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Laumontite and Heulandite-Clinoptilolite Pseudomorphous after Jurassic Gastropods from Ponganui, New Zealand

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ABSTRACT. At two rich fossil localities in Ponganui (eastern Port Waikato), zeolite-facies, mid-Jurassic metasandstones and metasiltstones of Murihiku Supergroup contain high-spired gastropods whose tests have been pseudomorphed by laumontite. Upper whorls of the spires are infilled by heulandite-clinoptilolite and laumontite, accompanied by minor potash-feldspar, quartz and pyrite. Body whorls are infilled by zeolitised rock matrix. Laumontite has low alkali and is closer to the ideal formula than other laumontites reported from metamorphic rocks of New Zealand. Dehydration of laumontite to leonhardite is indicated by x-ray diffraction: a = 14.75, b = 13.13, c = 7.57Å, ß = 111.84°. Thermal analysis of heulandite-clinoptilolite gives ambiguous results consistent with the transitional composition these crystals possess within this mineral series. The crystal chemistry and associations of both zeolites is in accord with genetic models proposed by Boles and Coombs for similar Murihiku metasedimentary zeolites.

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Zeolite facies metamorphism is widely developed in thick, Triassic to Jurassic Murihiku Supergroup sandstones and siltstones of both North and South Islands of New Zealand (Coombs, 1954, 1960; Coombs *et al.*, 1959; Boles, 1977; Boles & Coombs, 1975, 1977; Ballance *et al.*, 1981; Clark, 1982). Characteristic mineral assemblages in the metasediments are: i) heulandite-analcime-quartz typically found in the upper levels of the stratigraphic succession and correlated with probable depths of more than 1 km and less than 10 km; and ii) laumontite-albite-quartz-chlorite and quartz-albite-adularia occurring predominantly in the lower half of the column and correlated with at least 9 km and perhaps as much as 20 km depth.

Typically, the zeolite minerals have developed at the expense of volcanic glass shards. They also occur as replacements for detrital minerals, particularly plagioclase, and as cement, fine-grained matrix, joint fillings and veins. In places laumontite replaces fossil molluscs and brachiopods (Coombs, 1954; Boles & Coombs, 1977; Clark, 1982). At two localities in mid-Jurassic metasediments of the Port Waikato section, laumontite is found consistently replacing high-spired gastropod shells, whose upper whorls are infilled by laumontite and heulandite associated with minor potash feldspar and quartz. Tests of other fossil species among the rich assemblages occurring at these localities are inconsistently and only partially zeolitised, e.g., *Nannolytoceras* sp., *Rotularia* sp., rhynchonellids (Table 1 [see Appendix]).

Setting

The Jurassic rocks of the Port Waikato district represent the northernmost and stratigraphically youngest exposures of Murihiku Supergroup in New Zealand. They consist of 6500 m of indurated, immature, volcanogenic sandstones and siltstones with occasional conglomerates and range in age from Aratauran to Puaroan (Purser, 1961; Rodgers & Grant-Mackie, 1978). Ballance *et al.* (1981) consider the original sediments to have been deposited as part of a fore-arc sequence on the southern margin of Gondwana. The beds are folded in a syncline striking north-north-west to south-south-east, with a small parallel anticline developed on the western limb. The mid-Jurassic rocks of interest outcrop in the east in the Ponganui-Opuatia area (lat. 37°23.5'S; long. 174°49.5'E).

Opuatia Cliff. Eighty metres of Temaikan strata are exposed on the bank of a small tributary of Opuatia Stream (NZ Fossil Record File locality R13/f6613, G.R. R13/721228 [Grid References based on national 1000 metre grid, New Zealand Mapping Series 260, 1:50,000]). Well jointed, hard, grey-brown, silty sandstone beds, 0.3-2 m thick, strike across the cliff face, alternating with thinner, more intensely jointed siltstones. Fossils occur throughout the exposure and the fauna (Table 1 [see Appendix]) is regarded as being of upper Temaikan age (Rodgers & Grant-Mackie, 1978; cf. Purser, 1961).

Moewaka (Ponganui) Quarry. Hard green-grey, coarse sandstone, approximately 5 m thick, is exposed in a former quarry on a farm track 1.5 km due south of Opuatia cliff (NZ Fossil Record locality no R13/f6500, G.R. R13/716219). A rich, shallow-water, dominantly molluscan fauna (Table 1 [see Appendix]) is considered to be of near basal Heterian age (Rodgers & Grant-Mackie, 1978).

Most of these fossils occur as internal and external moulds and steinkerns. Belemnite guards, brachiopods and *Rotularia* are found consistently in calcareous form, albeit darkly stained, but moulds are more common even among these, particularly in deeply weathered portions of the exposures. The pink and white casts of the zeolitised high-spired gastropods contrast with the other fossils, particularly when exposed on freshly broken rock surfaces (Fig.1). Often these gastropod tests break longitudinally to show zeolite crystals partly or completely infilling upper whorls. Only rarely does the rock break to show the outer surface of the cast and hence its sculpture.

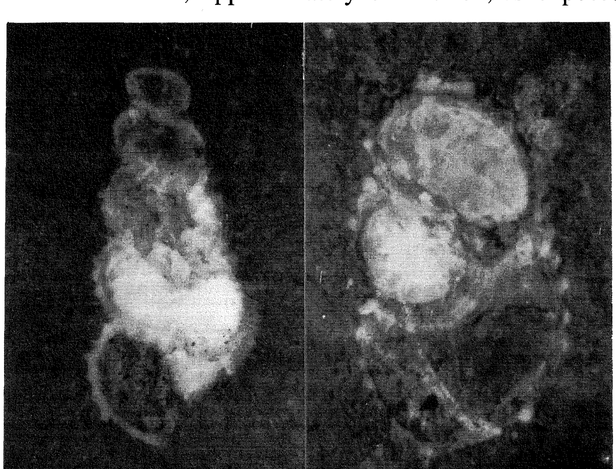

Fig.1. Photomicrographs of polished sections through zeolitised gastropod tests, Opuatia Cliff. Base of left photo equals 6.5 mm; base of right photo equals 4 mm.

Petrography

Host sandstones are fine- to medium-grained volcanoclastic wackes containing rounded granules and pebbles of non-porphyritic lava. Abundant plagioclase laths (some zeolitised, some fresh), occasional grains of quartz and chloritised ferromagnesians, and numerous crystals of zeolites are scattered through a dense matrix of chlorite, clays and zeolites, presumably derived in part from devitrified glass. Body whorls of the gastropod tests have been occluded by extensively zeolitised sediment differing from that of the surrounding rock in being appreciably finer grained (Fig.2a). One specimen (Auckland University Palaeontology Collection G6963) has the upper portion of the body whorl stoppered by well sorted, angular to subrounded, highly altered volcanoclastic granules set in a zeolite matrix (Fig.2b). Small grains of pyrite are scattered throughout both the zeolite infilling and the enclosing rock matrix.

All shell material has been replaced by coarse crystals of laumontite with no obvious pre-cursor mineral phase other than original carbonate. Additional laumontite grows chamberwards as passive syntaxial rim cement and replaces earlier-formed, coarse heulandite-clinoptilolite. A faint yellow-brown stain often marks the former inner wall of the test (Fig.2b). Where this stain separates passive infilling laumontite from wall-replacing laumontite there is an approximation to optical continuity across the stain. Where the stain is absent complete continuity may be present. Where infilling laumontite replaces sediment in body whorls it is generally finer grained and appears more translucent than crystals replacing the test with which it is in contact.

X-ray powder diffraction analysis of zeolite fragments of the replaced shell and from within the casts showed strong signatures for both laumontite-leonhardite and heulandite-clinoptilolite. Weakly developed major reflections of both quartz and potash feldspar occurred in some samples.

Crystal chemistry

Analyses. Hey (1932: 57) showed that in "a first class" zeolite analysis the sum Al+Si should equal 40±0.20, calculated on the assumption of 80 oxygens per unit cell. Coombs (1952) took Al+Si = 24±0.12 for 48 oxygens. Presumably for 72 oxygens Al+Si = 36±0.18.

Gottardi & Galli (1985: 1-2) suggest discarding analyses of zeolites where the "balance error"

$$E\% = \frac{(Al+Fe) - (Li+Na+K) - 2(Mg+Ca+Sr+Ba)}{(Li+Na+K) + 2(Mg+Ca+Sr+Ba)} \times 100$$

lies outside ±10%. This test has an advantage in being applicable to microprobe analyses where water has not been determined and, hence, where a check on the analysis total is not possible (cf. Hey, 1932). Further, the balance error, E, affords a useful check on possible volatilisation of light elements during microprobe analysis (cf. Boles, 1972). While a high E does not imply that volatilisation has occurred, a low E would suggest this has not been the case.

Boles (1972) adopted stringent procedures to guard against such volatilisation during microprobe analysis. In part this involved low sample currents of 28-30 x 10^{-9}A at 13.5kV and a beam diameter of 10 m. In the present study an energy dispersive system was employed (Link 860 analyser fitted with an L25 detector). Operating currents of 0.5 x 10^{-9}A at 15kV were nearly two orders of magnitude less than those used by Boles. Even when the beam diameter was reduced to 3 µm little or no volatilisation appeared to take place.

Twenty four spot analyses were made of four mineralised gastropod tests. All laumontite results lay within both Hey's and Gottardi & Galli's limits. However, several heulandite analyses did not. Some fulfilled Hey's criterion, while at the same time possessing E values ranging from 11 to 16% (e.g., Table 2, cols 1 & 2 [see Appendix] [cf. Fig.5]). All of Coombs' (1952) and Boles' (1972) results meet or lie close to the required limits. All of Clark's (1982) analyses are plotted in Figures 4 to 7 as representing the few data available for North Island Murihiku rocks, but only those which fit the above criteria are considered in subsequent discussion and tabulations (e.g., Table 3 [see Appendix]).

Laumontite and leonhardite. Euhedral prismatic crystals infilling the upper chambers show well developed forms {110}, {100}, {001}, {201} and possibly {010}. Crystals average 0.2-0.3 mm long and 0.05-0.1 mm across the prism (Fig.3a) being of comparable size to those replacing carbonate in test walls.

Least squares calculation of x-ray powder data of Ponganui laumontites gives unit cell dimensions consistent with their being partially dehydrated to leonhardite (e.g., sample G6964 gave a = 14.753, b = 13.132, c = 7.574Å, ß = 111.84° (V = 1362Å^3)). Representative analyses of laumontites replacing shell, infilling upper whorls and occurring as grains in matrix infilling the body chambers are shown in Table 2, cols 4-8 [see Appendix], along with calculated unit cell contents. A summary of these is compared with the analysis of Coombs (1952) and those of Clark (1982) in Table 3 (see Appendix) and Figure 4.

The Ponganui results plot towards the more aluminium rich end of Clark's North Island Murihiku Supergroup results but are less aluminous than Coombs' sole South Island analysis (Fig.4). Generally, the Ponganui crystals are more calcium-rich, alkali-poor and more closely approximate the ideal laumontite composition, $CaAl_2Si_4O_{12}.nH_2O$, than do any other Murihiku zeolite facies analyses (cf. Boles, 1977). Spot analyses failed to show any systematic variation in alkali content

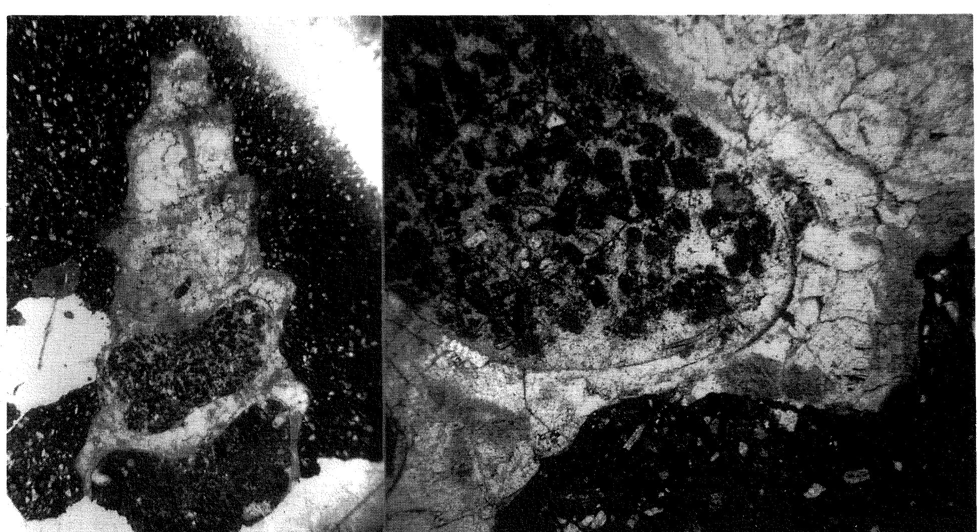

Fig.2. Photomicrographs of thin section through laumonitised test, Moewaka Quarry. Left: replaced and infilled test in fine sandstone; body whorl contains finer silt matrix; base of photo equals 10.5 mm. Right: coarse laumontite crystals replacing test walls with dark line marking original inner wall and junction between pore-filling syntaxial laumontite; upper portion of body whorl has well sorted granules set in zeolite matrix; base of photo equals 2 mm. Plane polarised light.

throughout a single crystal, group of crystals or a cast as a whole, indicating that substitution has occurred by free cation exchange, restricted solely by charge balance requirements (cf. Coombs, 1952; Mumpton, 1977).

Thermal analytical (TGA and DTA) behaviour of Ponganui laumontite (Fig.8a,b) shows typical medium to strong endothermal events peaking close to 100, 280 and 400°C corresponding to loss of 3, 5 and $5H_2O$ respectively (Gottardi & Galli, 1985); the staged weight loss corresponding to the main dehydration events. Decomposition of the zeolite structure starts at around 680°C, peaking at about 800°C followed by a strong endothermal base line drift. No exothermic event (sintering) was observed above 950°C as reported by Smykatz-Kloss (1974).

Heulandite-clinoptilolite. Crystals infilling tests are lamellar (Fig.3b) as is typical of this zeolite species, the habit being developed in a manner more akin to that of clinoptilolite rather than heulandite (Gottardi & Galli, 1985). Crystals are up to 0.5 x 0.2 mm across the (010) lamellae surface and about 0.05 mm thick.

Representative analyses of Ponganui heulandites are given in Table 2, cols 1-3 [see Appendix]. Results which fulfil the criteria of Hey (1932) and Gottardi & Galli (1985) posses Si/Al ratios in the range 3.81-4.11. They bridge the arbitrary dividing line of Boles (1972) between silica-rich heulandites (Si/Al : 3.5-4.0) and silica-poor clinoptilolites (Si/Al : 4.0-4.5), as well as lying within and near the 3.75-4.00 Si/Al range for which Boles found few published analyses (cf. Fig.5). On the basis of the criterion of Mason & Sand (1960) all Ponganui heulandites (s.l.) would be heulandites (s.s.) with (Na+ K) much less than Ca (Fig.6).

Whatever the subtleties of this arbitrary nomenclature, the Ponganui results resemble other Murihiku results which range "continuously from typical heulandites to relatively silica-poor, Ca- and K-rich clinoptilolites" (Boles & Coombs, 1977: 989). However, although K/Na is comparable to Murihiku heulandite-clinoptilolites with comparable Si/Al ratios (Coombs, 1954; Boles, 1972; Clark, 1982) total alkalis and magnesium are generally lower than Boles (1972) found to be the case among South Island examples (cf. Figs 6,7).

The x-ray diffraction signature for this zeolite was more like clinoptilolite than typical heulandite (cf. Boles, 1972; Mumpton, 1960) but no powder diffraction data free from patterns of other minerals, particularly laumontite-leonhardite, could be obtained to permit refined analysis. Further, difficulties were experienced in confirming the thermal character of the species. The limited (and impure) separates available for analysis (less than 20 mg) necessitated running both the differential and thermogravimetric units of the Shimadzu DTG-2B analyser at maximum sensitivities of ±10 μv and 50 mg (full scale) respectively. Signals recorded were small and a minimum error of at least ±0.5 mg, corresponding to ±3wt%, is believed present in the gravimetric analysis. The record is ambiguous (Fig.8c,d) but is somewhat akin to that shown by Mumpton (1960) for clinoptilolite. In broad terms the TG curve is also similar to that of clinoptilolite (Gottardi & Galli, 1985; Ullrich *et al.*, 1988) with no abrupt changes in gradient as may occur with heulandite (s.s.). Atypically, for clinoptilolite, onset of initial weight loss is largely delayed until after 100°C. This probably results from the samples used being those which had been held in vacuo for microprobe analysis. The minor endothermal event close to 300°C in the differential thermal curve (Fig.8d) could indicate thermal behaviour of heulandite *type 2* (Gottardi & Galli, 1985). Assuming the record as a whole is correct, such ambiguous behaviour may reflect the transitional position which the Ponganui gastropod crystals occupy within the heulandite-clinoptilolite series.

Discussion

The zeolites described here are distinctive within

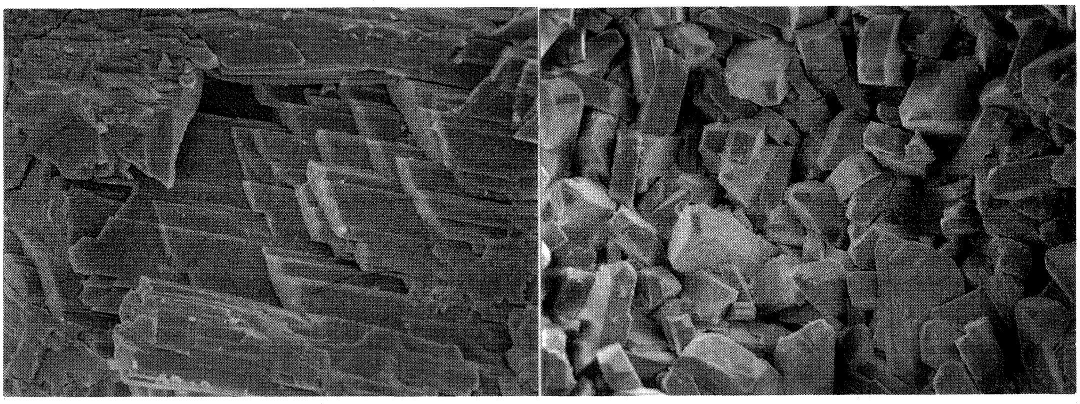

Fig.3. Scanning electron photomicrographs of drusy zeolites passively infilling upper whorls of zeolitised gastropod tests, Ponganui: (left) laumontite, base of photo equals 0.15 mm; (right) heulandite, base of photo equals 1.2 mm. Photos: Susan F. Courtney.

the Murihiku Supergroup in a) the markedly low levels of sodium, magnesium and potassium in both species, b) the completeness and consistency with which the high-spired gastropods have been replaced in each fossil assemblage, and c) the presence of both laumontite and heulandite infilling formerly empty shells whorls.

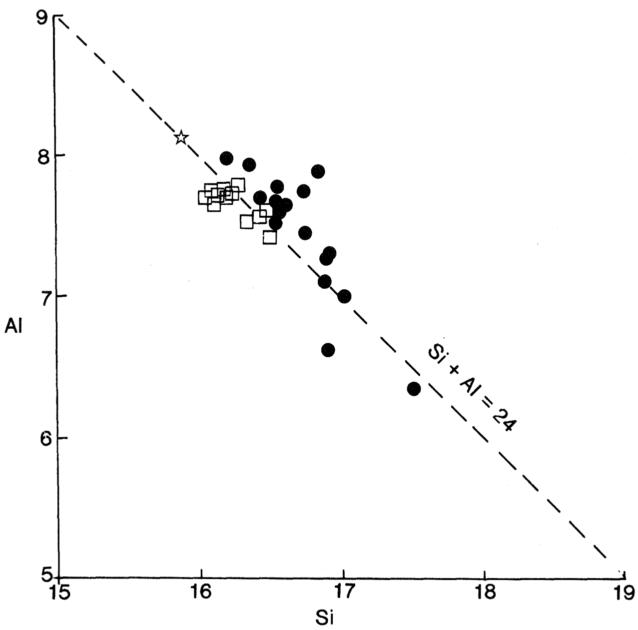

Fig.4. Si:Al plot of laumontites analysed from Murihiku Supergroup metasediments. Analyses based on 48 oxygens. Star = Coombs (1952); solid circles = Clark (1982); open squares = this study.

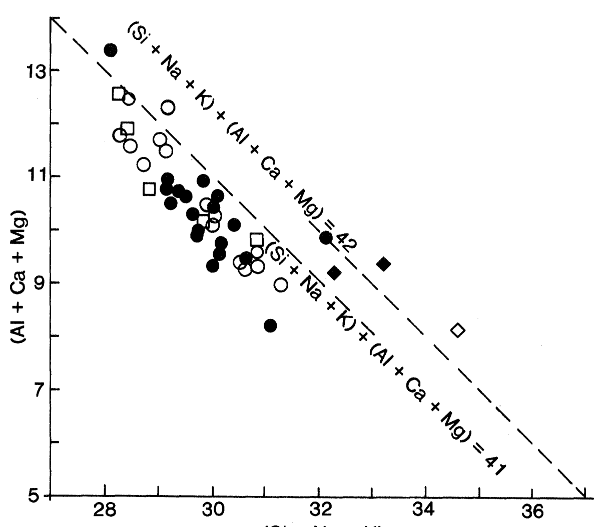

Fig.6. (Al+Mg+Ca):(Si+Na+K) diagram for heulandite-clinoptilolites analysed from Murihiku Supergroup metasediments. Analyses recalculated on a basis of 72 oxygens. Open circles = South Island analyses (Boles, 1972; Boles & Coombs, 1975); solid circles = North Island analyses (Clark, 1982); open squares = this study; open diamond = Miocene Waitemata Group (Sameshima, 1978); solid diamond = Miocene Waitemata Group fossil pseudomorphs (Rodgers & Sameshima, 1978).

Precise details of the mineralisation sequence are unclear. Available textural evidence suggests occlusion of the aragonite test with sediment was followed by transportation and crystallisation of heulandite in the upper chambers, probably with little alteration to the shell material. Laumontitisation of shell carbonate

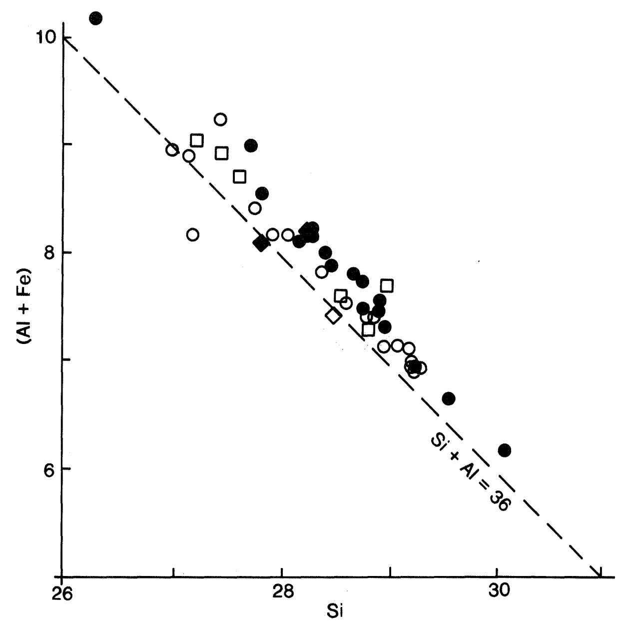

Fig.5. Si:Al+Fe plot of heulandite-clinoptilolites analysed from Murihiku Supergroup metasediments. Analyses based on 72 oxygens. Open circles = South Island analyses (Boles, 1972; Boles & Coombs, 1975); solid circles = North Island analyses (Clark, 1982); open squares = this study; open diamond = Miocene Waitemata Group (Sameshima, 1978); solid diamond = Miocene Waitemata Group fossil pseudomorphs (Rodgers & Sameshima, 1978).

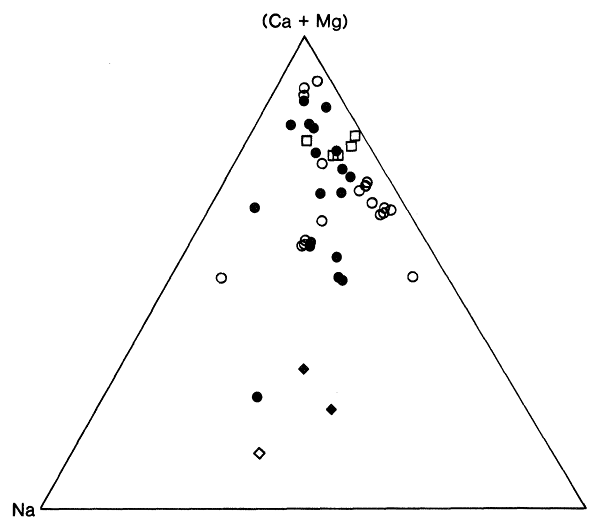

Fig.7. (Mg+Ca):K:Na ternary diagram for heulandite-clinoptilolites analysed from Murihiku Supergroup metasediments. Open circles = South Island analyses (Boles, 1972; Boles & Coombs, 1975); solid circles = North Island analyses (Clark, 1982); open squares = this study; open diamond = Miocene Waitemata Group (Sameshima, 1978); solid diamond = Miocene Waitemata Group fossil pseudomorphs (Rodgers & Sameshima, 1978).

followed with heulandite persisting metastably, and subsequent partial replacement of heulandite by further laumontite. However, the possibility exists that the tests were laumonitised prior to transportation as may have occurred in a selectively clinoptilolitised Miocene thanatocoenose (Rodgers & Sameshima, 1978).

While heulandite is common in the upper levels of the Murihiku stratigraphic pile and laumontite widely developed in the lower levels, neither mineral shows a simple zonation related to depth of burial. Clark (1982) found laumontite to be the predominant zeolite in North Island Murihiku Jurassic rocks. Boles & Coombs (1977: 982) concluded "The complexity of mineral distribution patterns is attributed to the interplay of many factors, including the effects of parent materials which include glass and less highly unstable mineral relics, incomplete reactions, permeability, ionic activity ratios in stratal waters, P_{CO2}, relationship of P_{fluid} to P_{total} in undisturbed beds and in occasional fractures, and the effects of rising temperature following deep burial". Both Boles & Coombs and Clark found the composition of individual zeolite species was related to and controlled by the composition of the parent material. While equilibrium is not generally attained, it is approached on a micro-domain scale. In particular, mass transfer of Ca and Na have occurred on a microscopic and sometimes larger scale.

Such considerations are apposite in understanding the peculiarities of the Ponganui zeolitisation. Local microscale conditions can account for the mineralisation without recourse to regional considerations such as

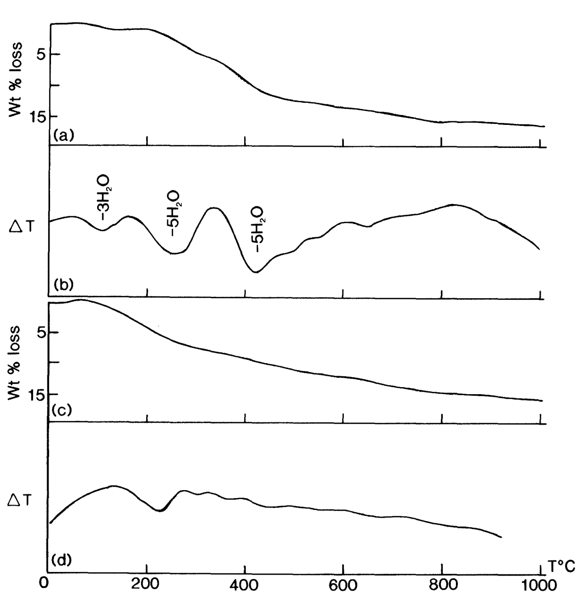

Fig.8. Thermal analytical records of Ponganui zeolites (a) thermogravimetric trace of laumontite infilling and replacing gastropod test, Moewaka Quarry; (b) differential thermal record of same sample; (c) thermogravimetric trace of heulandite-clinoptilolite infilling gastropod test, Opuatia cliff; (d) differential thermal record of same sample.

depth of burial (e.g., Ballance *et al.*, 1981.)

Boles & Coombs (1977: 997) described the replacement of fossils by laumontite by the reaction

$$CaCO_3 + 2Al^{3+} + 4SiO_2 + 7H_2O \rightarrow CaAl_2Si_4O_{12}.4H_2O + CO_2 + 6H^+;$$

probable sources of Al being clay minerals and albite. These authors give no analyses of laumontites replacing fossils in this or earlier papers and it is notable that the present laumontite and associated heulandite-clinoptilolite have calcium/total alkali ratios higher than most other Murihiku Supergroup analyses.

Calcium carbonate is generally absent from most rocks of the Supergroup. Fossils are not abundant and calcareous rocks are the exception, being represented by the occasional bioclastic limestone lens or calcareous concretions within non-calcareous mudstones. The calcium component for most Murihiku Supergroup zeolites has been derived from the clastic silicate minerals and glasses which also contain appreciable alkali levels. If the present mineralisation is in the main the product of microscale element transfers then zeolite composition would be controlled principally by the composition of the carbonate shell, whose dissolution would determine the relative calcium and alkali activities of the mineralising fluids. Laumontite is known to form preferentially at low temperatures under appropriate chemical conditions. Sands & Drever (1978) related formation of laumontite in DSDP core at Site 323 (Bellinghausen Abyssal Plain) instead of the more common heulandite, to high Ca concentration [?activity] of interstitial waters; highest temperature of the deepest sample was less than 60°C. Presumably, crystallisation of laumontite was initiated at Ponganui when dissolution of shell carbonate had raised calcium activity of the interstitial solutions to a sufficient level.

Boles & Coombs (1977) also concluded that laumontite cements found high in the Murihiku stratigraphic sequence may have formed from quartz-equilibrated waters at quite low temperatures similar to those from which clinoptilolite-heulandite may crystallise in a high a_{SiO2} environment controlled by glass. These authors (1977: 999) indicate that while laumontite can exist in equilibrium with a quartz-saturated fluid, at the same P and T heulandite may exist with solutions of even higher a_{SiO2}. Thus, earlier formed heulandite can persist metastably until its conversion to laumontite plus quartz and Na/K - feldspars is activated by rising temperatures or by lowered p_{H2O}:

$$Ca_4KAl_9Si_{27}.26H_2O \rightarrow 4CaAl_2Si_4O_{12}.4H_2O + 8SiO_2 + KAlSi_3O_8 + 10H_2O$$

(Boles & Coombs, 1975: 168). The presence of such an assemblage within the tests indicates that such conditions existed during latter stages of mineralisation.

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References

Ballance, P.F., R.F. Heming & T. Sameshima, 1981. Petrography of the youngest known Murihiku Supergroup, New Zealand: latest Jurassic arc volcanism on the southern margin of Gondwana. Pp. 161-166. **In** M.M. Creswell & P. Vella (eds). Gondwana Five. Proceedings of the Fifth International Gondwana Symposium, Wellington.

Boles, J.R., 1972. Composition, optical properties, cell dimensions and thermal stability of some heulandite group zeolites. American Mineralogist 57: 1463-1493.

Boles, J.R., 1977. Zeolites in low-grade metamorphic grades. Pp. 103-135. **In** F.A. Mumpton (ed.). Mineralogy and Geology of Natural Zeolites. Mineralogical Society of America Short Course Notes 4.

Boles, J.R. & D.S. Coombs, 1975. Mineral reactions in zeolitic Triassic tuff, Hokonui Hills, New Zealand. Geological Society of America Bulletin 86: 163-173

Boles, J.R. & D.S. Coombs, 1977. Zeolite facies alteration of sandstones in the Southland Syncline. American Journal of Science 277: 982-1012.

Clark, A.B.S., 1982. Zeolite facies metamorphism of the Murihiku Supergroup, North Island, New Zealand. Unpublished MSc thesis. University of Auckland Library.

Coombs, D.S., 1952. Cell size, optical properties and chemical composition of laumontite and leonhardite. American Mineralogist 37: 812-830

Coombs, D.S., 1954. The nature and alteration of some Triassic sediments from Southland, New Zealand. Transactions of the Royal Society of New Zealand 82: 65-109.

Coombs, D.S., 1960. Lower grade mineral facies in New Zealand. International Geological Congress XXI, Norden 13: 339-351.

Coombs, D.S., A.J. Ellis, W.S. Fyfe & A.M. Taylor, 1959. The zeolite facies with comments on the interpretation of hydrothermal syntheses. Geochimica et Cosmochimica Acta 17: 53-107.

Gottardi, G. & E. Galli, 1985. Natural Zeolites. Springer, Berlin, pp.1-409.

Hey, M.H., 1932. Studies on the zeolites. Part II: thomsonite and gonnardite. Mineralogical Magazine 23: 51-125.

Mason, B. & L.B. Sand, 1960. Clinoptilolite from Patagonia. The relationship between clinoptilolite and heulandite. American Mineralogist 45: 341-350.

Mumpton, F.A., 1960. Clinoptilolite redefined. American Mineralogist 45: 351-369.

Mumpton, F.A., 1977. Natural zeolites. Pp.1-17. **In** F.A. Mumpton (ed.). Mineralogy and Geology of Natural Zeolites. Mineralogical Society of America Short Course Notes 4.

Purser, B.H., 1961. Geology of the Port Waikato region. New Zealand Geological Survey Bulletin 69: 1-36, maps.

Rodgers, K.A. & J.A. Grant-Mackie, 1978. Aspects of the Geology of the Port Waikato region. Geology Department, University of Auckland, pp.1-99.

Rodgers, K.A. & T. Sameshima, 1978. Clinoptilolite pseudomorphs after calcite and aragonitic Miocene fossils, Kaipara Harbour, New Zealand. Mineralogical Magazine 42: 410-412.

Sameshima, T., 1978. Zeolites in tuff beds of the Miocene Waitemata Group, Auckland Province, New Zealand. Pp. 309-318. **In** L.B. Sand & F.A. Mumpton (eds). Natural Zeolites: Occurrence, Properties, Use. Pergamon, Oxford.

Sands, C.D. & J.I. Drever, 1978. Authigenic laumontite in deep-sea sediments. Pp. 269-273. **In** L.B. Sand & F.A. Mumpton (eds). Natural Zeolites: Occurrence, Properties, Use. Pergamon, Oxford.

Smykatz-Kloss, W., 1974. Differential thermal analysis: application and results in mineralogy. Springer, New York, 1-185 pp.

Ullrich, B., P. Andolphi, J. Schomburg & H. Zwahr, 1988. Kombinierte thermoanalytische Untersuchungen an Zeolithen. Teil II: Heulandit-Stilbit-Gruppe. Chemie der Erde 48: 141-154.

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APPENDIX

Table 1. Mid-Jurassic faunal assemblages from Opuatia Cliff and Moewaka Quarry, eastern Port Waikato, indicating completely (*) and partly (§) zeolitised species.

Opuatia Cliff (NZ Fossil Record File locality R13/f6613):
§Rhynchonellidae indet., *Kutchithyris* sp., Terebratuloida indet.;
§*Rotularia* sp.;
§*Leptomaria* sp., **Uchauxia* sp. (high spired);
Paleonucula sp., ?*Paleoneilo* sp., §?*Nuculana* sp., *Retroceramus (Retroceramus) marwicki* (Speden), *Propeamussium (Parvamussium) clamosseum* (Marwick), *Camptonectes* (*Camptonectes*) cf. *laminatus* (Sowerby), *Chlamys* (s.l.) sp., *Entolium (Entolium)* sp., §?*Otapiria* sp., **Kalentera* sp., §*Astarte* sp., §*Neocrassina* sp., *Pleuromya milleformis* Marwick, Bivalvia indet.;
?*Phylloceras* sp., *Holcophylloceras* sp., *Lytoceras* sp., §*Nannolytoceras* sp., Sphaeroceratinae n.gen. and n.sp.;
Hibolithes catlinensis (Hector), Belemnitidae indet.;
crinoid;
carbonaceous material.

Moewaka Quarry (N.Z. Fossil Record locality no R13/f6500):
Nodosariad Foraminifera, Foraminifera indet;
§Rhynchonellidae indet., *Terebratulina* sp., Terebratuloida indet.;
§*Rotularia* sp.; *Serpula* sp.;
§*Leptomaria* sp., *Paracerithiinae n.gen. and sp. (high spired), *Proconulinae n.gen. and sp., *Gastropoda indet. (including other small high spired gastropods);
Scaphopoda indet.;
Palaeonucula sp., ?*Nucluana* sp., Nuculoida indet., §*Grammatodon* (*Indogrammatodon*) sp., *Pinna kawhiana* Marwick, *Retroceramus (Retroceramus) galoi* (Boehm), *Camptonectes (Camptonectes)* cf. *laminatus* (Sowerby), *Entolium (Entolium)* sp., *Pseudolimea* sp., *Vaugonia kawhiana* (Trechmann), *Myophorella* (*Scaphogonia*) *macnaughti* Fleming, ?*Astarte* sp., §*Anisocardia* (*Antiquicyprina*) sp., *Pholadomya* sp., *Pleuromya milleformis* Marwick, *Thracia* (*Thracia*) sp., Bivalvia indet.;
Phylloceras sp., *Holcophylloceras* sp., phylloceratid ammonite indet.;
Belemnopsis annae Challinor;
Odonaster priscus Fell, star fish ossicles,
Mecochirus marwicki Glaessner,
barnacle plate,
shark tooth,
wood fragments.

Table 2. Representative electron microprobe analyses of heulandite-clinoptilolite and laumontite replacing mid-Jurassic gastropod tests, Murihiku Supergroup, Ponganui.

	1	2	3	4	5	6	7	8
SiO_2	64.67	62.01	64.16	53.10	54.16	53.42	55.05	54.74
TiO_2	0.03	0.01	0.11	0.06	0.03	0.01	n.d	0.04
Al_2O_3	14.39	12.81	13.75	20.92	21.57	20.95	22.55	22.31
Fe_2O_3	0.28	0.71	0.04	0.03	n.d	0.06	0.15	n.d
MnO	n.d	n.d	0.04	0.04	n.d	n.d	n.d	n.d
MgO	0.66	n.d	0.17	0.08	0.24	n.d	0.37	n.d
CaO	6.00	5.80	5.80	11.85	10.97	10.77	12.27	11.73
Na_2O	n.d	0.06	0.32	0.09	0.43	0.11	0.23	n.d
K_2O	1.19	1.22	1.23	0.27	0.59	0.75	0.11	0.46
Total	86.44	82.62	85.62	86.44	87.99	86.07	90.73	89.28

Number of cations on basis of 72 (heulandite) or 48 (laumontite) oxygens

	1	2	3	4	5	6	7	8
Si	28.52	28.93	28.79	16.29	16.40	16.52	16.10	16.24
Ti	0.01	0.00	0.04	0.01	0.01	0.00	0.00	0.01
Al	7.48	7.04	7.27	7.57	7.56	7.59	7.77	7.80
Fe^{3*}	0.10	0.28	0.02	0.01	0.00	0.01	0.03	0.00
Mn	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.00
Mg	0.44	0.00	0.11	0.14	0.11	0.00	0.126	0.00
Ca	2.84	2.90	2.79	3.90	3.49	3.55	3.84	3.73
Na	0.00	0.06	0.28	0.05	0.25	0.06	0.13	0.00
K	0.33	0.73	0.70	0.11	0.22	0.30	0.04	0.16
Si+Al	36.00	35.97	36.06	23.88	23.97	24.03	23.90	24.05
Si/Al	3.81	4.11	3.96	2.15	2.17	2.16	2.07	2.08
R	3.61	3.69	3.88	4.06	3.96	3.91	4.01	3.89
R'	6.89	6.59	6.78	3.98	3.72	3.77	3.92	3.81
E%	10.0	11.08	7.52	-5.7	-1.4	-1.8	-4.5	2.4

1. Heulandite infilling gastropod test, Moewaka Quarry, G6965.
2. Clinoptilolite infilling gastropod test, Moewaka Quarry, G6963.
3. Heulandite infilling gastropod test, Moewaka Quarry, G6963.
4. Laumontite crystal growing in matrix infilling body whorl of gastropod, Opuatia Cliff, G6966.
5. Laumontite replacing gastropod shell wall, Opuatia Cliff, G6966.
6. Laumontite infilling gastropod test, Opuatia Cliff, G6966.
7. Laumontite replacing gastropod shell wall, Opuatia Cliff, G6967.
8. Laumontite infilling gastropod test, Moewaka Quarry, G6965.

R = $Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}$

R' = $2(Ca^{2+}+Mg^{2+})+Na^{+}+K^{+}$ (heulandite); $Ca^{2+}+(Na^{+}+K^{+})/2$ (laumontite)

Table 3. Comparative range recorded for unit cell contents of laumontites from Murihiku Supergroup zeolite facies rocks on basis of 48 oxygens

	1	2	3
Si	16.10 - 16.52	16.44 - 17.05	15.87
Al	7.45 - 7.81	7.01 - 7.79	8.17
Ca	3.36 - 3.90	2.62 - 3.55	3.60
Na	n.d. - 0.28	0.04 - 0.77	0.65
K	0.04 - 0.30	0.07 - 1.1	0.18

1. Present study
2. Clark (1982), E% < ±10% only
3. Coombs (1954)

Full-text PDF of each one of the works in this volume are available at the following links :

Bevan, 1992, *Rec. Aust. Mus., Suppl.* 15: 1–27
http://dx.doi.org/10.3853/j.0812-7387.15.1992.80

Inegbenebor et al., 1992, *Rec. Aust. Mus., Suppl.* 15: 29–37
http://dx.doi.org/10.3853/j.0812-7387.15.1992.81

Lawrence, 1992, *Rec. Aust. Mus., Suppl.* 15: 39–43
http://dx.doi.org/10.3853/j.0812-7387.15.1992.82

Robertson and Sutherland, 1992, *Rec. Aust. Mus., Suppl.* 15: 45–54
http://dx.doi.org/10.3853/j.0812-7387.15.1992.83

England, 1992, *Rec. Aust. Mus., Suppl.* 15: 55–72
http://dx.doi.org/10.3853/j.0812-7387.15.1992.84

Rodgers and Hudson, 1992, *Rec. Aust. Mus., Suppl.* 15: 73–81
http://dx.doi.org/10.3853/j.0812-7387.15.1992.85

Torrence et al., 1992, *Rec. Aust. Mus., Suppl.* 15: 83–98
http://dx.doi.org/10.3853/j.0812-7387.15.1992.86

Branagan, 1992, *Rec. Aust. Mus., Suppl.* 15: 99–110
http://dx.doi.org/10.3853/j.0812-7387.15.1992.87

Chalmers, 1992, *Rec. Aust. Mus., Suppl.* 15: 111–128
http://dx.doi.org/10.3853/j.0812-7387.15.1992.88

Barron, 1992, *Rec. Aust. Mus., Suppl.* 15: 129–135
http://dx.doi.org/10.3853/j.0812-7387.15.1992.89