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Optical data on some authigenic feldspars from Western Australia

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SUMMARY. Authigenic envelopes up to 0·18 mm thick on clastic potassium feldspar grains from arkoses and subgreywackes of the Devonian Nannyarra Greywacke have been examined with the four-axis universal stage. The plane of the optic axes is parallel to (010) in some segments of individual envelopes and normal to (010) in others, and the range of $2V_\alpha$ over all envelopes is from close to 0° to 65°. The optics are ascribed to modifications of potassium feldspar corresponding to high- and low-sanidine and orthoclase.

AUTHIGENIC minerals grow in sedimentary rocks near the surface of the Earth or at moderate depths in the crust at fairly low temperatures. Authigenic outgrowths on feldspar grains in the Nannyarra Greywacke apparently formed at less than 100 °C, although they contain segments with optics like those of high-sanidine, which is generally reported from volcanic rocks, where it characteristically grows at higher temperatures than other potassium feldspars. This paper describes the petrology of the Nannyarra Greywacke, presents details of the optics of the feldspars, and discusses the possible origin of the authigenic outgrowths.

The Nannyarra Greywacke is Devonian and has its type section on the eastern margin of the Carnarvon Basin, Western Australia (23° 58′ S, 115° 14′ E). Despite its name, the formation at its type section contains little greywacke as defined by Pettijohn (1957) and is made up mainly of arkose and subgreywacke. It is a transgressive unit about 190 ft thick resting nonconformably on a Precambrian basement and overlain conformably by 1700 ft of limestone, sandstone, and shale of the Middle Devonian Gneudna Formation. The sequence has not been metamorphosed, intruded, sheared, or strongly folded, and dips west into the Carnarvon Basin at about 35°.

Thin sections of eleven rocks from the formation reveal a range in the main constituents as follows: quartz 26–64 % (average 50 %), K-feldspar 9–25 % (average 20 %), schist, chert, and other rock fragments 2–59 % (average 16 %), argillaceous and ferruginous matrix 4–16 % (average 9 %).

The rocks that contain feldspars with the best developed overgrowths on K-feldspar grains are nos.[1] 58040 and 58041, which come from intervals 88–112 and

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[1] Catalogue numbers of the Geology Department, University of Western Australia.

112–22 ft above the base respectively. These rocks are subgreywackes, and unless otherwise indicated, all petrographical and petrological observations that follow deal with them.

Practically all quartz grains in specimens 58040 and 58041 have been authigenically enlarged, but many grains lack well-developed faces. Faces, where present, are prisms and rhombohedra. The potassium feldspars are invariably enlarged and tend to develop prisms and basal pinacoids, whereas the plagioclase feldspars show no enlargement. The origin of the muscovite is uncertain, for it may be authigenic or clastic.

The authigenic outgrowths clearly grew at low temperatures. Similar outgrowths are present in sandy beds of the conformably overlying Gneudna Formation, and its well-preserved fossiliferous limestone would have responded rather easily to thermal metamorphism. Burial of more than 2 km would have been necessary to raise the temperature of the Nannyarra rocks to 100 °C with a normal geothermal gradient (30 °C per km), but because of their position on the margin of the basin, the depth of burial was probably far less.

Thin sections of the rocks were studied with the Leitz four-axis universal stage. There are no chemical data on the cores of the feldspars or their outgrowths, and the influence of variations in composition on their optics is unknown. Principal optical directions, optic axes, cleavages, and faces were plotted, after location, by the Fedorov procedure. Where possible, optic axial angles were measured by the direct method of Fairbairn and Podolsky (1951), and these are commonly reproducible to within 2°. Results are recorded as approximate if the direct method was not used, or if measurements were made on small, possibly overlapping, segments. Cleavages and faces were identified by the method of Gilbert and Turner (1949).

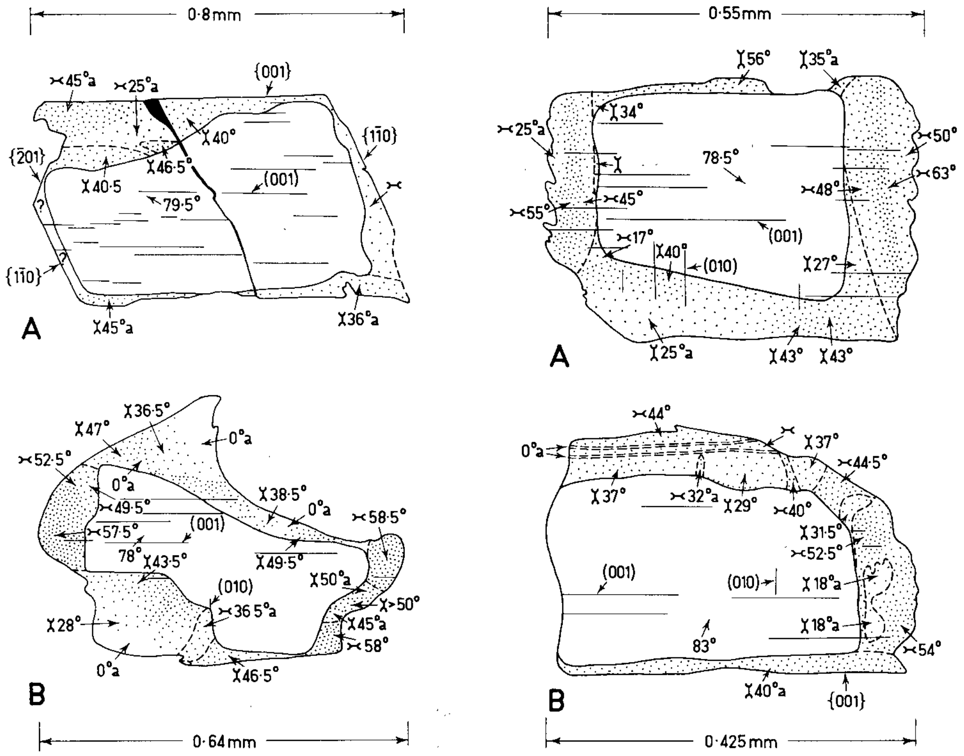
The potassium feldspars

The cores. Most of the enlarged feldspar grains contain clear or slightly kaolinized subspherical cores of potassium feldspar somewhat flattened in the (001) plane. The cores range between 0·15 mm and 0·8 mm long, and their clear authigenic envelopes are up to 0·18 mm thick.

The cores of 25 potassium feldspar grains were measured in detail. They have a wide range of 2V [$2V_\alpha = 74°$ (1 grain), 76·5° (1 grain), 77–80° (10 grains), 81–4° (12 grains), 85° (1 grain)] and many show crosshatching. One grain is also divided into halves with a Carlsbad relationship.

Habit and composition of the authigenic envelopes. The cores and envelopes have similar refractive indexes, and Carlsbad twins and pinacoid and prism cleavages pass from one to the other without apparent break. Nevertheless, the boundaries between most cores and envelopes are obvious either because they are marked by lines of minute grey inclusions, or because they separate cores that may be crosshatched, or kaolinized, or contain perthite or quartz blebs, from envelopes that show none of these features. Cleavages in the cores are generally more pronounced than in the outgrowths, presumably because they opened slightly during transportation and kaolinization.

Almost all envelopes have some faces, and they invariably correspond to common faces of the core. Many envelopes have faces of the forms {001}, {110}, and $\{1\bar{1}0\}$, and where these are strongly developed, grains look rhomb-shaped in sections close to the (010) plane (fig. 1A). Other forms are rare on the authigenic envelopes, and only one, $\{\bar{2}01\}$, has so far been identified. Where the plane of section is normal to *a*, uneven surfaces more or less parallel to (010) are commonly apparent, but {010} is never developed (fig. 2). The uneven surfaces contain numerous small sharp projections bounded by surfaces that are too small for determination, but which seem to be faces of the forms {110}, $\{1\bar{1}0\}$, and {001}.



FIGS. 1 and 2. Numbers represent $2V_\alpha$ and are preceded by a vertical symbol where the optic plane is in (010), and a horizontal symbol where the optic plane is normal to (010). $2V_\alpha$ is reproducible to within 2° unless followed by the letter a (approximate). Variation in $2V_\alpha$ indicated by intensity of stippling. Fig. 1 (left). A. Feldspar sectioned roughly normal to (001) and roughly parallel to (010). Grain contains chlorite-filled crack. Orientation prevents complete measurement of grain. B. Feldspar sectioned roughly normal to *a*. Fig. 2 (right). Feldspar grains sectioned roughly normal to *a*.

The feldspar of the envelopes ranges in $2V_\alpha$ from close to 0° to 65°, indicating potassium feldspar ranging from sanidine to orthoclase. Each envelope is made up of numerous segments of variable shape and size, some with the optical plane parallel or almost parallel to the (001) cleavage of the core, and some with the plane normal or almost normal to it. In fact, the principal vibration directions are not all precisely parallel in different segments, and α for some crystals falls on the Schmidt net within an area of diameter up to 12°—too great to be accounted for entirely by errors of measurement and plotting. Many contiguous segments differ not only in optical orientation, but also in the magnitude of $2V_\alpha$ (see figs. 1–3). The segment boundaries are generally fairly sharp and rather irregular, but some are more or less parallel to pinacoids, prisms, or pyramids. Cleavages, where present, pass without apparent deviation through adjacent segments.

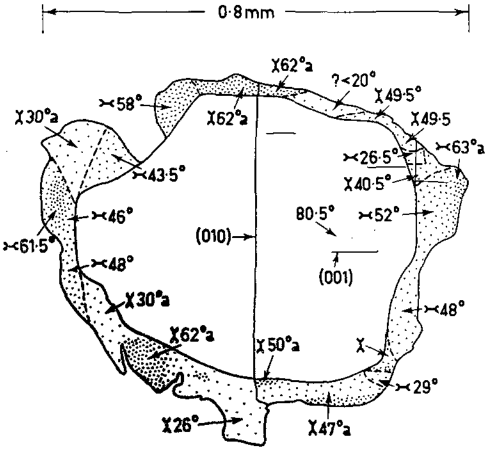


FIG. 3. Feldspar grain with Carlsbad twins persisting into authigenic envelope. Numbers represent $2V_\alpha$ and are preceded by a vertical symbol where the optic plane is in (010) and a horizontal symbol where the optic plane is normal to (010). $2V_\alpha$ is reproducible to within 2° unless followed by the letter a (approximate). Variation in $2V_\alpha$ indicated by intensity of stippling.

The possibility that twinning might account for the rotation of the optic axial plane has to be considered. Baveno twinning would rotate the plane through 90° but would also rotate the (001) and (010) cleavages and faces through 90°, and there is no evidence for this in the outgrowths. In fact, although an authigenic face is commonly well developed parallel to the (001) cleavage of the core, no crystal contains an authigenic face developed at 90° to it (i.e. parallel to (010) in the core), as the Baveno relationship would require. An uneven surface, described earlier, develops in place of {010}.

Strain causes considerable variation in the optic axial angle of minerals in some strongly deformed rocks, but that is unlikely here. Tectonic deformation of the Nannyarra Greywacke has been negligible, and there is no evidence of strain in the authigenic quartz outgrowths. A few feldspar grains have cracked apparently after growth of their authigenic envelopes, perhaps because of weakness in the cores. One of these grains is illustrated (fig. 1A).

The unusual features of the authigenic feldspar are best ascribed to the presence of several modifications of potassium feldspar within individual envelopes. The segments with their optic axial plane parallel to (010) range in 2V from close to 0° to about 62° and therefore are optically like high-sanidine. Segments with their optic axial plane normal to (010) and $2V_\alpha$ ranging from close to 0° to 25° and from 25° to 65° respectively are like low-sanidine and orthoclase as sometimes described. The terms high- and low-sanidine and orthoclase will be used for these segments in the rest of this paper.

Envelope walls that have grown out to basal pinacoids are mainly high-sanidine, and those that have grown out to the uneven surfaces that are roughly parallel to (010) are mainly orthoclase. Authigenic feldspar between the core and prism faces commonly consists of three modifications (orthoclase, low- and high-sanidine).

The size of the optic axial angle varies considerably within many large segments of orthoclase and sanidine to give a blotchy effect in some orientations under crossed nicols where the variation is irregular, and a zoned effect where it is regular.

Formation of the Nannyarra feldspars

Authigenic feldspars have been described by many authors, with important recent contributions by Baskin (1956) and Michaelis de Sáenz (1963). Despite their low temperature of formation, many of these feldspars do not have a highly ordered Al/Si distribution in the lattice, and some authors feel that fast growth has hindered ordering. The literature has been reviewed by Deer, Howie, and Zussman (1963) and Van der Plas (1966).

A satisfactory hypothesis of origin for the envelopes should account for the presence of segments showing various degrees of ordering, and should explain their distribution in the envelopes. Growth in the direction of the *c* crystallographic axis has been less in most crystals, and thus presumably slower, than in other directions, yet the optics indicate that the feldspar along *c* is generally the least ordered. This is opposite to what might be expected if rate of growth were the only influence on the ordering. Other features, such as variations in the K/Na ratios, or in the amount of iron or other elements in different parts of the envelopes may be significant. Crystallization from highly aqueous solutions may have influenced ordering in some way not yet understood. It seems, however, that the factors overwhelming forces tending to form ordered crystals were generally more effective in some crystallographic directions than others. Irregularities in the resultant general pattern may have been caused by highly localized influences such as the shape and volume of intergranular pores, which could significantly affect the passage of solutions to different parts of individual crystals. There may have been partial inversion of some envelopes to more highly ordered forms. Variations within the segments themselves could have been due to changing compositions in the fluids that bathed the grains, restrictions on flow caused by decreasing pore space, temperature variations, or combinations of these causes.

Conditions during the growth of the authigenic envelopes of the Nannyarra Greywacke do not seem to have been exceptional, and investigation of other sedimentary rocks is needed to see if authigenic sanidine is as uncommon as is now generally believed.

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