Celeste Engel indicated an impurity of 0.62 percent K_2O. Nepheline from Ontario was used. Analysis by Celeste Engel showed that our nepheline contained approximately 6 percent K_2O. Runs, using this nepheline as a starting material, agreed with runs using nepheline prepared by breakdown of jadeite.

Intimate mixtures of nepheline and albite were prepared by heating samples of jadeite for 48 hours at 1050°C. The sample was then slowly cooled to 800°C and quenched. This treatment produced a fine mixture of nepheline and glass. This mixture was then sealed with dis-

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[1] Since preparation of this manuscript, the data by Newton and Smith (1967) on the reaction jadeite + quartz = albite have become available. The results are consistent with the data presented in this paper.

tilled water in gold capsules and held overnight in a hydrothermal bomb at 750°C and 500 bars water pressure. This resulted in forming a fine intimate mixture of nepheline and albite. Mixtures of nepheline, albite, and jadeite were then sealed with or without water in short lengths of 1/16 in. OD platinum tubing and placed in the high pressure assembly.

The cylinder of our piston cylinder apparatus was of 1 in. diameter and 2 in. height. Talc was used as the pressure transmitting medium. A very large cylinder diameter was used in order to minimize friction in the current experiments because extreme pressures were not required. None the less, a friction correction of 5 percent was made on all the results in accordance with our best measurements of friction in systems of this particular design, in this pressure and temperature regime. Temperatures were measured with alumel-chromel thermocouple elements encased in a ceramic sheath. The measured temperature gradient across the sample was no more than 2° to 3°C. The runs were examined both optically and by X-ray. In all cases the starting material consisted of both products and reactants, and changes in relative intensities of X-ray peaks were used to determine the direction of the reaction.

TABLE 2

Runs of jadeite composition. Starting material is jadeite + nepheline + albite

Run	T°C	P Kb	Time (hours)	Result
1	500	9.5*	7	Analcite
2	500	10.5*	6	Analcite
3	500	10.9*	6	Jade
4	500	11.4*	8	Jade
5	500	11.4*	7	Jade
6	500	11.4*	5	Jade
7	500	13.2*	15	Jade
8	550	10.5*	7	Analcite
9	600	8*	4	Ne + Ab
10	600	10.5*	1	Analcite
11	600	10.5*	4	Analcite
12	600	11.4*	5	Analcite
13	600	12.3*	5	Jade
14	600	13.3*	6	Jade
15	640	10.5*	1	Ab + glass
16	700	13.3	16	Ne + Ab
17	700	14.2	15	Jade
18	800	13.4	8	Ne + Ab
19	800	14.2	8	Ne + Ab
20	800	15.2	4	Ne + Ab
21	800	16.1	14	Ne + Ab
22	800	16.7	13	Jade
23	800	16.7	15	Jade
24	800	17.1	15	Jade
25	800	17.1	15	Jade

* Runs where $P_{H_2O} = P_{Total}$

EXPERIMENTAL RESULTS

Twenty-one experiments were carried out with mixtures of albite composition. This starting material was a mixture of albite, jadeite, and quartz. The results are shown in table 1 and plotted in figure 1. The boundary which separates the field of albite from the field of jadeite + quartz is shown and is represented by the equation

$$P \text{ bars} = 6800 + 18.6\ T°C$$

Our experimental curve is in remarkable agreement with that published by Birch and LeComte (1960). Our curve as drawn lies at pressures approximately half a kilobar below that of Birch and LeComte, but certainly this is not significant as the difference is within the experimental uncertainty of the apparatus.

Ten experiments were made at temperatures of 700° and 800°C with the starting material a fine and intimate mixture of nepheline + albite + jadeite and bulk composition that of jadeite.

A series of runs were made in order to locate the boundary for the reaction of albite + nepheline = 2 jadeite. These runs are presented in table 2 and plotted in figure 2. The slope of the curve as shown in figure 2 is

$$P \text{ bars} = 25T°C\text{-}4000.$$

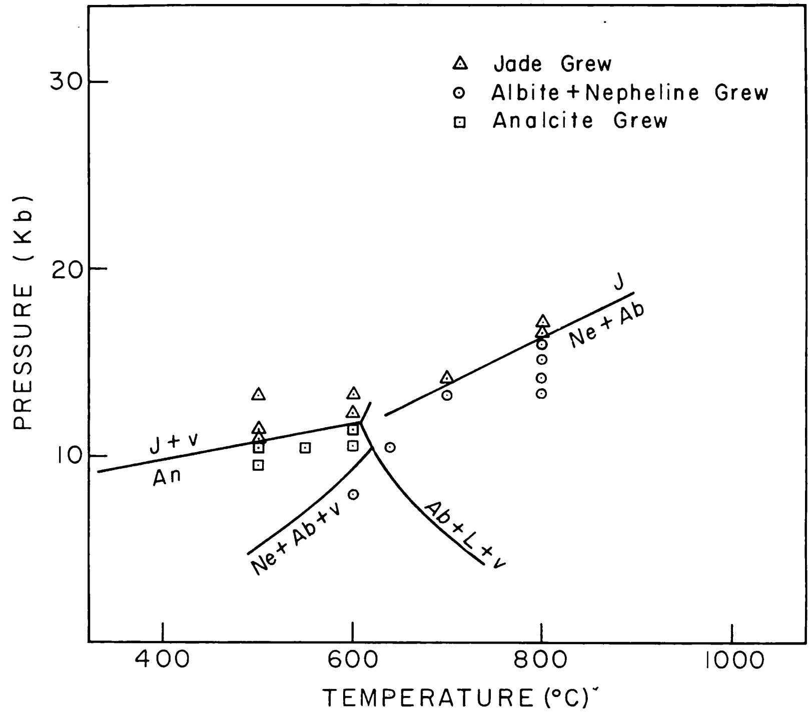

Fig. 2. Equilibrium curve for the reactions nepheline + albite = jadeite and for the reactions analcite = jadeite + vapor.

Figure 3 compares and contrasts our experimentally determined curve with the prior published curve of Robertson, Birch, and MacDonald (1957). The slope of our experimental curve is significantly greater than either that of the curve calculated by Kelley and others (1953) or the experimental curve of Robertson, Birch, and MacDonald. This is startling in view of the near identity of the results showing the reaction of jadeite + quartz to albite, and we have no ready explanation for the differences between the slopes of the two experimental curves.

A number of runs are also shown in figure 2 in which the partial pressure of water in our capsule was essentially equal to the total pressure on the system. These runs fix the position and slope of the reaction analcite = jadeite + vapor. The slope of this curve shown in figure 2 is P bars = 9.5T + 6000. A single run is shown in the field of nepheline + albite + vapor and in the field of albite + liquid + vapor. The effect of high pressures is to lower drastically the liquidus of nepheline + albite, and two triple points are found when the partial pressure of water is equal to the total pressure on the system. These triple points lie at approximately 620°C and 11 kilobars where the fields of analcite, nepheline + albite + vapor, and albite + liquid + vapor meet, and a

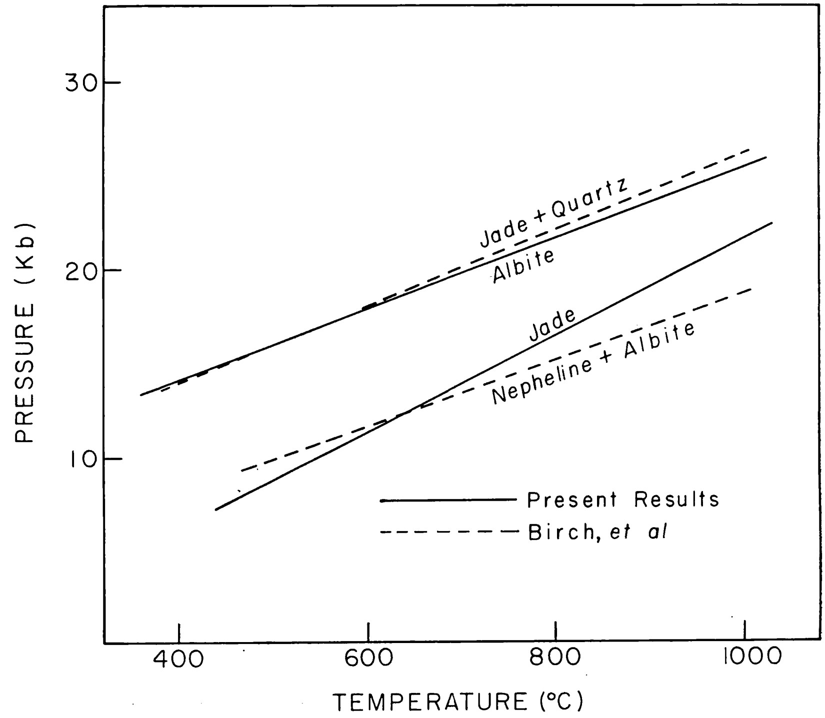

Fig. 3. Comparison of results.

second triple point is found approximately at 610°C and 11.8 kilobars where the fields of analcite, jadeite + vapor and albite + liquid + vapor meet.

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