SIGNIFICANCE OF GRANULITE METAMORPHISM FOR STABILIZATION OF
PLANETARY CRUST: CHARNOCKITE FORMATION AT KABBALDURGA; S. INDIA: ROLES OF
CO₂ AND H₂O; SPECULATIONS ON VENUS AND MARS; J. V. Smith and R. C. Newton,
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Stabilization of the Earth's crust is enhanced by loss of volatiles, thereby providing greater resistance to melting and deformation. We describe (i) conversion of amphibolitic gneiss to charnockite at Kabbaldurga, (ii) formation of granulite rocks by CO₂-rich solutions escaping from Archaean basaltic magmas, and (iii) speculations on crustal metamorphism in the inner planets.

Charnockite formation at Kabbaldurga (1). The development of the abundant suite of charnockite rocks (i.e. dark, green-to-brown, orthopyroxene-bearing granitoids) in Precambrian terrains is fundamental to evolution of the crust. Charnockite apparently derives from both igneous and sedimentary rocks (2) by metamorphism, in which associated pore fluids are low in H₂O because the associated opx-K-feldspar is limited to P(H₂O) < 700 b, being replaced by either biotite-quartz or melting at higher P(H₂O). Primary CO₂-rich inclusions are characteristic of granulite (3) and charnockite (4), and CO₂ probably dilutes the H₂O.

The Kabbaldurga quarry will become classic for partial conversion of Archaean amphibolitic gneiss (~2700 my) to charnockite. Diffuse patches and stringers of charnockite obliterate the gneissic foliation, and their textural positions strongly suggest local action of volatiles whose access is controlled by deformation. Rock analyses show little chemical change except for H₂O, CO₂ and perhaps K(5). The Kabbaldurga occurrence is one of many in S. Karnataka. These lie in the northern fringe of development of charnockite massifs in the south (6), and provide a key to the wholesale conversion of continental crust to granulite.

Optical petrography and electron microprobe analyses show that increasing alteration of acid gneisses causes green-brown discoloration of the feldspars, ultimate loss of hornblende and biotite with growth of orthopyroxene. Basic inclusions (probably relics of basaltic dykes) transform via symplectites to equigranular diopside-hornblende plagioclase rocks. The ubiquitous green veins which lase the feldspar consist of Fe-rich, Al-poor chlorite (SiO₂:33 Al₂O₃:11 total Fe as FeO 32.2 MnO:0.2 MgO 11.6 CaO 0.4 wt.%) and Mn-bearing calcite (e.g. 4.8% MnO). These veins account for the greenish color of the feldspars, and represent texturally the waning phase of metamorphism.

We conclude that (i) the granulite metamorphism involved localized action of volatiles low in H₂O (because of absence of melting), and by implication rich in CO₂, with no major change of P and T, (ii) charnockitization occurred at high level, probably at P = 3 to 5 kb, (iii) the waning phases of metamorphism were characterized by cooler solutions, richer in H₂O, which were confined to localized channels and which deposited chlorite and Mn-calcite.

Thus we envisage copious streaming of CO₂-bearing solutions along pathways generated by brittle deformation, and go on to consider how granulites may be formed by action of CO₂-rich solutions ascending through the crust during Archaean time.

Formation of granulite rocks. Key aspects of the postulated charnockitization of the Archaean crust include (i) the source and vector of the carbonic solutions, and (ii) the possible P-T regime which would avoid melting or capture of CO₂ into scapolite.

Decarbonization of the mantle is the most likely source, but free CO₂
cannot coexist with peridotite under any but extreme geothermal conditions, as in a rising plume, because of the high thermal stability of mantle carbonates (7). Basaltic magma would be generated in such an upwelling, and there should be insufficient carbonate to saturate the magma with CO₂ (8, p.119), so that basalt emplaced copiously into the lowermost crust is the likely CO₂ vector (9, p.248). During crystallization, nearly pure CO₂ is emitted while H₂O is retained quantitatively in the rest-magma at deep crustal pressures (8). The congealed basalt is a massive addition to the continental base, and, as geotherms steepen over the rising plume, partial melting provides the voluminous tonalite magmas which rise to give higher-level Archaean terranes (10). Widespread granulite metamorphism and depletion of LIL-elements are contemporaneous (11).

Fig. 1 shows how CO₂ could be supplied by crystallizing basalt at the base of the continental crust with the Archaean geotherm lying between moderate (12) and extreme (13) limits still under controversy. The possible thickness of the crust is limited by the dry basalt solidus to 15-40km. The passage of free CO₂ through a deep crust, either of basic or intermediate composition, is constrained by two curves for the stability of orthopyroxene & scapolite [of composition essentially 3 labradorite + Ca(CO₃,SO₄)] relative to plagioclase, diopside + quartz + CO₂. The two curves, labeled AN90 and AN50, respectively, were constructed from experimental (14) and thermodynamic (15) data. Streaming of CO₂ could have produced intermediate (tonalitic) scapolite-free granulites to within about 12km of the surface under a very steep geotherm, and to even higher levels in acid rocks with more sodic plagioclase. Charnockitization of the Kabbaldurga acid gneisses at 600°C and 3-5kb would require only moderately steep geotherms. At depths less than several km on Earth, the process might not operate because of low temperatures (<500°C) and readily accessible H₂O to dilute the CO₂.

Speculations on Mars and Venus. Fig. 2 summarizes pertinent phase equilibria and model pressure-temperature curves for Mars and Venus. For Mars, amphibole...
Fig. 2. Controls on storage of CO\(_2\) and H\(_2\)O in Venus and Mars. All curves from (16), except AA, BB from Fig. 1. Dotted and dashed lines are estimated pressure-temperature curves for Mars and Venus. Generalized stability curves for phlogopite mica and amphibole are compared with the solidus for H\(_2\)O-saturated peridotite. Heavy lines show stability in presence of CO\(_2\), and mica would become unstable at G and H (23 and 29kb) for the depicted P-T curve in peridotite with the same Fe/Mg ratio as Earth. If Mars is richer in Fe\(^{2+}\) than Earth, these depths are reduced. Storage of CO\(_2\) in solid carbonate should cease at I (33kb), but trapped CO\(_2\)-rich magma could exist below I to give a low-velocity zone.

For Venus, we prefer to use the higher of the P,T curves, which is based on analogy with an oceanic geotherm rising from 470°C at the surface, and indeed earlier PT curves should be hotter. For the present curve, CO\(_2\) would be liberated at all depths above F, and the released CO\(_2\) would flush out H\(_2\)O from overlying rock by analogy with Kabbaldurga charnockite. Scapolite is restricted to a shallow layer above J for basic rocks, and cannot occur in an andesitic crust. This is consistent with the CO\(_2\)-rich atmosphere. A thickness of (say) 10km basalt with (say) 5% scapolite (~5 wt.% CO\(_2\)) corresponds to only ~25m of limestone, which is much less than the amount in the Earth, and much less than the CO\(_2\)-equivalent in the Venus atmosphere. Can volatiles be returned by subduction? No obvious mechanism is available for H\(_2\)O, and the implication is that Venus is essentially dry. Thus any primordial water must have lost its H through the atmosphere. For CO\(_2\), subduction is possible for scapolite-bearing basalt, but may be less efficient than subduction of limestone on Earth. In general, the Venus crust should show the greatest development of granulite for any planet.