Discovery of New Types of Chain Silicates By High Resolution Electon Microscopy

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Summary The existence of infinite one-dimensional structures consisting of linked triple-, quadruple-, and sextuple-chains of SiO_4 tetrahedra has been unambiguously established by electron microscopy.

DURING the course of detailed studies of nephrite jade using direct, lattice-imaging techniques at resolutions down to 0·38 nm, we have discovered several novel features which throw new light on the structural principles upon which chain silicates are built. These discoveries demonstrate, *inter alia*, the occurrence of multiple chains (3-, 4-, 6-, and greater; see Figure) of condensed tetrahedra, and serve to eliminate the hitherto puzzling absence, amongst rock-forming minerals, of progressively wider strips of linked-tetrahedra lying between the single and double chains (pyroxenes and amphiboles respectively) on the one hand and the infinitely wide chains (*i.e.* the sheet silicates) on the other.

The principles of high resolution electron microscopy (HREM) have been given elsewhere.[1] For present purposes the essential points to note are: (i) lattice images of very thin specimens (<10 nm) can directly and quantitatively reveal periodicities, or infractions to regularity, at

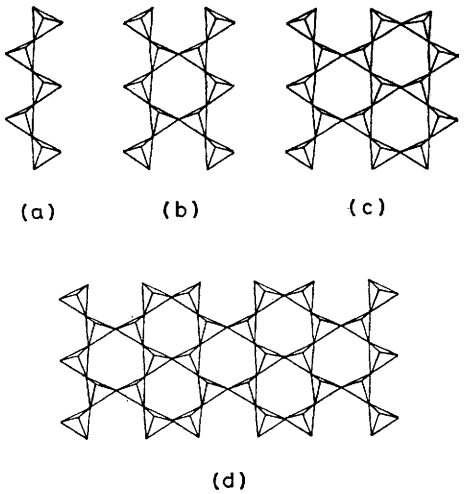

FIGURE. (a) Single-chain (pyroxene), (b) double-chain (amphibole), along with the newly discovered triple (c) and sextuple (d) chains which, together with multiply linked structures, have been revealed by high resolution electron microscopy.

the unit cell level; and (ii) techniques are available,[2] based on the so-called, dynamical, multi-slice procedures, which enable electron microscopic image contrast for a given structure to be accurately computed, so that a stringent test for particular assumed local structures is possible.

Apart from identifying one-dimensionally extended single-, triple-, quadruple- and sextuple-chains occurring as isolated faults in a surrounding matrix of unfaulted double-chain (amphibole) structure (see our previous reports, ref. 3), evidence has also been found for the existence of:

(a) ordered sequences of triple-chain structure (total width *ca.* 40 nm), thus constituting a new structural type, in coherent topological contact with surrounding amphibole structure;

(b) isolated double-chains within a sequence of 'ordered' triple chains (*i.e.* a unit-cell width of amphibole intergrown with surrounding triple-chain structure);

(c) linear structural faults which predicate a degree of sub-unit-cell rearrangement so seemingly improbable as not to have been hitherto considered. Thus over a distance of *ca.* 10 nm along the *c*-axis (chain axis), a contiguous pair of triple chains gradually becomes a triple and double pair, as if the contiguous structures had undergone a twist, and a single pyroxene chain is inserted into the surrounding matrix to preserve regularity.

Nephrites from widely different geological provenances (kindly supplied by Dr. A. C. Bishop and his staff, British Museum) have been examined and these show large variations in internal structure, though not large enough to be detected by conventional *X*-ray structural methods.[1,4]

Since this work, to be reported more fully elsewhere, was begun, Veblen *et al.*[5] have confirmed the existence of triple- and other multiply-linked chain structures, in particular two minerals with ordered triple chains.

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