shown that after about 5 km, the fluid pressures begin to approach the rock pressure; the escaping fluids are almost lifting the rocks to escape. It is interesting to note that this effect may play a large part in the formation of enormous gravity slides where mountain-sized blocks of rock slide at very low angles. Friction is reduced by high-pressure gas lubrication. There is a considerable body of evidence to suggest that when wet sediments are deeply buried and progressively dehydrated, fluid pressures are about equal to (or possibly slightly exceed at some places) the total overburden or lithostatic pressure. Chemical reactions may thus proceed in a wet environment where water pressures and temperature are both simple functions of depth.

In principle the reactions are simple; in detail often very complex on account of the complex chemistry of the average rock. Examples of some simple reactions are:

 $\begin{array}{c} quartz + clay \rightarrow pyrophyllite \rightarrow silicate\\ 2SiO_2 + Al_2Si_2O_5(OH)_4 \rightarrow Al_2Si_4O_{10}(OH)_2 + H_2O \rightarrow Al_2SiO_5 + 3SiO_2 + H_2O\\ zeolite \rightarrow feldspar\\ SiO_2 + NaAlSi_2O_6 \cdot H_2O \rightarrow NaAlSi_3O_8 + H_2O\\ clay + feldspar \rightarrow mica \rightarrow silicates\\ Al_2Si_2O_5(OH)_4 + 2KAlSi_3O_8 \rightarrow 2KAl_2Si_4O_{10}(OH)_2 + H_2O \rightarrow 2KAlSi_3O_8\end{array}$ 

 $AI_{2}SI_{2}O_{5}(OH)_{4} + 2KAISI_{3}O_{8} \rightarrow 2KAI_{2}SI_{4}O_{10}(OH)_{2} + H_{2}O \rightarrow 2KAISI_{3}O_{8} + AI_{2}SiO_{5} + SiO_{2} + H_{2}O$ 

At rather high temperatures, carbonates may begin to lose CO<sub>2</sub> and become silicates:

calcite + quartz 
$$\rightarrow$$
 wollastonite + CO<sub>2</sub>  
CaCO<sub>3</sub> + SiO<sub>2</sub>  $\rightarrow$  CaSiO<sub>3</sub> + CO<sub>2</sub>

The low temperature assemblages of sediments are dominated by zeolitesclays-chlorites-silica-carbonates; at moderate temperatures micas-feldsparsepidotes-chlorites-quartz become dominant and at the highest temperatures when little water remains minerals such as feldspar-amphiboles-biotites-garnet begin to dominate the mineralogy. The P-T conditions for most of these dehydration reactions are approximately known from laboratory studies.

By the time we reach the highest grades of metamorphism the original mud which perhaps contained 20 per cent  $H_2O$ , will contain only 1 or 2 per cent. If burial or depression by convective forces is extreme, these slightly wet rocks may begin to melt. The rock now becomes a mixture of an aqueous silicate melt and a very dry residue. The melt is called magma and when we see a rock which shows the mixture we call it a migmatite. Such regions of the crust are often seen in the eroded roots of old mountain regions.

Rocks which are wet or partly wet melt at much lower temperatures than dry rocks. Consider a system  $A-H_2O$ , where a hydrate,  $A \cdot H_2O$  of great thermal stability is formed. The melting relations of A will normally be as in Fig. 4(a). Pressure increases most melting points. If a large amount of water is present,

## Phase changes in the earth's crust

enough to saturate the melt at all times, the melting in the wet system will appear as in Fig. 4(b). If the vapour-pressure curve of the hydrate intersects the melting curve as shown in Fig. 4(b), then the system A  $\cdot$  H<sub>2</sub>O (no excess water) will melt as in Fig. 4(c). These curves, intermediate between the totally dry and wet curves, are those that are most likely to be significant if melting occurs near the base of the earth's crust.

Experiment shows that the first fractions of melt likely to be formed by this process have a composition similar to rhyolites which occur as surface volcanic rocks and granites which form huge intrusive bodies of igneous rocks invading various crustal levels. The accumulation of this liquid into huge drops which rise, is possibly related to the viscosity contrast between a partially molten zone and unmelted cooler crust. Small drops of light liquid can rise rather rapidly in



**Fig. 4.** Melting relations in a system A with and without water. (a) The dry system. (b) The system with excess water,  $P = PH_2O$ . (c) The system when water is contained only in a hydrate A. H<sub>2</sub>O where the vapour-pressure curve of the hydrate intersects the depression of freezing curve.

the hot zone but will slow down in the cool zone. If we apply Stoke's law to such a problem we see why only large drops can invade the viscous solid crust.

As soon as partial melting commences dehydration reactions now proceed via the general process:

## hydrated minerals + anhydrous minerals

## melt+less hydrated residue

The water of dehydration now rises to the surface as part of a fluid phase dominated by silicate liquid. While the condition

## $P_{\rm fluid} \simeq P_{\rm Lithostatic}$

may still apply, it must be remembered that  $P_{H_2O}$  is only a part of  $P_{fluid}$  possibly a part as small as 10 per cent. Thus in the migmatite zones we must consider dehydration reactions where the solids are under greater pressure than the