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Fault rocks and differential reactivity of minerals in the Kanawa Violaine uraniferous vein, NE Nigeria

C. E. SUH and S. S. DADA

Geology Programme, Abubakar Tafawa Balewa University, Bauchi, Nigeria

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Abstract—The Kanawa Violaine uraniferous vein occurs in a narrow granitic shear zone. Mylonitic fault rocks at the centre of the vein grade outwards into cataclasites and fault breccias. The mineralization is associated with pervasive silicification and phyllosilicate alteration of the feldspar phases. The uranium mineralization occurs as uraninite-rich veinlets within brittle structures.

Feldspars were the phenocryst phases most affected by alteration during the brittle–ductile deformation of the host rock. Plagioclase was extensively altered to micas, chlorite ± epidote, ± albite. Alkali-feldspar deformed mainly by transgranular fracturing as a result of shearing to yield clasts with lensoid shape. Quartz shows little evidence of brittle deformation but extensive *in situ* recrystallization. A mylonitic foliation is defined by monomineralic lenses. Microcracks in the feldspar are oblique to this foliation.

The greenschist-facies secondary mineral assemblage, pervasive silicification, deformation mode of alkali-feldspar and the presence of quartz subgrains point to deformation of granites in the epizone by simple shearing within a hydrothermal-fluid-infiltrated medium. Alteration temperatures did not exceed 250°C. The hydrothermal fluid remobilized and subsequently concentrated the uranium. This fluid was enriched in Si^{4+}, Na^{+} and K^{+}, possibly derived from plagioclase alteration. This lead to association of the ore with phyllosilicate and silicification alterations. © 1997 Elsevier Science Ltd.

INTRODUCTION

Uranium occurrences in Nigeria are associated with either sedimentary–volcanosedimentary sequences (secondary mineralization) or with basement rocks of granite affinity (primary and secondary mineralization). Although most of these occurrences are small and scattered, the major ones include the Ghumchi and Mika prospects (Maurin and Lancelot, 1990), the Kanawa (Gubrunde horst) Violaine vein (Funtua *et al.*, 1992) and the Monkin–Manza occurrences (Oshin and Rahaman, 1986). Primary uranium occurrences in NE Nigeria are highly localized and are confined to zones of brittle–ductile deformation in granitic plutons.

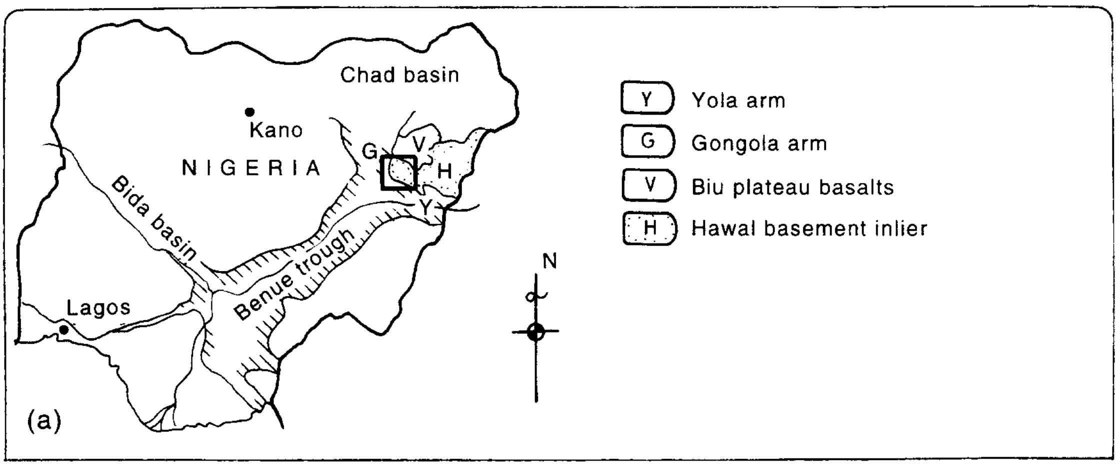
The Kanawa Violaine vein is a typical example of a vein-type uranium occurrence within the north-eastern belt of Nigeria. The vein is hosted in the pre-tectonic granites of Pan-African age (Dada *et al.*, 1993) that have experienced ductile and brittle deformation related to the development of the Benue Trough. A significant aspect of exploration in these bodies involves the mapping and characterization of the fracture zones and narrow ductile deformation zones in an attempt to seek a possible correlation between intensity of deformation (ductile or brittle) and uranium ore occurrence on a microscopic scale.

The deformation of granitic bodies, and the relative susceptibility of the various mineral phases in them, have been extensively documented especially along fracture zones, and these and experimental studies suggest that feldspars are generally less deformable than quartz at low- to medium-grade metamorphic conditions (Boullier, 1980; Chester *et al.*, 1985; Evans, 1990; Fitz Gerald and Stunitz, 1993; Kamineni *et al.*, 1993). However, Tullis and Yund (1980) noted that under certain conditions below 350°C feldspar may be the weaker phase. The relative stability of various minerals during cataclasis is controlled by the relative activities of cations in the fluid phase, and deformation may enhance reaction rates by decreasing grain size through fracturing (Kamineni *et al.*, 1993) and the release of cations into the fluid–host rock system. Which set of cations will be leached from the minerals in a rock depends on which minerals disintegrate first. The differential reactivity of the minerals in a rock allows us to speculate on the nature of the infiltrating fluid as well as the temperature of deformation; both are vital to understand the mineralization processes associated with deformation.

This paper describes the geometry of a uranium mineralization vein within a shear zone in a granite body. In addition, the spatial relationships between the mineralization, fault rocks and volcanic lenses within the brittle structures are described. We show here that the plagioclase feldspars were most susceptible to alteration during deformation, releasing Si which contributed to the silicification of the host rock. Conversely, alkali-feldspar and quartz underwent essentially transgranular fracturing and recrystallization, respectively.

GEOLOGICAL BACKGROUND

The Kanawa Violaine vein occurs in deformed granites of the basement inlier between the Gongola and Yola arms of the Upper Benue Trough (Fig. 1). This inlier known as the Hawal basement exposure (Maurin *et al.*,



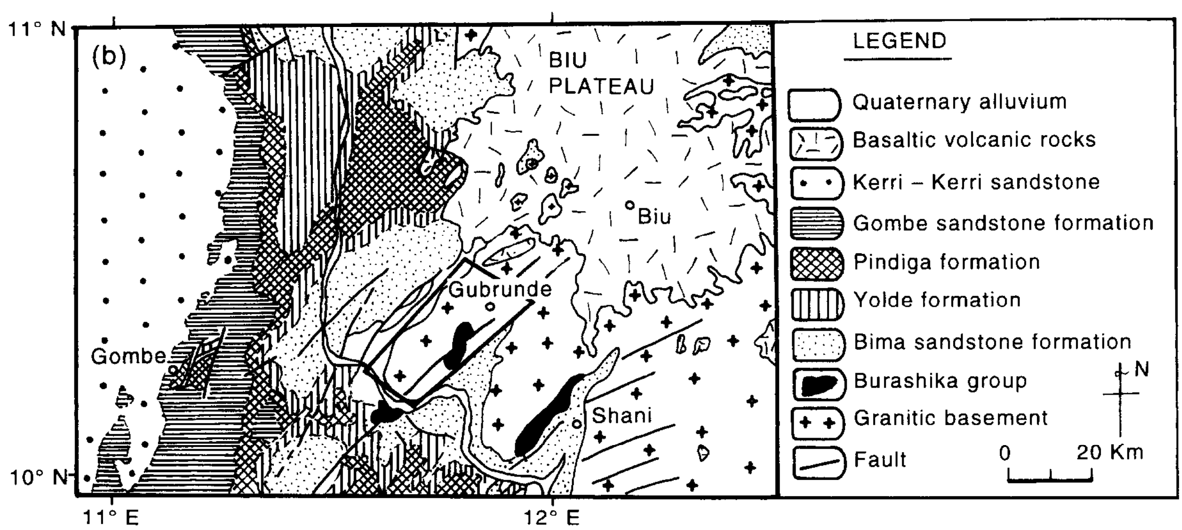


Fig. 1. (a) Sketch map of Nigeria showing the location of the Hawal Basement Inlier in relation to the NE–SW-trending Benue Trough. Inset: location of (b). (b) Simplified geological map of the Upper Benue Trough (modified after Maurin *et al.*, 1986). Inset: location of Fig. 2.

1986) is covered in the north by the extensive Biu basalt plateau.

The Benue Trough is a NE–SW elongate intracontinental basin filled with Cretaceous–Tertiary sediments comprising sandstones, siltstones, limestones, shales and claystones depicting various environments of deposition in response to alternating marine transgressive and regressive phases. Excellent reviews on the origin, structure and lithologic units of this trough are provided in Ziegler (1992).

The Kanawa vein is situated within the Gubrunde horst (Fig. 2), which is a major structure in the Hawal exposure. This horst is a product of Lower Cretaceous block faulting between two series of NE–SW-striking border faults. These faults acted as conduits for intruding pegmatitic and aplitic veins, as well as mafic volcanics which occur in the area. The host rock is a pinkish porphyritic granite with localized primary alignment of the micas (biotite + muscovite). Occasionally, the host rock grades into a grey fine-grained variety. This granite body is elongated in outline and is generally discordant to the foliation in the adjoining gneisses. The granite is rich in pink potash feldspars occurring as phenocrysts, white–grey plagioclase and quartz. The mica content is rather low. This granite is cut by various pegmatitic and aplitic bodies along three main structural trends (Fig. 2): (1) a N40E–N60E trend which runs parallel to the NE–SW trend of the Benue Trough and to lineaments defined by faulted blocks, such as the Kaltungo inlier lineament (Maurin *et al.*, 1986); (2) the N10E–N20E Kanawa trend, the principal trend of the Kanawa uraniferous vein; and (3) a less important N120E trend defined by joints bearing quartz veins that cut across the other two trends mentioned above.The N40E–N60E structures are steeply-dipping (> 60°E) normal faults with silica-coated and polished surfaces bearing vertical straitions. Meanwhile, the N10E–N20E trend is a network of sub-horizontal strike-slip faults with a predominant sinistral shear sense and are associated with numerous anastomosing extensional fractures. They are clearly displaced by the N40E–N60E faults. The cataclasites, granite fault breccias and mylonites are more or less confined to the

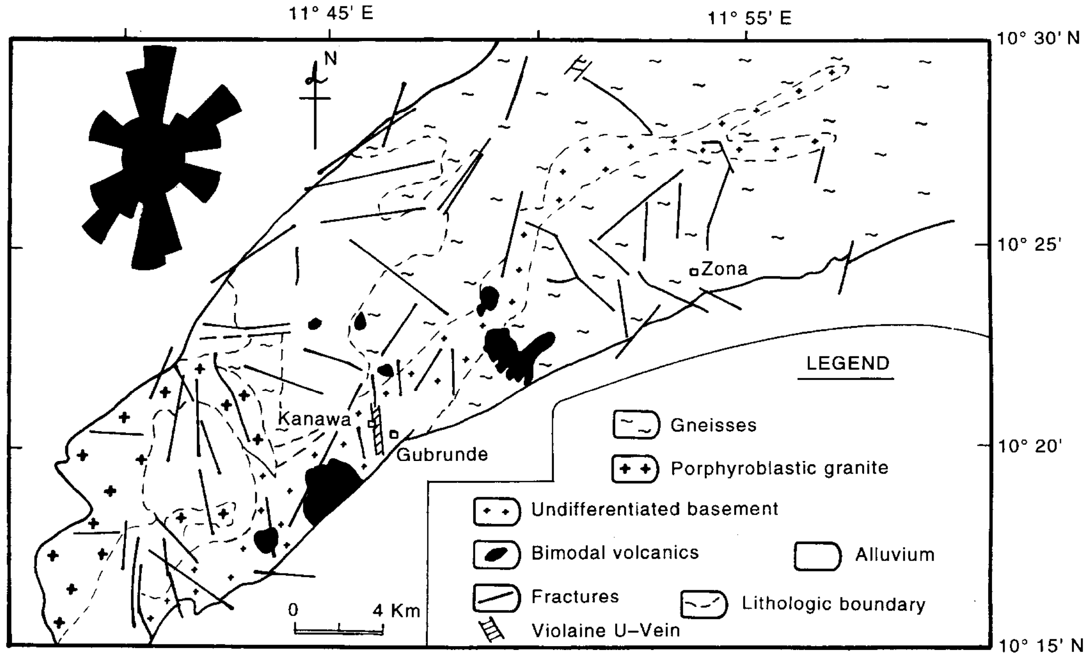


Fig. 2. Geological sketch map of the Gubrunde horst (modified from Ojo, 1988). Rose diagram shows the major N10E–N20E; N120–N130E and N40E–N60E trends. Violaine uraniferous vein not drawn to scale (see Fig. 3).

N20E–N40E structures. Also, the density of the mafic volcanic veins along the N20E–N40E trend far exceeds that along the N40E–N60E structures, which are rather typified by pegmatitic and aplitic veins.

The Kanawa vein is confined to a N–S-trending brittle–ductile shear zone about 20 m wide and which extends well over 1 km along the strike (Fig. 3). At the centre of the vein are narrow anastomosing mylonitic bands with a subhorizontal mylonitic foliation and a horizontal stretching lineation, consisting of aligned quartz ribbons and a few sigmoidal feldspar porphyroclasts. Where the ductile deformation was very intense, ultramylonites with a high haematitic silica content developed. This central ductile zone grades outwards into a brittle zone comprising cataclasites which give way to fault breccias towards the margins of the vein. The cataclasites consist of randomly-oriented angular clasts of feldspars and quartz in a very fine-grained siliceous matrix. The peripheral fault breccias are marked by angular centimetre- to metre-size fragments of both undeformed and deformed (mylonites and cataclasites) granitic rocks similarly set in a whitish (siliceous) to dark iron-rich matrix. On the whole, there is a progressive increase in grain size from the centre of the vein outwards. However, these zones are not very distinct in some parts of the vein and often show gradational boundaries. The zones also vary in relative thickness along the length of the vein. The ductile event is definitely older because, within the gradational boundary between the mylonitic and cataclasite zones, the brittle structures rework the ductile mylonitic bands predominantly by sinistral shearing. These zones have undergone widespread silicification, haematization and other phyllosilicate alterations due to hydrothermal activity.

The mineralization occurs as discontinous fault/fracture-controlled veinlets, especially within the brittle cataclasite zone. In addition, the few mineralized veinlets within the ductile–brittle transition zone follow the mylonitic schistosity. These mineralized portions which give very high radiometric readings (> 15,000 cps SPP_2) are characterized by fine-grained reddish haematitic silica, previously identified as rhyolites (Funtua *et al.*, 1992) but which may be a deformation product of the granite under oxidizing conditions (Kamineni *et al.*, 1993). It is very important to note here that most of the mafic volcanic lenses within this shear zone are in close proximity to these mineralized areas. The major uranium phases are uraninite and uranophane.

Several volcanic bodies occur within the Gubrunde horst, especially to the north-east and south-west of the uranium mineralization. These volcanic rocks form part of the bimodal Burashika Group (Ojo, 1988) comprising mafics (basaltic), rhyolites, aplites and felsites. The host granite is enriched in uranium (> 1000 ppm in some instances); and in terms of metallogeny the volcanic event is widely assumed to be the factor responsible for the remobilization of the uranium from the granite, subsequently concentrating it in the favourable brittle discontinuities. This is quite possible as we believe that oxidizing conditions prevailed during the deformation of the granite as inferred from the reddish haematite-rich deformation products of the granite. During oxidizing conditions, uranium becomes transportable and later it can be reduced to form uranium minerals in veins. The spatial relationship between the mineralization and mafic volcanic lenses, as mentioned earlier (see also Fig. 3), suggests that the volcanism might not have only provided the thermal energy required to circulate the hydrothermal

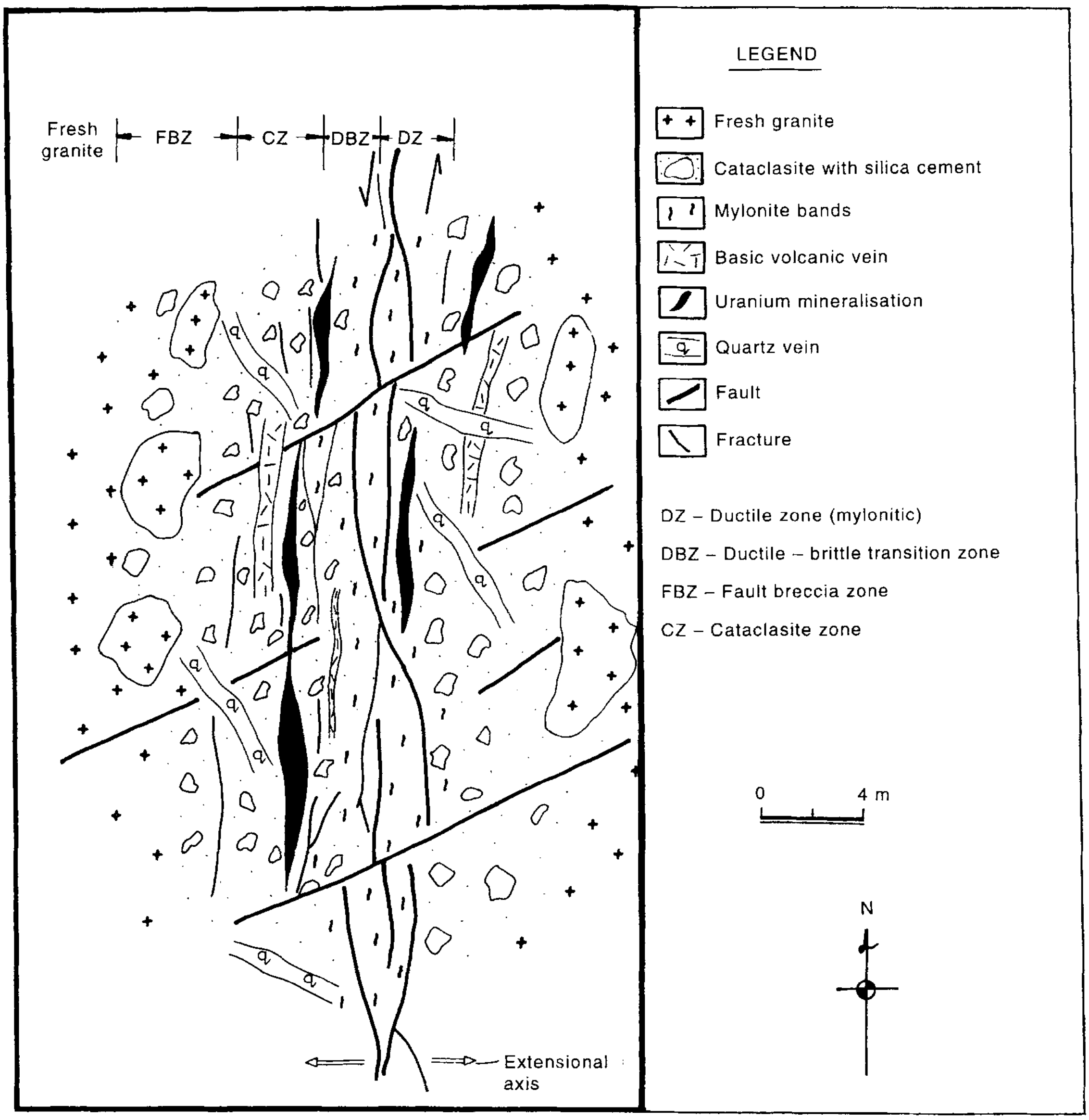


Fig. 3. Structural outline of the southern end of the Kanawa Violaine uraniferous vein.

fluids but was possibly also involved in reduction reactions leading to the precipitation of the uranium. In fact, Leroy (1978) has demonstrated the potential of mafic volcanics as preferential physico-chemical traps for uranium concentration. However, detailed geochemical and metallogenetic studies to determine the path of uranium in this deposit have not been carried out. The granitic and volcanic units described here are underlain by relics of migmatites and gneisses of the old basement (Dada *et al.*, 1993).

The Mika and Ghumchi uranium mineralizations which lie further east of the Kanawa vein have been dated at 148 ± 12 and 14 ± 3 Ma, respectively, using the U–Pb method (Maurin and Lancelot, 1990). The 148 ± 12 Ma age is contemporaneous with the emplacement of the bimodal volcanic rocks of the Burashika Group dated at 147 ± 7 Ma on the basis of K–Ar data (Popoff *et al.*, 1982). The structural similarities between the Mika and Kanawa veins allow us to speculate that they may be of the same age. Geochronological data are not available on the Kanawa vein.

MICROSCOPIC ANALYSIS

Methodology

All the slides examined in this study were cut in a plane normal to the mylonitic foliation (*S*) and parallel to the mylonitic stretching lineation (*L*). A high mica + amphibole content may have an effect on the deformational properties of granites but our samples were low in these phases. Moreover, Fitz Gerald and Stunitz (1993) pointed out that most works on deformation of granitoids do not take mica and amphibole into account, and treat granitoids mechanically as more or less two-phase mixtures of quartz and feldspars.

Results and interpretation

The fresh granite has a porphyritic texture with mineral composition: K-feldspar (38%); quartz (27%); plagioclase (20%); biotite + muscovite (10%); and accessory zircon, monazite and apatite (5%). The granite lacks a principal penetrative cleavage and has well-preserved igneous textures. Phenocrysts do not show any clear preferred orientation. The only visible signs of strain in the granite are undulose extinction of all phases, some recrystallization of quartz and micas, as well as a weak alignment of the interstitial biotite.

Within the mylonitic bands K-feldspars and quartz porphyroblasts are stretched. The feldspar clasts have an augen or ellipsoid shape. They are often fragmented and boudinaged oblique to their long axes (Fig. 4a–c). A mylonitic foliation is mainly developed at the edges of the phenocrysts and boudins due to a stress concentration at the boundaries of mechanically dissimilar materials (Fowler and Lennox, 1992). Some of the cataclasites samples are also foliated, and the foliation is defined by mafic seams (Fig. 4d).

Secondary alteration to micas, chlorite and epidote along microcracks is a common feature (Fig. 4b). The feldspars are also deformed by transgranular fracturing and these intragranular microcracks make a small angle (usually $< 30°$) with the apparent lineation defined by the direction of maximum elongation. A mylonitic foliation defined by quartz ribbons, feldspars and neocrystallized micas is obvious (Fig. 5a). A few of the feldspar megaclasts have shallow etch-surfaces, particularly along the cleavage and microcrack surfaces, which we regard as dissolution textures due to fluid activity along these fissures. The micrographic groundmass in highly deformed samples is strongly silicified and represented by feldspar relics surrounded by granoblastic quartz.

Quartz exhibits different modes of deformation. Most grains have been drawn out into ribbons during plastic deformation (Fig. 5a). A few grains, especially around disintegrating plagioclase, occur as pressure shadows with neocrystallized albite + mica mosaics at the tail ends. Some of the quartz bands contain polygonal quartz grains reflecting *in situ* recrystallization (White, 1977). Most of such quartz-rich bands in the mylonitic

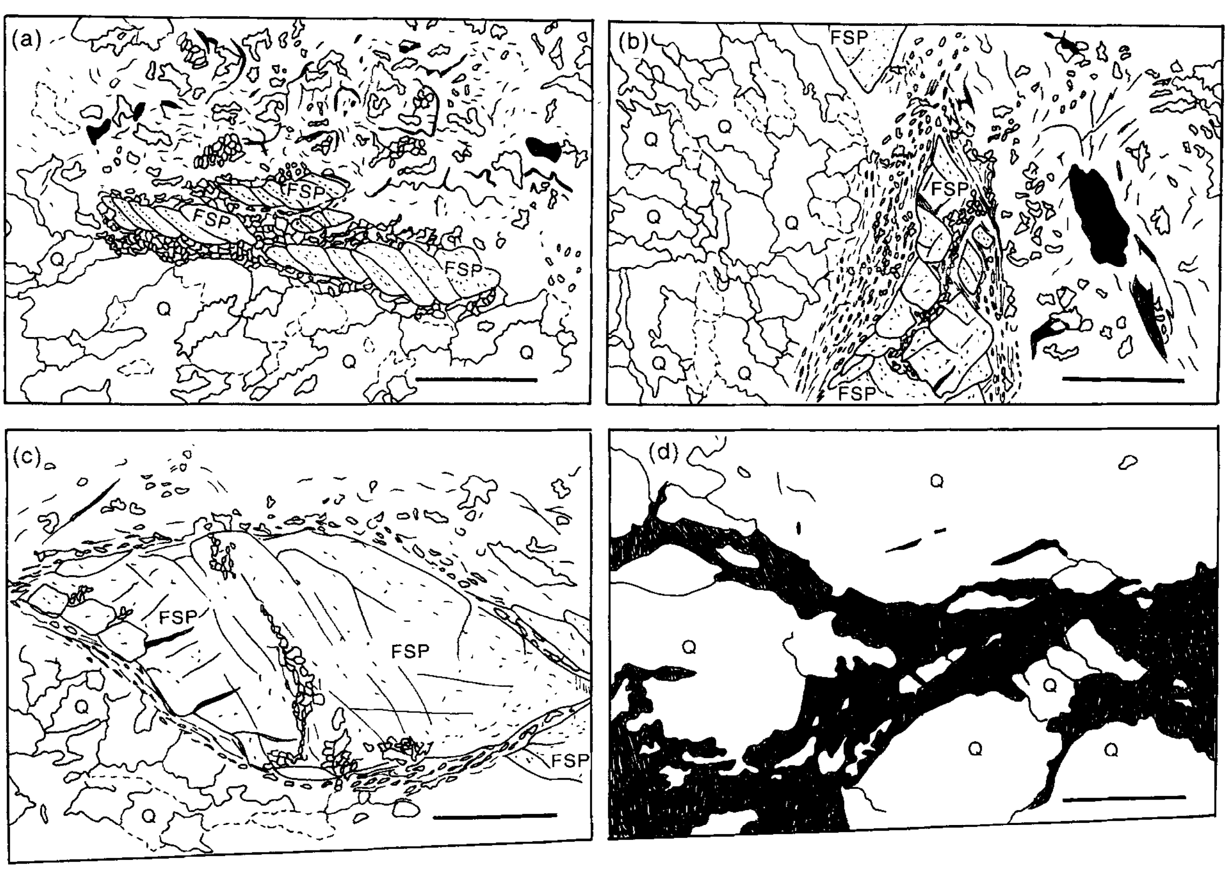


Fig. 4. (a) Feldspar porphyroclasts (FSP) depicting transgranular fracturing parallel to the cleavage directions. The lower half of the figure shows weakly deformed but not fractured quartz (Q) grains separated from the feldspar clasts by a thin band of phengitic mica + chlorite. The finer-grained upper half consists of neo-micas + chlorite + opaques derived from the chemical disintegration of plagioclase feldspars. Scale bar: 1 mm. (b) Tail end of a feldspar clast (FSP) with two directional cleavage-controlled microcracks. The fractures are healed by secondary mica and epidotes, which also form a band around the clast separating it from the relatively undeformed quartz (Q) mosaic at the left-hand end of figure. Scale bar: 1 mm. (c) Lensoid alkali-feldspar clast (FSP) rimmed by a thin mica and chlorite band. The quartz (Q) crystals do not show any sign of brittle deformation. Scale bar: 1 mm. (d) Foliated cataclasite. Mafic seams enclosing subrounded undeformed quartz (Q) grains define the foliation. Scale bar: 1 mm.

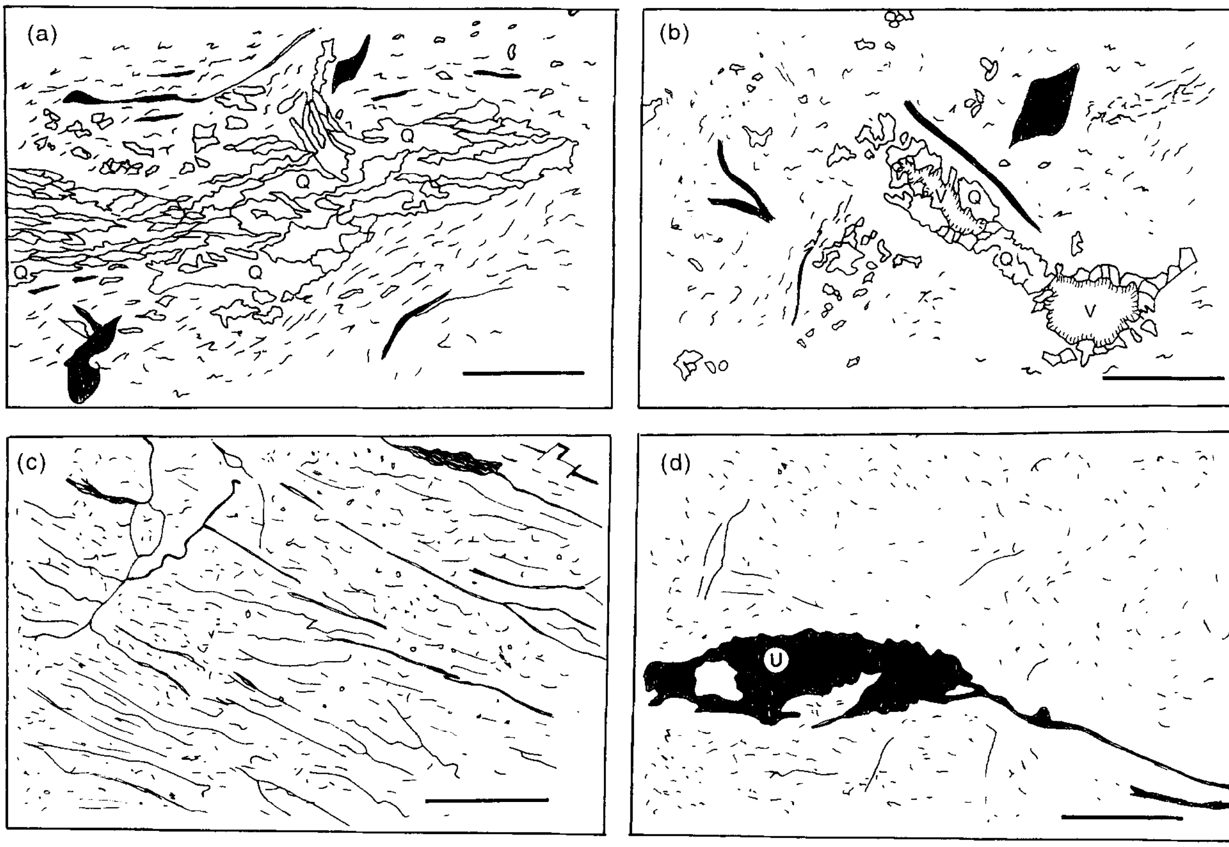


Fig. 5. (a) Mylonite showing plastic deformation in quartz (Q, stretched crystals) set within a micrographic groundmass. All the feldspars have disintegrated. Scale bar: 1 mm. (b) Veined structure or cockade texture defined by newly crystallized and symmetrically arranged quartz (Q) crystals around a vug (V) in an ultramylonite sample. Scale bar: 1 mm. (c) Ultramylonite with opaque (iron oxide) trails filling microfractures. Scale bar: 1 mm. (d) Silicified ultramylonite with opaque (iron oxide) and mineralized (U) veinlet. Scale bar: 1 mm.

samples have a larger grain size than layers dominated by feldspar. In such samples subhedral to euhedral quartz grains, occurring as symmetrical clusters in veined structures, are observed. We interpret these veined structures to represent a mosaic of new quartz grains crystallized from silica-rich fluids trapped within voids during and/or after the deformation of the rock. In all samples most of the quartz grains show undulose extinction with well-developed subgrains occurring as aggregates. Some of these grains with undulose extinction are mantled by overgrowths of neocrystallized quartz + albite. Such neocrystallized quartz occurs as an optically continuous mass, significantly different from recrystallized quartz grains which will occur as tiny angular crystals. Such neo-quartz grains are therefore indicative of redeposition from siliceous fluids. Quartz grains are generally less deformed, particularly by fracturing, than feldspars. Shear-sense indicators such as σ- and δ-structures (as defined by Passchier and Simpson, 1986) or *S–C* fabrics (Berthé *et al.*, 1979) are absent in our samples.

Most of the plagioclase feldspars have been altered into reddish-brown trails associated with neo-micas, chlorites and epidotes. As plagioclase was not stable in this environment, myrmekite did not replace K-feldspar in any of the slides examined. With progressive deformation, the mylonitic parts of the ductile shear zone have a remarkable decrease in grain size, locally grading into ultramylonites (Fig. 5b–d).

DISCUSSION

The Kanawa uranium mineralization is confined to a brittle–ductile shear zone characterized by mylonitic fault rocks. The mineralization is controlled by predominantly N–S-trending brittle structures (faults and fractures). The brittle structures rework the mylonitic bands mainly by sinistral shearing. These brittle structures are clearly posterior to the ductile event. This age relationship between brittle and ductile deformation episodes is quite common within the lineaments of basement rocks in NE Nigeria.

In thin section, plagioclase is the most susceptible of the main phenocryst phases to both brittle deformation and chemical alteration, followed by K-feldspar and quartz as the most chemically stable phase. This sequence conforms to that derived by Lasaga (1984) based on thermodynamic calculations of the lifetimes of minerals. Tullis *et al.* (1990) attributed the differential reactivity of quartz and feldspars under stress to the cleavage properties of these mineral phases. This is particularly true at low-grade metamorphic conditions, the two good cleavages in feldspars may be responsible for fragmentation of feldspars into small clasts, while the absence of good cleavages in quartz means that fragmentation of this mineral is more difficult (Fitz Gerald and Stunitz, 1993). The nature of feldspar microcracking in our samples supports this view. However, mineral stability under such conditions also depends on the bulk rock chemistry and the type of fluids which infiltrates. Fluid geochemical data on the mylonitic rocks are still incomplete but indicate an oxidizing environment. These data also show that the fluids were enriched in F (>64 ppm) and Br (>4 ppm), with only trace amounts of Cl (Suh, unpublished data).

From the appearance of secondary minerals, the mylonite must have formed at low temperature, probably within the epizone, at the expense of the feldspars. Low confining pressure in the epizone permits dilatant brittle deformation including microcracking and shearing. The overall abundance of silica-saturated aqueous fluids in this zone also promotes both brittle and ductile deformation behaviour by enhancing microcrack propagation (Bell and Etheridge, 1976). The growth of these microcracks leads to grain-size reduction and eventually yields the fine-grained mylonites. We therefore believe that the mechanism forming these mylonites occurs mainly by microcrack propagation and progressive grain-size reduction, as documented in the microscopic analysis. This is at variance with the mechanism proposed by Fowler and Lennox (1992) which viewed the mylonites in their study to have formed by intense strain partitioning into the weaker lithologies.

The secondary products associated with feldspar alteration are albite, sericite–phengite micas $\pm$ chlorite $\pm$ epidote; various clay minerals and reddish-brown iron oxide coatings. This assemblage is typical for sub-greenschist metamorphic conditions, and was probably attained at about 200–250°C. The presence of subangular primary quartz grains mantled by neocrystallized quartz, the occurrence of subhedral quartz in veined structures and the silica-rich micrographic groundmass in the ultramylonites are indicative of pervasive silicification events in these mylonitised granites. Furthermore, the reactions of plagioclase to albite, and subsequent formation of chlorite $\pm$ epidote and phengitic mica, all release Si (Kamineni *et al.*, 1993). Because quartz is least deformed and few grains occur as pressure shadows, it is unlikely that extensive dissolution of quartz would have occurred during cataclasis; this suggests that the aqueous fluid was probably saturated with respect to quartz. In the field the main fracture and fault surfaces are covered with silica, which also forms a major part of the matrix in the cataclasites. This study suggests that most of this silica was derived from the breakdown of primary minerals, notably plagioclase feldspars. Because the deformation temperature is very low, we invoke hydrothermal fluid action (leaching of uranium from the host rock and subsequent concentration in the fractures) rather than magmatic injection as the mechanism of uranium concentration in this rock.

Carter *et al.* (1981) suggested that deformation of granitoid rocks at low-grade metamorphic conditions is controlled by quartz and that the role of feldspars may only become significant at upper greenschist to amphibolite facies. However, fluid-assisted reaction of feldspars can take place at much lower metamorphic grade (Fitz Gerald and Stunitz, 1993), as documented here. The deformational style of plagioclase in these granites is typical for plagioclase deformation under fluid-infiltrated conditions. This is a general phenomenon during cataclasis (Hirth and Tullis, 1989; Kamineni *et al.*, 1993). The alteration products of feldspar are favourable for subsequent ductile deformation. The alteration of plagioclase produced free ions such as K^+, Na^+, Al^{3+} and Si^{4+} which can easily be mobilized, together with the uranium, by the hydrothermal fluids into the brittle structures. This may explain why alkali metasomatism and silicification are principal alterations associated with the mineralized rock. Recent bulk rock geochemical data (Suh, unpublished data) show the mineralized cataclasite samples to have mean K_2O and Na_2O concentrations of 5.09 and 2.77 wt%, respectively, both values being higher than 2.86 wt% for K_2O and 2.04 wt% for Na_2O in the fresh granite. Amazingly, a typically mylonitised and non-mineralized sample has <1 wt% K_2O and insignificant trace amounts of Na_2O. These results confirm leaching and chemical mass transfer as active processes in the ore formation process, but we must stress here that the geochemical data we have obtained so far are too small to warrant a detailed discussion here. Funtua *et al.* (1992) confirmed from lithogeochemical data that the Kanawa uranium mineralization is in fact accompanied by remobilization of Na, K and Mg but could not identify the source of these ions: magmatic, hydrothermal or remobilized from within the host rock. We show here that the disintegration of feldspars is a plausible source.

CONCLUSIONS

The results of this study are as follows.

(1) The mylonite shear zone hosting the Kanawa Violaine uraniferous vein shows evidence of both brittle and ductile deformation. At the centre of the vein are mylonitic and ultramylonitic bands that grade outwards into cataclasites and fault breccias.

(2) The mineralization occurs as veinlets along N–S-trending brittle structures (faults/fractures) and along the mylonitic foliation. The brittle structures are posterior to the ductile event.

(3) Plagioclase feldspars were the chemically most unstable phase and disintegrated within the fluid-infiltrated-medium. Their breakdown contributed to the

free Si^{4+}, K^{+} and Na^{+} ions responsible for the extensive silicification and phyllosilicate alterations associated with the mineralization. The silica-saturated fluid remobilized and subsequently concentrated the uranium.

(4) The alkali feldspars deformed mainly by transgranular fracturing along planes with microcracks healed by secondary micas and chlorite. Some of these microcracks, especially in the disintegrating plagioclase feldspars, show dissolution textures.

(5) Quartz underwent much *in situ* recrystallization and plastic deformation, and shows little evidence of brittle deformation. It was chemically the most stable phase during the alteration process, probably because the infiltrating fluid was saturated with respect to quartz.

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REFERENCES

Bell, T. H. and Etheridge, M. A. (1976) The deformation and recrystallisation of quartz in a mylonitic zone, Central Australia. *Tectonophysics* **32**, 235–267.

Berthé, D., Choukroune, P. and Jegouzo, P. (1979) Orthogneiss, mylonite and non-coaxial deformation of granites: the example of South Armorican shear zone. *Journal of Structural Geology* **1**, 31–42.

Boullier, A. M. (1980) A preliminary study on the behaviour of brittle minerals in a ductile matrix: example of zircons and feldspars. *Journal of Structural Geology* **2**, 211–217.

Carter, N., Anderson, D. A., Hansen, F. D. and Kranz, R. L. (1981) Creep and creep rupture of granitic rocks. *American Geophysical Union, Geophysical Monograph* **24**, 61–82.

Chester, F. M., Friedman, M. and Logan, J. M. (1985) Foliated cataclasites. *Tectonophysics* **111**, 139–146.

Dada, S. S., Tubosun, I. A., Lancelot, J. R. and Lar, A. U. (1993) Late Archaean U–Pb age for the reactivated basement of NE Nigeria. *Journal of African Earth Science* **16**(4), 405–412.

Evans, J. P. (1990) Textures, deformation mechanisms and the role of fluids in the cataclastic deformation of granitic rocks. In *Deformation Mechanisms, Rheology and Tectonics*, eds R. J. Knipe and E. H. Rutter, pp. 29–41. Geological Society of London Special Publication **54**.

Fitz Gerald, J. D. and Stunitz, H. (1993) Deformation of granitoids at low metamorphic grade. I: Reactions and grain size reduction. *Tectonophysics* **221**, 269–298.

Fowler, T.J. and Lennox, P.G. (1992) Low pressure deformation of a small high-level pluton: the syntectonic Davys Creek Granite from the SE Lachland Fold Belt, N.S.W. In *The Palaeozoic eastern margin of Gondwanaland: Tectonics of the Lachland Fold Belt, SE Australia and related orogens*, eds C. L. Fergusson and R. A. Glen. *Tectonophysics* **241**, 293–310.

Funtua, I. I., Okujeni, C. D., Abaa, S. I. and Elegba, S. B. (1992) Geology and genesis of uranium mineralisation at Kanawa Gubrunde horst, NE Nigeria. *Journal of Mining Geology* **28**(2), 171–178.

Hirth, G. and Tullis, J. (1989) The effects of pressure and porosity on the micromechanics of the brittle–ductile transition in quartzite. *Journal of Geophysical Research* **94**, 17,825–17,838.

Kamineni, D.C., Kerrich, R. and Brown, A. (1993) Effects of differential reactivity of minerals on the development of brittle to semi-brittle structures in granitic rocks: Textural and oxygen isotope evidence. *Chemical Geology* **105**, 215–232.

Lasaga, A. C. (1984) Chemical kinetics of water–rock interactions. *Journal of Geophysical Research* **B89**(B6), 4009–4025.

Leroy, J. (1978) The Margnac and Fanay uranium deposits of the Crouzille district (western Massif, Central France): Geological and fluid inclusion studies. *Economic Geology* **73**, 1611–1634.

Maurin, J. C., Benkhelil, J. and Robineau, B. (1986) Fault rocks of the Kaltungo lineament, NE Nigeria, and their relationships with Benue Trough Tectonics. *Journal of the Geological Society of London* **143**, 587–599.

Maurin, J. C. and Lancelot, J. R. (1990) Structural setting and U–Pb dating of uranium mineralisations from the northeastern part of Nigeria (Upper Benue Region). *Journal of African Earth Sciences* **10**(3), 421–433.

Ojo, O. M. (1988) Stream sediment geochemistry of the Gubrunde horst, 'Gongola Basin', Upper Benue Trough, Nigeria. *Journal of African Earth Sciences* **1**, 91–102.

Oshin, I. O. and Rahaman, M. A. (1986) Uranium favourability study in Nigeria. *Journal of African Earth Sciences* **5**(2), 167–175.

Passchier, C. W. and Simpson, C. (1986) Porphyroclast systems as kinematic indicators. *Journal of Structural Geology* **8**, 831–843.

Popoff, M., Kampunzu, A. B., Coulon, C. and Esquevin, J. (1982) Decouverte d'un volcanisme mesozoic dans le NE du Nigeria. *Travaux de Laboratoire de Sciences de la Terre, St Jerome, Marseille* **19**, 47–49.

Tullis, J., Dell'Angelo, L. and Yund, R. A. (1990) Ductile shear zones from brittle precursors in feldspathic rocks: the role of dynamic crystallisation. In *The Brittle–Ductile Deformation in Rocks*, eds A. G. Duba, W. B. Durham, J. K. Handin and H. F. Wang, pp. 67–82. American Geophysical Union, Geophysical Monograph **56**.

Tullis, J. and Yund, R. A. (1980) Hydrolytic weakening of experimentally deformed Westerly granite and Hale albite rock. *Journal of Structural Geology* **2**, 439–451.

White, S. H. (1977) Geological significance of recovery and recrystallisation processes in quartz. *Tectonophysics* **39**, 143–170.

Ziegler, P. A. (ed.) (1992) *Geodynamics of Rifting. II. Case History Studies on Rifts: North and South America and Africa. Tectonophysics* **213** (special volume).