

The reaction talc + forsterite = enstatite + H₂O: New experimental results and petrological implications

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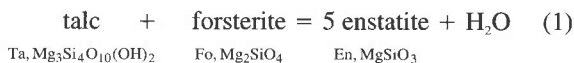
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ABSTRACT

The reaction talc + forsterite = enstatite + H₂O has been investigated between 6 and 20 kbar. Previous high-pressure experimental studies suggested various reaction positions, mostly with positive *P-T* slopes. The new results show that the reaction has a negative slope in the pressure range studied. It was bracketed between 640 and 680 °C at 10 kbar, between 620 and 640 °C at 15 kbar, and between 580 and 600 °C at 20 kbar. The growth of antigorite at high pressures prevented the reaction from being determined above 20 kbar. The reaction position is consistent with the previous low-pressure data of Chernosky et al. (1985), is in very good agreement with the position calculated using the thermodynamic database of Berman (1988), and is in reasonable agreement with the calculation using the thermodynamic database of Holland and Powell (1990). The high reaction temperatures suggested by previous high-pressure experiments may reflect metastable or quench growth of talc in those experiments. Talc in equilibrium with forsterite is stable over a wide *P-T* range in hydrothermally altered and metamorphosed ultramafic rocks and may be important for carrying H₂O into subduction zones. However, talc dehydration occurs at too shallow a depth for the H₂O to contribute directly to subduction zone volcanism.

INTRODUCTION

Talc, Mg₃Si₄O₁₀(OH)₂, is a common mineral in hydrothermally altered and metamorphosed ultramafic rocks. In these rocks it is commonly associated with olivine and other hydrous minerals such as serpentine and amphibole. The maximum stability of end-member talc, as given by the reaction talc = enstatite + quartz + H₂O, occurs at ~800 °C at 10–30 kbar (Chernosky et al. 1985; Jenkins et al. 1991). However, in typical altered ultramafic rock in which talc coexists with olivine, it breaks down at lower temperatures through reaction with the olivine. The end-member reaction in the system MgO–SiO₂–H₂O (MSH) is:



This reaction is significant because it determines not only the maximum stability of talc in equilibrium with forsterite but also the highest temperature at which H₂O can be stored in typical altered ultramafic rock at moderate to high pressures. The amphibole-bearing MSH assemblage anthophyllite + forsterite is stable to higher temperatures than talc + forsterite but is not stable above ~8 kbar (Chernosky et al. 1985). Serpentine is more abundant than talc at low pressures and temperatures, but below ~15 kbar it breaks down at a temperature lower than reaction 1. Reaction 1 could therefore play an important role in affecting the conditions of H₂O storage in the Earth's mantle, particularly in subduction zones. Here, hydrated oceanic lithosphere is subducted into the mantle

and releases its H₂O through a series of dehydration reactions. These reactions may play a major role in subduction zone processes by providing the H₂O necessary for volcanism or by triggering earthquakes. In addition, H₂O released by these actions may become incorporated in new high-pressure hydrous phases, e.g., dense hydrous magnesium silicates or in nominally anhydrous minerals. These phases may transport the H₂O to much greater depth than the stability of common metamorphic minerals such as talc.

Several experimental investigations of reaction 1 have been published. For example, as part of a comprehensive study of phase equilibria in the system MSH at low pressures, Chernosky et al. (1985) determined its position up to 6 kbar. Their results on this reaction and others involving talc formed the basis for the determination of the enthalpy of talc in the internally consistent thermodynamic databases of Holland and Powell (1990) and Berman (1988). The experimental data of Chernosky et al. (1985) and the position of reaction 1 calculated using the databases are shown in Figure 1, together with other previous data on reaction 1.

The results of Chernosky et al. (1985) on talc reactions are generally self-consistent and so the calculated reaction 1 passes through their low-pressure brackets. However this consistency does not extend to the previous high-pressure experimental studies, which have produced results inconsistent with each other and with the calculations. The most-cited high-pressure reversal experiments are those of Kitahara et al. (1966), who obtained phase-

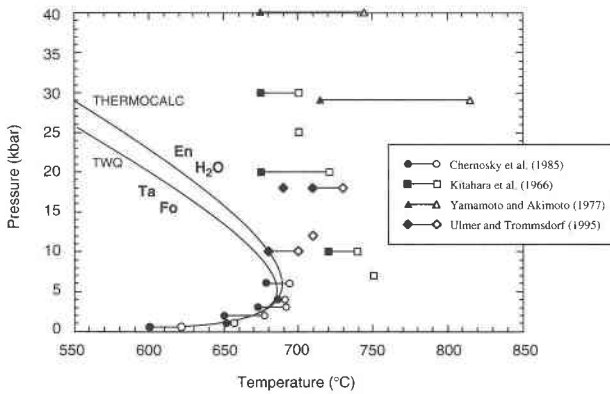


FIGURE 1. Results of previous studies on the reaction $Ta + Fo = En + H_2O$, and calculation of the reaction using the computer programs THERMOCALC (Powell and Holland 1988) and TWQ (Berman 1991). Program versions are THERMOCALC v2.5 (thermodynamic data generated February 1997) and TWQ v1.0. Reaction temperatures were also calculated using TWQ v2.01 (March 1997) and up to 30 kbar are within 2 °C of those calculated using v1.0. The calculation using v2.01 is not shown, however, as this version of the database does not include antigorite, as required for the other reactions shown in Figure 2. Closed symbols = $Ta + Fo$ grew, open symbols = En grew.

equilibrium brackets between 10 and 30 kbar. As shown in Figure 1, their bracket at 10 kbar occurs at a much higher temperature than the 6 kbar bracket of Chernosky et al. (1985). Given that the data of Chernosky et al. (1985) suggest that the maximum thermal stability of $Ta + Fo$ is at ~5–6 kbar, with the reaction bending back to lower temperatures at higher pressures, the two sets of results cannot be reconciled. Chernosky et al. (1985) suggested that the apparently higher-temperature brackets of Kitahara et al. (1966) are because of inaccurate calibration of their piston-cylinder apparatus, whereas Berman (1988) suggested that the error lies in the use of poorly characterized starting materials synthesized in very short experiments. This substantial discrepancy between high- and low-pressure data indicates the need for a redetermination of reaction 1 at pressures above 6 kbar.

Reaction 1 has been investigated in other studies of the MHS system. For example, in synthesis experiments at ≥ 29 kbar, Yamamoto and Akimoto (1977) obtained a reaction position ~80 °C higher than that suggested by Kitahara et al. (1966), which is itself much higher than the calculated curve (Fig. 1). Yamamoto and Akimoto (1977) accepted the possibility of disequilibrium in their short synthesis experiments and cited the need for reversal experiments.

The assemblage $Ta + Fo$ was produced in the investigation of serpentine stability by Ulmer and Trommsdorff (1995) and again appeared to be stable to higher temperatures than calculated. Those experiments, although not designed specifically to investigate reaction 1, reinforce the need for a redetermination of this reaction by reversal experiments.

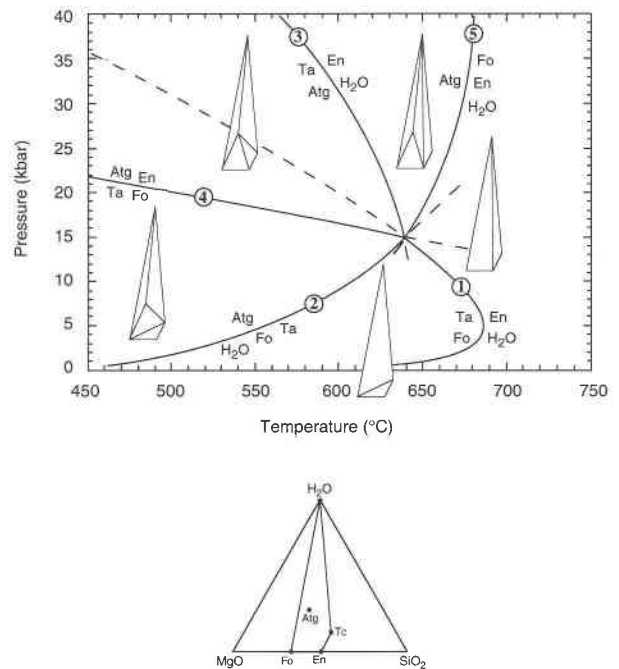


FIGURE 2. Equilibria in the system MSH around the invariant point involving Ta , Atg , Fo , En , and H_2O , calculated using TWQ. Solid lines are stable equilibria, dashed lines metastable. Compatibility diagrams are shown for stable assemblages in each field. The numbers correspond to the reactions given in the text. Note that stability levels relate to this invariant point only.

The stabilities of other hydrous MSH phases are also relevant to this study. For example, the experiments of Ulmer and Trommsdorff (1995) showed that the serpentine mineral antigorite [Atg , $Mg_{48}Si_{34}O_{85}(OH)_{62}$] is stable at low temperatures and high pressures. At low pressures and high temperatures, antigorite dehydrates through the reaction



which has been reversed between 2 and 15 kbar by Evans et al. (1976). Their brackets were used by Berman (1988) in deriving the enthalpy data for antigorite in his database. The position of reaction 2 and all others around the invariant point involving Ta , Atg , Fo , En , and H_2O , as calculated using the program TWQ, are shown in Figure 2. (Because antigorite is not present in THERMOCALC, a similar calculation cannot be performed using that database.)

Anthophyllite is another mineral potentially relevant to the present study, because at low pressures and high temperatures $Ta + Fo$ react to anthophyllite rather than enstatite. However the reaction is not directly relevant to this study, because below 700 °C anthophyllite is only stable below 8 kbar, breaking down at higher pressures to $Ta + En$ (Chernosky et al. 1985).

This paper reports the reinvestigation of reaction 1 between 6 and 20 kbar. The results are in very good agreement with the position of the reaction calculated using

TWQ and are close to the position calculated using THERMOCALC. The reasons for the discrepancies with previous experiments are examined.

EXPERIMENTAL PROCEDURES

Starting materials for the experiments on reaction 1 were 1:1:5 mixtures of natural or synthetic talc, synthetic forsterite, and synthetic enstatite. The natural talc has been used in previous studies (Pawley et al. 1995; Pawley and Wood 1995) and is of ideal composition except for a 1 atom% replacement of Mg by Fe. The synthetic samples were prepared from oxide mixes, talc at 2 kbar, 650 °C for 120 h and enstatite at 5 kbar, 900 °C for 48 h. The forsterite was kindly provided by S.J. Kohn (University of Bristol). Characterization by X-ray diffraction (XRD) and optical examination showed well-crystallized samples, with negligible impurities in the talc and forsterite and a trace of quartz in the enstatite. The reaction of this quartz during the experiments has an insignificant effect on reaction 1.

Starting materials were sealed in 2 mm diameter platinum capsules with 6–9 wt% distilled H₂O. This ensured that there was ~5 wt% H₂O in excess of that required to react the entire sample to Ta + Fo.

All experiments were carried out in a half-inch piston-cylinder apparatus with NaCl as the pressure medium. A non-end-loaded piston-cylinder apparatus was used for experiments up to 15 kbar. These experiments were run "hot-piston-out", whereby they were pressurized to ~1 kbar above the desired experiment pressure, heated to experiment temperature, and then the pressure bled off. For experiments above 15 kbar an end-loaded piston-cylinder apparatus was used, and experiments were run "hot-piston-in", in which the pressure was taken to experiment pressure while heating.

In both apparatus, pressure was maintained within ±0.05 kbar during the experiment by means of a small motorized variable-volume oil reservoir attached to the pressure system. Pressure was calibrated at 600 °C using the reaction albite = jadeite + quartz (Holland 1980) and no pressure correction was found to be necessary for either apparatus. The pressure uncertainty is ±0.5 kbar.

Temperatures in the experiments were measured using Pt/Pt10Rh thermocouples with no correction for pressure, and controlled within ±1 °C. Capsules were flattened and placed perpendicular to the thermocouple, separated by a thin ruby disc to prevent puncturing during the experiment. Temperatures in the capsules were not calibrated independently, but an experiment on the melting of albite + H₂O was utilized to check that temperatures were not underestimated. At 11 kbar, 680 °C, 10° below the melting point determined by Goldsmith and Jenkins (1985), albite + H₂O did not melt.

Experiment products were examined optically and by XRD. In many cases, reaction direction could be determined from the optical examination but was inferred more unambiguously by comparing ratios of XRD peak heights between starting material and experiment product.

TABLE 1. Experimental results

Experiment number	Starting material	P (kbar)	T (°C)	Duration (hours)	Results
The reaction talc + forsterite = enstatite + H₂O using natural talc					
23	TFE	6.0	670	280	No reaction
21	TFE	6.0	679	312	No reaction
19	Expt 4	8.0	660	353	Ta + Fo ↑*
8	TFE	10.0	620	792	Ta + Fo ↑
5	TFE	10.0	640	258	Ta + Fo ↑*
7	TFE	10.0	640	845	Ta + Fo ↑*
4	TFE	10.0	660	237	No reaction†
3	TFE	10.0	680	163	En ↑
9	TFE	15.0	600	740	Ta + Fo ↑
10	TFE	15.0	620	580	Ta + Fo ↑‡
11	TF	15.0	620	674	No reaction
16	TFE	15.0	640	238	En ↑
18	TFE	20.0	580	431	Ta + Fo ↑ (+ Atg)
17	TFE	20.5	600	574	En ↑ (+ Atg)
1	TFE	20.0	660	93	En ↑
20	TFE	25.0	550	185	Ta + En + Atg
22	TFE	25.0	530	312	Ta + En + Atg
The reaction talc + forsterite = enstatite + H₂O using synthetic talc					
13	Expt 12	10.0	660	484	No reaction
14	STFE	10.0	680	390	En ↑§
15	Expt 14	10.0	680	520	En ↑
12	STFE	15.0	620	690	Ta + Fo ↑
The reaction talc + antigorite = enstatite + H₂O					
24	Expt 20	20.0	620	163	Ta + Atg ↑
25	Expt 22	20.0	640	289	En ↑

Notes: Starting materials: TFE = natural talc + synthetic forsterite + synthetic enstatite. TF = natural talc + synthetic forsterite + seeds of enstatite.

Results: All results are determined from changes in XRD peak height ratios from the starting material: ↑ = >30% increase, ↓ = >30% decrease. Behavior of Ta and Fo is consistent except as footnoted. The presence of a small amount of Atg can be ignored in experiments 17 and 18 (Atg in brackets) but not in experiments 20 and 22 (no brackets). See text for further discussion.

* Fo: En ↑ but no change in Ta: En.

† No change in Fo: En but Ta: En ↓.

‡ Fo: En ↑ but Ta: En ↓.

§ Fo: En ↓ but Ta: En ↑.

Only the ratio of Fo to En peak heights (hereafter Fo:En) could be used, because talc peak heights sometimes gave inconsistent results, as explained in the next section. When reaction was observed, the change in Fo:En was always >30%.

RESULTS

The reaction talc + forsterite = enstatite + H₂O

Results of experiments on the reaction Ta + Fo = En + H₂O are listed in Table 1 and plotted in Figure 3. The experiments using natural talc appear first followed by those using synthetic talc. Also listed are the results of two experiments on the reaction



In several experiments, the apparent reaction direction suggested by changes in Ta:En is different from that implied by changes in Fo:En (see Table 1). In those inconsistent experiments using natural talc, the apparent Ta:En either did not change or went down, whereas Fo:En increased or did not change. Thus, the reaction position

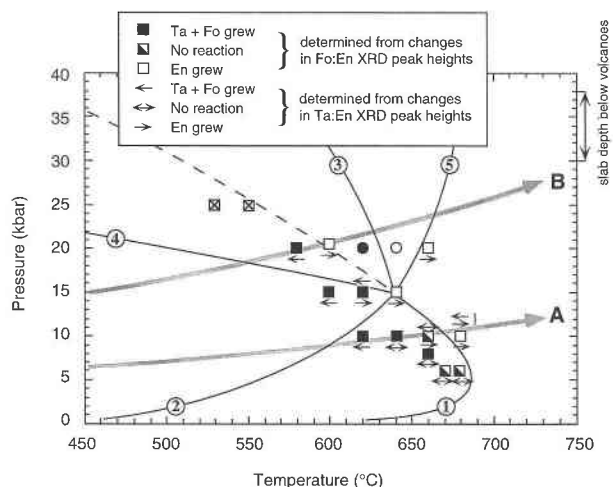


FIGURE 3. Results of experiments on the reaction $Ta + Fo = En + H_2O$ (squares). Reaction direction was inferred from changes in Fo:En XRD peak height ratios relative to the starting material. Arrows below squares show reaction direction inferred from Ta:En peak heights in experiments using natural talc; arrows above squares show Ta:En changes in experiments using synthetic talc. Experiments in which reaction direction could not be inferred because of significant antigorite growth are shown as crosses within squares, and experiments on the reaction $Ta + Atg = En + H_2O$ are shown as circles (filled = Ta + Atg grew, open = En grew). Also shown are calculated stable curves and the metastable extension of reaction 1 from Figure 2, two calculated P - T paths of a subducting slab (Peacock 1990) and the range in depths (in kbar of lithostatic pressure) of subducting slabs below subduction zone volcanoes (Gill 1981). See text for further discussion.

suggested by a comparison of Ta with En peaks would be at a lower temperature than indicated by a comparison of Fo with En peaks. The temperature difference is ~ 20 °C at 10 and 15 kbar.

In one experiment using synthetic talc, peak height ratios were also inconsistent. In this case, the relative behavior of Ta:En and Fo:En was opposite to that of the natural talc experiments in that Ta:En increased whereas Fo:En decreased. Thus, if only Ta:En changes were used to infer reaction position, at 10 kbar the position of the reaction involving natural talc would apparently be more than 20 °C below the position involving synthetic talc. Such a difference is considered unlikely because it has not been observed in previous studies on the higher-temperature reaction $talc = enstatite + coesite + H_2O$. Work in this laboratory has shown no difference in the position of that reaction using natural and synthetic talc at 30 kbar (Chinnery, unpublished data). However, other studies have yielded a lower-temperature reaction for the dehydration of synthetic talc than of natural talc (e.g., Bose and Ganguly 1995). This is one reason to suspect that Ta:En changes from the starting material do not give a true indication of reaction direction.

The unreliability of Ta:En peak height ratios was confirmed by rerunning an experiment using synthetic talc.

In the original experiment, the change in Ta:En suggested that talc had increased whereas the follow-up experiment actually produced a decrease in Ta:En (experiment 15 = rerun of 14). Clearly enstatite is stable at the conditions of those experiments, as indicated by the Fo:En changes. Thus, whether the assemblage Ta + Fo is stable or not, it appears that talc initially recrystallizes during all experiments, giving XRD peaks with different intensities from the starting material. The effect on natural talc is clearly different from the effect on synthetic talc, and hence their peak heights behave differently.

Experiment 10, in which the starting material contained $\sim 50\%$ enstatite, showed an apparent decrease in Ta:En, suggesting that enstatite is stable at 15 kbar and 620 °C. To test this result, experiment 11 was carried out at the same conditions using enstatite seed crystals in the starting material. If enstatite were stable at these P - T conditions, then an increase in its amount would be more noticeable from seeds. No reaction was observed, a result that is not conclusive, but may support the interpretation from the increase in Fo:En observed in experiment 10 that Ta + Fo is the stable assemblage at these conditions.

Experiments involving antigorite

At high pressures and low temperatures, experimental products contained antigorite. This is consistent with these conditions being at higher pressures than the reaction



Three different forms of antigorite-containing experimental products were produced. At 20 kbar, 580 °C (experiment 18) there is a significant decrease in the amount of En relative to both Ta and Fo from the starting material and some antigorite is also present. This experiment is probably at a temperature below the metastable extension of reaction 1, because such a strong increase in Ta + Fo is unlikely to occur far out of its stability field. However, it is possible that no reaction occurs on reaction 1; instead $Atg + Ta$ formed from $En + H_2O$ in reaction 3, which also produces an increase in Fo:En.

These proportions of phases contrast with the appearance of experiment 17 (carried out at 20 °C higher), which, relative to Ta + Fo, contains a little more antigorite than experiment 18 and considerably more enstatite. It is not possible to determine the absolute proportions of the phases, so it is not clear whether the increase in $En:(Ta + Fo)$ in experiment 17 relative to experiment 18 is because of crossing reaction 1 or an increase in the extent of reaction 4. It is assumed here that the contrast in $(Ta + Fo):En$ between experiments 17 and 18 is good reason for placing the metastable extension of reaction 1 between these two P - T points.

The changes in ratios of Ta, Fo, and En XRD peak heights in experiments 17 and 18 are roughly consistent with those in the lower-pressure experiments. This suggests that the appearance of antigorite can be ignored, as discussed above. However, the same is not true for ex-

periments 20 and 22 at 25 kbar in which Fo disappeared, but there was no change in Ta:En XRD peak height ratios. These are the only experiments using natural talc in which a decrease in Fo:En is not accompanied by an obvious decrease in Ta:En. Clearly, forsterite is reacting out in an antigorite-producing reaction. The compatibility diagrams (Fig. 2) show that in this field the stable assemblage is either En + Atg + Ta or Atg + Ta + H₂O, depending on the H₂O content of the bulk composition. The nominal H₂O content places the bulk composition very close to the Atg-Ta join, so at equilibrium, the sample should contain no more than a minor amount of enstatite. Given longer experiments, it is expected that enstatite would almost disappear from experiments 20 and 22.

The products of experiments 20 and 22, in which forsterite had reacted out, were used as starting material for the two experiments on reaction 3. Reaction direction was unambiguously determined in both experiments from changes in heights of Ta + Atg peaks relative to En peaks in XRD patterns. Consequently, these experiments bracket reaction 3 between 620 and 640 °C at 20 kbar. This is consistent with the position of this reaction calculated using TWQ (Figs. 2 and 3).

DISCUSSION

Comparison with calculated reactions and with previous experimental results

This reinvestigation of the reaction $Ta + Fo = En + H_2O$ was carried out because previous studies had produced a wide range of reaction positions at high pressures, none of which agreed with the position calculated using existing thermodynamic data. The new results do agree with the calculated reaction. As shown in Figure 3, the position of reaction 1 calculated using TWQ is in very good agreement with the brackets obtained in this study: it passes through the 10 kbar bracket and is at the high-temperature end of the brackets at 15 and 20 kbar. The reaction position calculated using THERMOCALC is 7 °C higher than the TWQ reaction at 10 kbar and 22 °C higher at 20 kbar, and so diverges slightly from the experimental brackets with increasing pressure. However, the divergence is not great, considering the uncertainties in the thermodynamic data used in the calculations, particularly in the equation of state of H₂O. The brackets on reaction 3 are also consistent with its calculated position using TWQ, and all experiments that produced antigorite lie in the calculated stability field of that mineral.

All the previous high-pressure brackets on reaction 1 are at higher temperatures than obtained in this study, the difference increasing from a few degrees Celsius at 10 kbar to ~100 °C at 20 kbar suggesting that perhaps temperatures in this study have been underestimated. However, this can be ruled out because the sample arrangement in the piston-cylinder apparatus is such that thermocouple and sample are equidistant from the furnace hot-spot. Moreover, the albite + H₂O melting ex-

periment demonstrated that measured temperature could not be more than 10 °C too low. Thus the new experimental results support the assertions of Chernosky et al. (1985) and Berman (1988) that the position of reaction 1 determined by Kitahara et al. (1966) is incorrect. The results of Kitahara et al. (1966) may be in error partly because of inaccurate piston-cylinder calibration, as suggested by Chernosky et al. (1985), and partly because of the poorly crystalline nature of their synthetic starting materials, as suggested by Berman (1988). However the increasing discrepancy from the calculated reaction with increasing pressure suggests that these are not the only sources of error. There are just three reversal experiments of Kitahara et al. (1966) in which Ta + Fo were apparently produced stably from En + H₂O. However, the amount of water in these experiments is not quoted. I suggest that it may have been sufficiently large that a significant amount of MgO and SiO₂ dissolved in the fluid during the experiment, with the resulting solid composition being displaced from enstatite toward forsterite (SiO₂ is more soluble than MgO). This produced the trace of forsterite observed in the experiments and the talc formed on quench.

The discrepancy with the observations of Ulmer and Trommsdorff (1995) of a positive *P-T* slope of reaction 1 up to ~20 kbar requires some consideration. The experiments that force the reaction to have a positive slope produced talc from a starting material of Atg + Fo + En (+ brucite to provide H₂O) at 18 kbar, and 690 and 710 °C (Fig. 1). According to the present study and the calculations using TWQ, at these *P-T* conditions, which are at temperatures above the invariant point (Figs. 2 and 3), the antigorite in the starting material should break down to Fo + En. The amount of antigorite in the experiments of Ulmer and Trommsdorff (1995) was observed to decrease but the amount of enstatite did not increase. The antigorite used was a natural sample, which contained minor impurities. Perhaps an Al-rich talc formed when antigorite broke down (chlorite formed at higher temperatures). Alternatively, talc may have formed on quench (or metastably) as antigorite broke down, because its structure is more similar to talc than to enstatite or forsterite. Because the experiments of Ulmer and Trommsdorff did not aim to determine talc stability, the position of reaction 1 does not affect their conclusions about the high-pressure stability of antigorite, but it does affect the stability of antigorite close to the invariant point. Clarification of this discrepancy between studies clearly requires a careful comparison of reaction positions determined using simple compositions in synthetic systems with those determined using complex natural compositions.

IMPLICATIONS FOR NATURAL TALC-BEARING ASSEMBLAGES

Talc typically forms by the hydrothermal alteration of ultramafic rocks or metamorphism of serpentinite. Much of the oceanic crust close to spreading centers experienc-

es hydrothermal alteration. Although most of the crust is basaltic, ultramafic rocks are also present at shallow levels in the crust, where they can become serpentinized (e.g., Cannat 1993). The extent of hydrothermal alteration of the mantle below the oceanic crust is unknown but may also be significant. Most of this oceanic lithosphere eventually is subducted. The H₂O incorporated in hydrous minerals is released and may trigger melting and subduction zone magmatism. The possibility of talc contributing H₂O to subduction zone magmatism can be evaluated by comparing its breakdown reactions with *P-T* paths of subducting slabs and with *P-T* conditions of subduction zone magma genesis. Two calculated *P-T* paths for the top of a subducting slab (Peacock 1990) are shown in Figure 3, along with the approximate range in lithostatic pressure of the slab below subduction zone volcanoes (Gill 1981). The calculated *P-T* paths are for two different ages of subducting lithosphere: 10 Ma (path A) and 50 Ma (path B).

Figure 3 shows that both *P-T* paths begin in the antigorite stability field, consistent with the common abundance of serpentine in altered peridotite. However the compatibility diagrams (Fig. 2) show that the H₂O content required to stabilize antigorite is greater than that required to stabilize talc. Consequently, if conditions in the slab are H₂O-undersaturated, talc might be stabilized instead of antigorite.

Under the relatively warm *P-T* path calculated for the subduction of young oceanic crust, reaction 2, Atg = Ta + Fo + H₂O, is crossed at ~600 °C, and so the amount of talc in the rock increases as antigorite reacts out. The talc then reacts with forsterite in reaction 1 at ~670 °C, which is close to the highest possible thermal stability of talc in equilibrium with forsterite. Under more typical cooler paths such as B, Ta + Fo does not survive above ~15–20 kbar, where reaction 4, Ta + Fo = Atg + En, is crossed. This reaction marks the highest pressure at which the assemblage Ta + Fo is stable. Clearly it occurs at a much shallower depth than the depth of magma generation in subduction zones, so the dehydration of talc in equilibrium with forsterite cannot be directly responsible for triggering subduction zone magmatism under any *P-T* path. However, under warm *P-T* paths, H₂O produced in reaction 1 may rise into a part of the subducting slab or overlying mantle wedge with a different bulk composition, allowing other assemblages involving hydrous phases to form. Under cool *P-T* paths, the antigorite produced in reaction 4 is able to transport H₂O to a greater depth until it dehydrates through reaction 5, Atg = Fo + En + H₂O. According to Ulmer and Trommsdorff (1995), this scenario may provide the H₂O for subduction zone volcanism.

Whereas Ta + Fo has a relatively low *P-T* stability, in bulk compositions more silica rich than enstatite, talc is still present above the Ta + Fo reactions and does not break down until the reaction talc = enstatite + quartz/coesite + H₂O is encountered. This occurs at ~800 °C in the quartz stability field (Chernosky et al. 1985; Jenkins

et al. 1991), decreasing to ~710 °C at 50 kbar (Pawley and Wood 1995). This result suggests that, in suitably silica-rich compositions, talc could transport H₂O to considerable depths in subduction zones. Silica enrichment of peridotite is not common at low metamorphic grades. However, SiO₂ solubility in H₂O increases with increasing pressure and temperature. As a result, silica metasomatism of mantle peridotite may occur at high pressures and temperatures in subduction zones (Manning 1994, 1995). Thus, metasomatism could convert Ta-Fo assemblages into Ta-En assemblages, with a corresponding expansion of the talc stability field.

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REFERENCES CITED

- Berman, R.G. (1988) Internally-consistent thermodynamic data for minerals in the system Na₂O-K₂O-CaO-MgO-FeO-Fe₂O₃-Al₂O₃-SiO₂-TiO₂-H₂O-CO₂. *Journal of Petrology*, 29, 445–522.
- (1991) Thermobarometry using multiequilibrium calculations: a new technique with petrologic applications. *Canadian Mineralogist*, 29, 833–855.
- Bose, K. and Ganguly, J. (1995) Experimental and theoretical studies of the stabilities of talc, antigorite and phase A at high pressures with applications to subduction processes. *Earth and Planetary Science Letters*, 136, 109–121.
- Cannat, M. (1993) Emplacement of mantle rocks in the seafloor at mid-ocean ridges. *Journal of Geophysical Research*, 98, 4163–4172.
- Chernosky, J.V., Day, H.W., and Caruso, L.J. (1985) Equilibria in the system MgO-SiO₂-H₂O: experimental determination of the stability of Mg-anthophyllite. *American Mineralogist*, 70, 223–236.
- Evans, B.W., Johannes, W., Oterdoom, H., and Trommsdorff, V. (1976) Stability of chrysotile and antigorite in the serpentinite multisystem. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 56, 79–93.
- Gill, J. (1981) *Orogenic andesites and plate tectonics*, 390 p. Springer Verlag, New York.
- Goldsmith, J. and Jenkins, D. (1985) The hydrothermal melting of low and high albite. *American Mineralogist*, 70, 924–933.
- Holland, T.J.B. (1980) The reaction albite = jadeite + quartz determined experimentally in the range 600–1200 °C. *American Mineralogist*, 65, 129–134.
- Holland, T.J.B. and Powell, R. (1990) An enlarged and updated internally consistent thermodynamic dataset with uncertainties and correlations: the system K₂O-Na₂O-CaO-MgO-MnO-FeO-Fe₂O₃-Al₂O₃-TiO₂-SiO₂-C-H₂O₂. *Journal of Metamorphic Geology*, 8, 89–124.
- Jenkins, D.M., Holland, T.J.B., and Clare, A.K. (1991) Experimental determination of the pressure-temperature stability field and thermochemical properties of synthetic tremolite. *American Mineralogist*, 76, 458–469.
- Kitahara, S., Takenouchi, S., and Kennedy, G.C. (1966) Phase relations in the system MgO-SiO₂-H₂O at high temperatures and pressures. *American Journal of Science*, 264, 223–233.
- Manning, C.E. (1994) The solubility of quartz in H₂O in the lower crust and upper mantle. *Geochimica et Cosmochimica Acta*, 58, 4831–4839.
- (1995) Phase-equilibrium controls on SiO₂ metasomatism by aqueous fluid in subduction zones: reaction at constant pressure and temperature. *International Geology Review*, 37, 1074–1093.
- Pawley, A.R. and Wood, B.J. (1995) The high-pressure stability of talc and 10 Å phase: Potential storage sites for H₂O in subduction zones. *American Mineralogist*, 80, 998–1003.
- Pawley, A.R., Redfern, S.A.T., and Wood, B.J. (1995) Thermal expansivities and compressibilities of hydrous phases in the system MgO-SiO₂-

- H₂O: talc, phase A and 10Å phase. *Contributions to Mineralogy and Petrology*, 122, 301–307.
- Peacock, S.M. (1990) Fluid processes in subduction zones. *Science*, 248, 329–337.
- Powell, R. and Holland, T.J.B. (1988) An internally consistent thermodynamic dataset with uncertainties and correlations: 3. Applications to geobarometry, worked examples and a computer program. *Journal of Metamorphic Geology*, 6, 173–204.
- Ulmer, P. and Trommsdorff, V. (1995) Serpentine stability to mantle depths and subduction-related magmatism. *Science*, 268, 858–861.
- Yamamoto, K. and Akimoto, S. (1977) The system MgO-SiO₂-H₂O at high pressures and temperatures—stability field for hydroxyl-chondrodite, hydroxyl-clinohumite and 10 Å-phase. *American Journal of Science*, 277, 288–312.

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