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The Pegmatite Veins of Western Oban Massif: Tectonic and Lithological Controls on Physical Properties

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Abstract: In this study, the pegmatite vein system in western Oban Massif, southeastern Nigeria, is presented against a background of the salient geological structures of the area. It is the ultimate interest of this author to determine the relative contributions of magmatic fluid pressure and prevailing structural control in the emplacement of these igneous bodies, the source of the magmatic fluids as well as any indication of the pressure of the fluid. Is there any simple relationship between present pegmatite dimensions and the paleo-pressures of the fluids or the stresses that existed at the time of emplacement? The granitic pegmatites of Uyanga- Akwa Ibami area in western Oban Massif have drawn reasonable attention since the beginning of the twentieth century. They are genetically related to Uwet granodiorite, a syn-tectonic pan-African granitoid with a long cooling history. The strongest pegmatite vein orientation is in the NNW-SSE, followed by ENE-WSW and E-W sets. Less prominent sets trend in the NNE-SSW and NW-SE directions. These veins are preferentially emplaced mainly in pre-existing discontinuities like fractures, joints, faults and foliations. Finite pegmatite lengths up to 20 m and the infinite variety over 40 m have been measured in this area, although the most frequently occurring lengths are between 2-3 m. Vein thickness generally varies from 0.3 m to 8.4 m, with the most frequently occurring value lying between 1.0 and 1.5 m. The most frequently occurring vein thickness is-1.75 m in schist and 1.25 m in granodiorite host rock. Pegmatite veins tend to dilate as they elongate and a relationship of the form Y = MX exists between their lengths and widths. The material constant M varies from 2.236 for schist to 5.159 for granodiorite. This is interpreted as lithological control on vein dimensions. The presence of veins in tensile (mode I) fractures at the schist level only and a more ubiquitous distribution in shear fractures mainly, at the granodiorite level, is a strong indication of interaction between long range tectonic stresses and magmatic fluid pressures.

Key words: Lithological control, oban massif, pegmatite veins, tectonic control, vein orientation

INTRODUCTION

When and where the study was conducted: This study was conducted from March 2008 through to September 2011 on the granitic pegmatites of Uyanga- Akwa Ibami (Uwet) area in the western part of the Oban Massif, which is a part of the western prolongation of the Cameroon Mountains into the Cross-River Plains of SE Nigeria and also a part of the Precambrian mobile belt of Nigeria. This area is more properly delineated by the co-ordinates 8º00′ - 8º30′E and 5º00′ - 5º30′N, which lies between the West African Craton and the Gabon-Congo Craton.

One of the rock types/structures that impressed Raeburn (1927) in western Oban Massif is the pegmatite veins, although he remarked that they were not as majestic as those in central Nigeria (i.e., Kwara and Nasarawa states). Attention was first drawn to the tin-bearing pegmatites of Calabar Province in 1903, when cassiterite was discovered there (Jacobson and Webb, 1946). From then till quite recently, there has been keen foreign and local interest in the pegmatites of western Oban Massif and Nigeria as a whole (Wright, 1970; Varlamoff, 1972; Kinnaird, 1983; Okunlola, 1998; De Saint Simon, 1999; Okunlola and King, 2003; Okunlola, 2005).

This interest stems from the fact that the primary occurrence of columbite, tantalite, wolframite and tin in Nigeria is in pegmatites. This is also the case with precious and semi-precious gemstones.

So far research on pegmatites in the Nigerian basement has focused on mineralogy and classification (Jacobson and Webb, 1946; Varlamoff, 1972; Odigi, 1986) as well as chemical analysis for the major and trace element content (De Saint Simon, 1999; Okunlola and King, 2003; Okunlola, 2005; Ero and Ekwueme, 2009). Little or no attention has been paid to the physical properties and structural relationships/configurations of pegmatite veins in the basement complex of Nigeria. The theories of sheet intrusions always place much emphasis

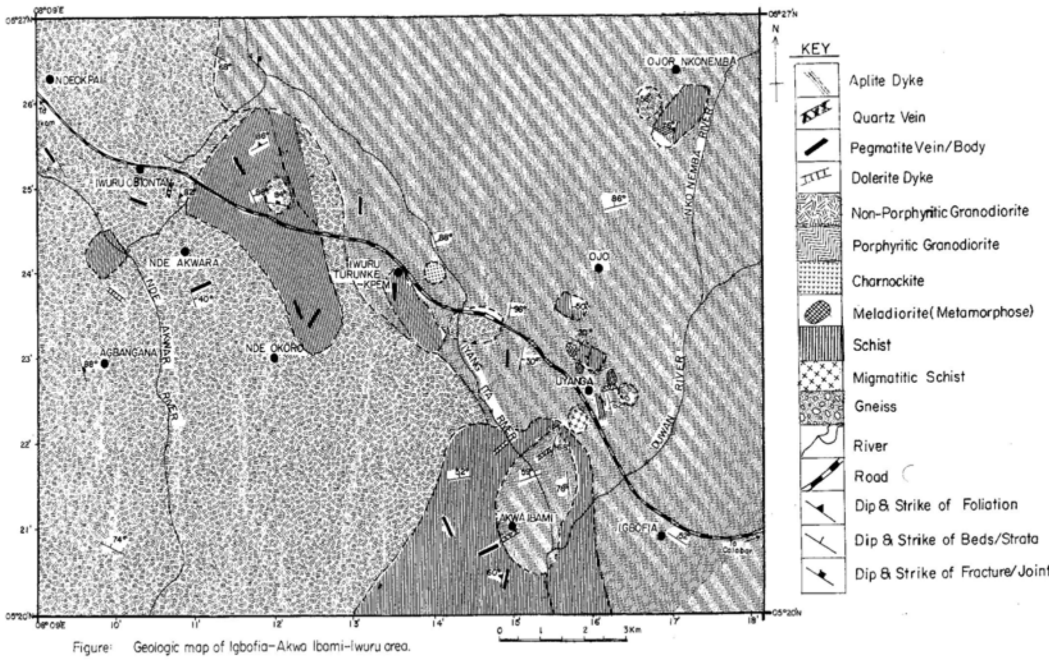

Fig. 1: Geclogic map of lgbofia -Akwo lbomi lwuru area

on the pressure of the magmatic or hydrothermal fluid from which the veins and dikes are formed (Jacobson and Webb, 1946; Jaeger and Cook, 1976; Suppe, 1985; Price and Cosgrove, 1990). Not much is made of the role of existing fractures joints and prevailing stress systems in the development of pegmatite veins.

In this study, the pegmatite vein system in western Oban Massif, southeastern Nigeria, is presented against a background of the salient geological structures of the area. It is the ultimate interest of this author to determine the relative contributions of magmatic fluid pressure and prevailing structural control in the emplacement of these igneous bodies the source of the magmatic fluids as well as any indication of the pressure of the fluid. Is there any simple relationship between present pegmatite dimensions and the paleo-pressures of the fluids or the stresses that existed at the time of emplacement?

MATERIALS AND METHODS

The study of pegmatites in the field (Uyangha-Akwa Ibami Area, Fig. 1), was preceded by a careful study of lineaments in Oban Massif basement complex, compilation of a lineament map and analysis of the lineaments of the area. During the field study exercise the general geology and field structures of the area were studied, while particular attention was paid to the location, mineralogy and physical characteristics of the pegmatite and quartz veins. Some of the pegmatite veins were sampled for chemical analysis, with a view to exposing their trace element composition. For each vein, the structural attitude, the length and width (aperture), as well as the coordinates were carefully measured, while the host rock, shape or habit, wall rock condition, major and accessory minerals as well as the nature of the vein container - (i.e., whether placed in a joint, fault or foliation), were determined.

Field characteristics: The granitic pegmatites of Uyangha-Akwa Ibami Area are mainly internal and external (Jacobson and Webb, 1946), in relationship to Uwet granodiorite, its most probable source. The internal pegmatites are placed in discontinuities (mainly joints, faults and shear zones) in the granodiorite, while the external pegmatites are found in foliations, joints, faults and shear zones in schistose host rocks. The schist and granodiorite are the most extensive host rocks (Fig. 1), while minor occurrences of gneiss, charnockite, meladiorite and dolerite dykes abound in the area. A total

Fig. 2: Small aperture vein in granodiorite host rock. The vein is broken by late stage joints, approximately perpendicular to its length

of 110 pegmatite, aplite and quartz veins were studied and their physical properties are presented in the following sections. They were divided 00 into finite pegmatites of measurable length and infinite pegmatites, being those with unexposed extremities and therefore of immeasurable length. Figure 2 and 3 show small aperture veins in granodiorite and schistose rock, respectively while Fig. 4 and 5 are large aperture, high angle veins emplaced concordantly in schistose foliation. The height

Fig. 3: Small aperture vein in schistose host rock

Fig. 4: Wall of a large aperture vein in schistose host rock

Fig. 5: Wall of another large aperture vein in the schistose host rock

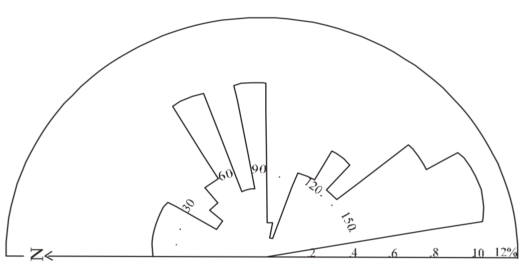

Fig. 6: Rose diagram showing orientations of all pegmatite veins measured in Uyango-Akwo lbami area (llo data points)

of veins 2(c) and 2(d) above ground surface is an indication of the relative resistance of the veins and the host rocks, to weathering. The pegmatite veins tend to be straight and unbranched, even if broken in some cases by late stage jointing (Fig. 2).

The most common mineralization in the veins is black tourmaline, which occurs in a wide range of crystal sizes, as well as some iron ore, garnet and accessory minerals suspected to be tin ore. Some of the veins are dry pegmatites (without mica) while others contain the major minerals quartz, feldspar and muscovite (wet veins).

Physical properties:

Orientation of veins: The 110 measured veins showed five preferred orientations of long axes (Fig. 6). These are the NNE-SSW or set (0º-30º strike), ENE-WSW set (60º-70º strike), E-W set (80º-90º strike), NW-SE set (120º-130º) and the NNW-SSE set (140º-170º strike). The most preferred pegmatite orientation is the NNW-SSE (140º-170º), which corresponds to the most preferred fracture orientation in Oban Massif (Fig. 9). Part of the NNE-

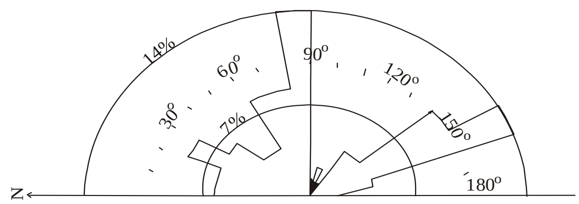

Fig. 7: Rose diagram pegmatite orientations in schist (52 data points)

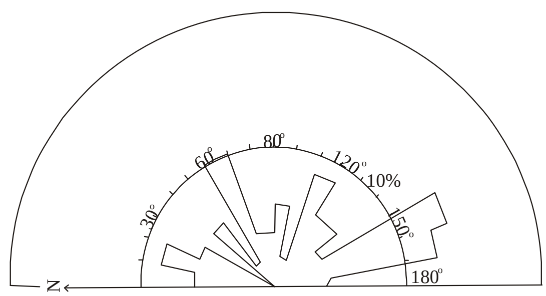

Fig. 8: Rose diagram pegmatite orientations in gronodiorite (58 data points)

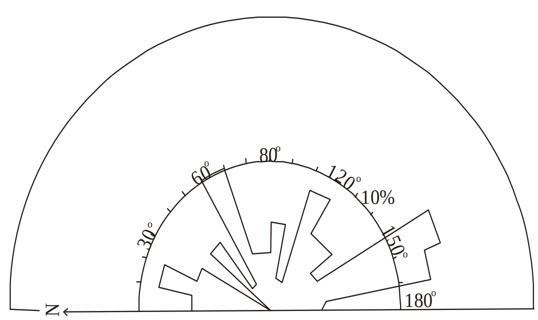

Fig. 9: Rose diagram of fracture lineaments in oban Massif(688 data points)

SSW, E-W and NW-SE pegmatites owe their orientations to preexisting fractures, as well, while the ENE-WSW set (60º-70º) most probably owes its strength and orientation to the foliation trend in schist (Fig. 10). Altogether, there seems to be strong structural control on vein orientation. Only the veins oriented between Oº and 20º (Fig. 6) appear to have intruded without assistance from pre-existing discontinuities (i.e., by sheer force of fluid pressure).

These constitute only 12.7% of all the veins measured and may be the true hydraulic fractures. Also only the pegmatite veins in E - W orientation were placed in tensile or extension fractures, the majority were placed in simple shear discontinuities (NE - SW and NW-SE) as well as some pure shear discontinuities (N-S orientation). The preferred orientations of pegmatite veins in schist and granodiorite are compared in Fig. 7 and 8. In schistose host rock (Fig. 7) vein orientations are strongest in two directions. E - W and NW-S E. The third set between 020º and 030º strike is not so well developed. In granodiorite host rock, the most prominent trends are the NNW -SSE and NE- SW sets. At least two other sets striking between 10º-20º and 110º-120º are minor in strength. There is actually no prominent pegmatite vein orientation in the E - W direction (Fig. 8), and the growth is more ubiquitous and radial in the granodiorite than in the schist.

Dimensions of pegmatite veins: Pegmatites of lengths more than 40 m have been measured in Uyangha-Akwa Ibami area, but many of the long ones are usually covered at one or both extremities. Of the finite pegmatites, even though lengths of the order of 20m have been measured, the most frequently occurring lengths are between 2.0 and 3.0 m (approximately 2.5 m, Fig. 11). Average length of pegmatites is greatest for veins striking 111º-120º (Fig. 12), followed by veins of NE - SW (041º-050º) and (161º-170º) orientations. Veins between 121º to 140º strike have the least average length while the 051º to 060º strike corridor had no veins at all. This indicates that only veins initiated in certain preferred orientations had the capacity to grow in length. Average vein width (aperture), on the other hand, is highest for those oriented between 031º and 050º as well as those between 151º - 160º strike (Fig. 13). These are actually veins in simple shear

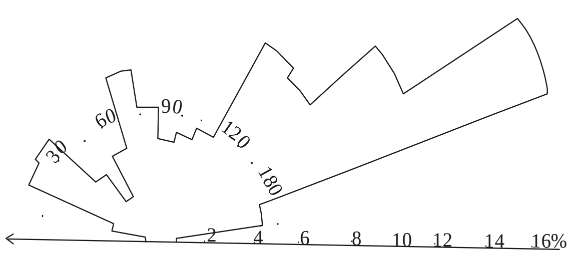

Fig. 10: Rose diagram orientation of foliation planes in schist, Uyanga-Akwa Ibami area

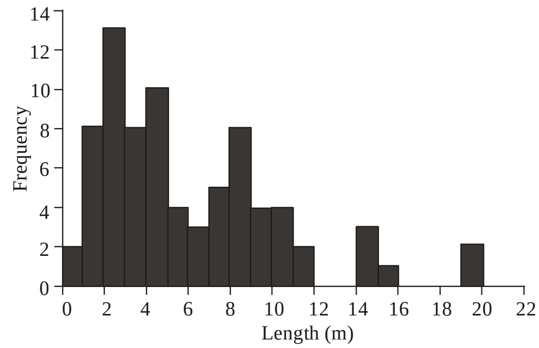

Fig. 11: Histogram showing frequency of pegmatite length intervals (finite pegmatites only). Veins with 2-3 m lengths are the most frequently occurring

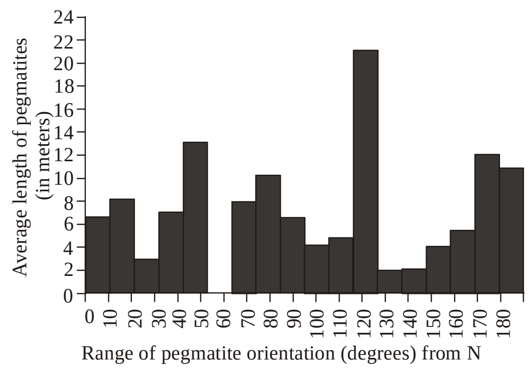

Fig. 12: Graph of average length against orientation range of pegmatites

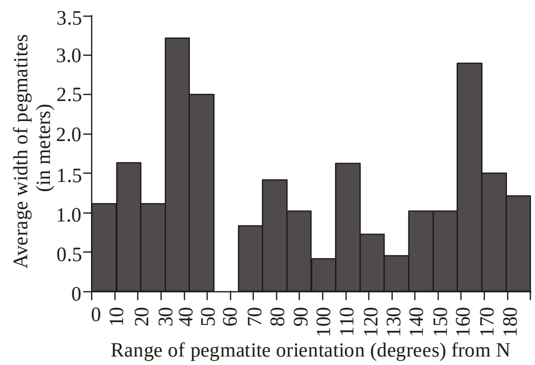

Fig. 13: Graph of average width against orientation range of pegmatites

orientations, while those in tensile or extension orientations (81º to 100º) are among the narrowest pegmatite veins in this area.

Although vein widths above 8.0 m have been measured, the most frequently occurring pegmatite widths are between 1.0 and 1.5 m (Fig. 14). Compared to the pegmatites of Kivu and Manono in eastern D.R. Congo (Varlamoff, 1972), those of western Oban Massif could be classified as small size veins. That pegmatite vein widths may be under the control of the host rock, even though to a little degree, is indicated in Fig. 15 and 16. The most are between 1.0 and 1.5 m (Fig. 14). Compared to the frequently occurring vein width in schist is 1.5 to 2 m, from a width range of 0.3 to 8. 4 m (Fig. 15), while that for granodiorite host rock is 1.0 to 1.5 m, from a width range of 0.2 to 7.5 m (Fig. 16). This could indicate that some host rocks are more compliant than others when it comes to vein widening - a phenomenon related to tensile strength of the rocks as well as the fluid pressure in the

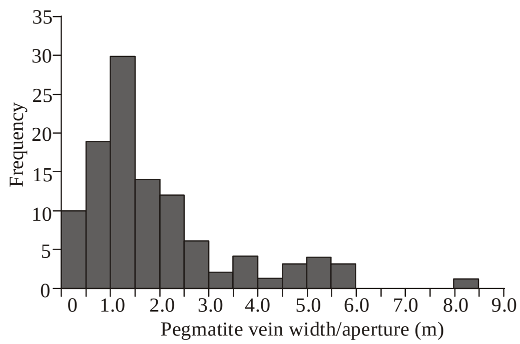

Fig. 14: Histogram showing the frequency of occurrence of different vein widths (aperture) segments. The most frequently occurring vein width is between 1.0 to 1.5 m

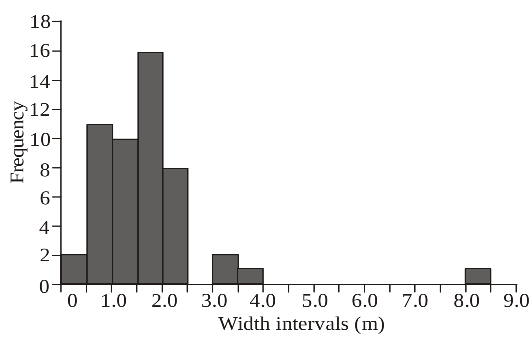

Fig. 15: Histogram of pegmatite vein width (aperture) in schistose host rock

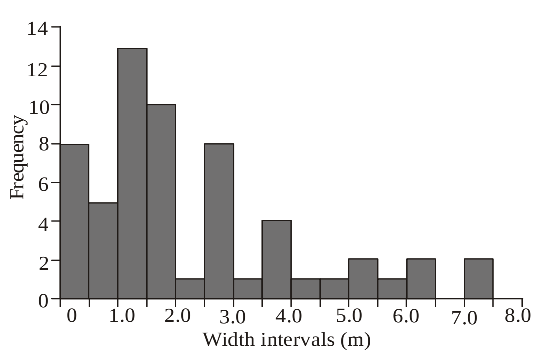

Fig. 16: Histogram of pegmatite vein width (aperture) in granodiorite host rock

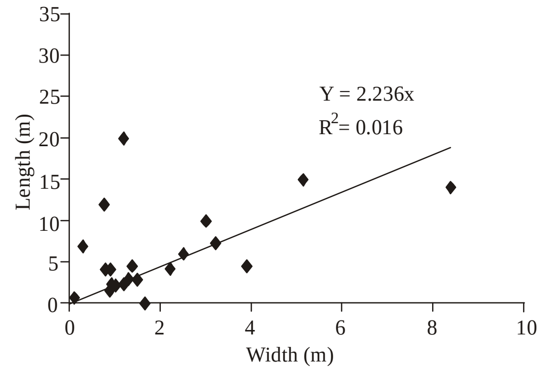

Fig. 17: Graph of length against width (aperture) of pegmatite veins in schistose host rock.

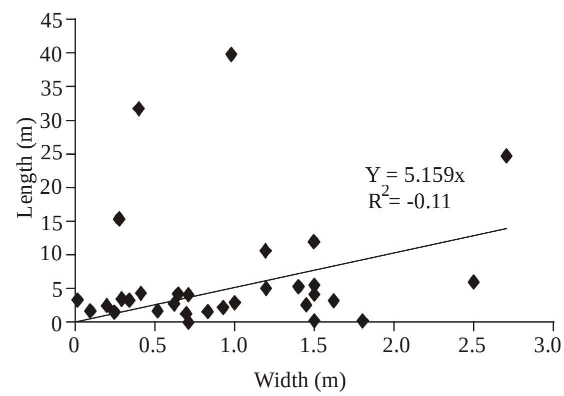

Fig. 18: Graph of length against width (aperture) of pegmatite veins in granodiorite host rock

medium. Comparing the distributions of pegmatite widths in schist and granodiorite (Fig. 14 and 15), it appears the latter is more thickness was also observed in eastern Iceland by Paquet *et al*. (2007). The length/width graphs of pegmatites show simple linear relationships of the form:

$$Y = 2.24X \quad (1)$$

in schistose host rock and

$$Y = 5.16X \quad (2)$$

in granodiorite host rock (Fig. 17 and 18). The inequality of the constants in the two equations is an indication of some control on pegmatite dimensions by the host rock and it indicates that for a given unit width of vein materials corresponding elongation will be greater in granodiorite than schist, in Oban Massif. The combined data in Fig. 19 confirms the general relationship:

$$Y = MX \quad (3)$$

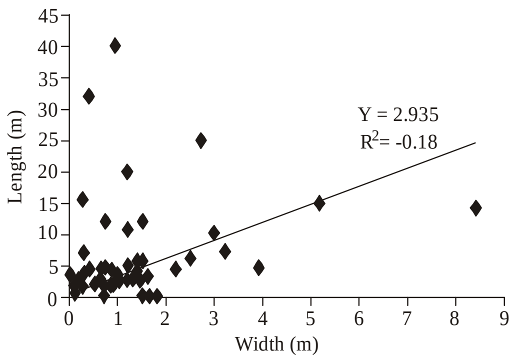

Fig. 19: Graph of length against width (aperture) of pegmatite veins in both schist and granodiorite host rock

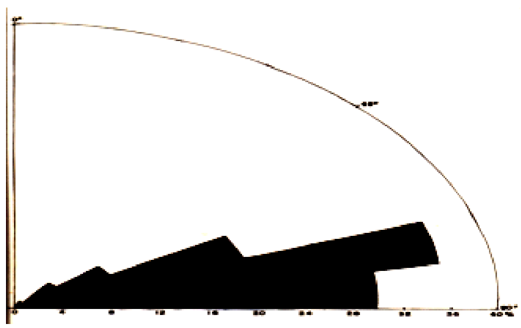

Fig. 20: Dip angles of pegmatites veins. Veins in uyanga-Akwa Ibami area are mainly high angle structures (>45º). the most frequently occurring veins have dips between 70º - 80º (108 data points)

Fig. 21: Conjugate shear bands cross-cutting on the side of a pegmatite vein wall. Note large books of muscovite and qtz have recrystallised in the shear bands

where M is a constant for a particular host rock, but varies depending on rock type.

Dip of structures: If 45º is the boundary between low and high angles of dip, then it appears that pegmatites in western Oban Massif occur generally in high angle structures (Fig. 20). More than 65% of pegmatites measured were found in structures of 70º to 90º dip, while over 94% of all measurements were found in structures dipping 50º and above. Since pegmatites are a late-stage rock type, they are more likely to have been emplaced in

pre-arranged structures in most cases, except for those that were initiated by pressure of the fluids.

Post emplacement structures: Figure 1 shows post emplacement jointing affecting a pegmatite vein in granodiorite terrain. Joints are indeed the most frequently encountered structures on the pegmatites. Shear bands have also been seen on the walls of some veins (Fig. 21). A rose diagram of these late-stage joints showed a very ubiquitous pattern. It is very likely that these joints were produced mainly during the processes of uplift and denudation.

DISCUSSION

The pegmatites of Uyangha - Akwa Ibami Area in western Oban Massif were derived as a residual melt from Uwet granodiorite, a panAfrican, syntectonic granitoid that was in fluid form from about 617 to 511 Ma (Ekwueme and Nganje, 2000). For most of the panAfrican deformation (600±150 m yrs ago), the main stresses that acted in the western Oban Massif were:

- A horizontal maximum compressive stress (E - W) S_1
- A vertical intermediate compressive stress - S_2
- A horizontal minimum compressive stress (N-S) S_3
- Fluid pressures of different magnitudes and sources, including that from the molten Uwet granodiorite. The stress system and the fluid pressures working together created a host of fractures with different orientations.

Most of the pegmatites intruded pre-existing discontinuities like joints, faults, fracture lineaments, shear zones and foliation planes. Intrusion into the schist took place in a more brittle environment, where tensile fractures played a major role because of lower confining pressure. Intrusion into fractures in granodiorite took place under a more ductile environment, where hydrostatic stress more or less prevailed (Brisbin, 1986) and the lithostatic stresses (S_1, S_2, S_3) were probably equal. Hence pegmatite vein orientations in the granodiorite (Fig. 8) are more ubiquitous and radial than those in the schistose host rock (Fig. 7). This high magmatic fluid volume and pressure at the granodiorite end did not translate easily to wider pegmatite veins, probably due to the presence of a large number of fractures, which generated very high hydraulic conductivity.

Pegmatite fluid pressures (p_f) must overcome the compressive stress conditions as well as the tensile strength of the host rocks in order to be able to intrude. That is:

$$P_f \geq S_3 + T \quad (4)$$

Since the tensile strength T of unhealed fractures is zero (Brisbin, 1986), magmatic pressures do not need to be so high before they can form veins in pre-existing fractures or discontinuities. Under this condition, Eq. (4) reduces to:

$$P_f = S_3 \quad (5)$$

Hence discontinuities are the sites of first choice for mineral vein emplacement. This is the structural control on mineral vein orientations.

That the most frequently occurring vein width in schist (~ 1.75 m) is greater than that for granodiorite (~ 1.25 m) is an indication of the relative roles of types of discontinuities bearing the veins. In schistose host rock the role of tensile fractures (mode I), (Olson *et al*., 2009; Olson and Pollard, 1989) is greater than that of shear fractures (modes II and III), while in granodiorite host rock, pegmatite veins are loaded more on shear fractures than tensile fractures. Tensile fractures are the only opening mode fractures parallel to S_1 - the maximum principal compressive stress (Price, 1966; Engelder and Geiser, 1980; Olson *et al*., 2009). Only S_3 is normal or has a closing relationship to tensile (extension) fractures. All the other fracture orientations have the resolved components of either S_1 or S_2 acting across and locking up the fracture planes. These scenarios demonstrate why veins closer to the earth's surface, like those in schistose host tocks, should be wider than those deeper in the crust.

The structural or tectonic control on vein growth also explains the existence of the length / width relationship of the form Y = MX. This implies that in the active tectonic regime, pegmatitie veins were not free to lengthen or dilate at will. For every unit dilation there was a corresponding fixed amount of propagation or elongation. This amount, which varies from one rock type to another, is approximately 2.4 in schist and 5.16 in granodiorite. The implication of this is that during growth, pegmatitie vein elongation per unit width or dilation was greater in granodiorite host rock than in schist. Only pegmatite veins that developed in the post-tectonic setting grew freely, both in orientation and dimensions. Simply stated, for tectonic pegmatites, the longer the vein, the wider or thicker it is. This same behaviour was noticed by Paquet *et al*. (2007) in the basaltic dykes of eastern Iceland. Vermilye and Scholz (1995) showed, using vertical hydrothermal extension mineral veins (calcite, quartz and chlorite) in different host rocks, that isolated (non segmented) veins display a linear relationship between length and maximum aperture (width). They also demonstrated that the proportionality constant, which they termed aspect ratio (i.e., 1/M), increases from igneous rocks, through quartz-rich sedimentary rocks to limestone.

There are two types of crack propagation currently invoked in fracture mechanics. The critical (or dynamic) propagation (Lawn and Wilshaw, 1975; Olson and Pollard, 1989; Olson *et al*., 2009) takes place when the stress intensity factor - K_I is equal to or greater than the fracture toughness - K_{Ic} of the rock:

$$K_I \geq K_{Ic} \quad (6)$$

On the other hand subcritical crack growth occurs even at stress intensity factors below the fracture toughness of the medium, due to the reaction of corrosive fluid at the crack tips (Rehbinder effect) to reduce the fracture toughness of the medium (Atkinson, 1984; Segall, 1984; Price and Cosgrove, 1990). The difference in the length/width proportionality constants for schist (2.24) and granodiorite (5.16) indicates that the fracture toughness of the former was more than the latter. This is the lithological control on pegmatite vein behaviour and it could be a result of the higher temperature, greater corrosive effects of fluids, proximity to the pegmatite fluids as well as greater intensity of the overburden pressure in the granodiorite than the schist. Vermilye and Scholz (1995) actually demonstrated the possibility of using the aspect ratios determined from hydrothermal veins to constrain the tensile yield strength ($б_Y$) of the host rock, the driving stress (бd) as well as depth of formation of the veins. With some adjustments of the appropriate equations, it may be possible to determine the same parameters using pegmatite veins.

SUMMARY AND CONCLUSION

The granitic pegmatites of western Oban Massif were emplaced as a residual melt derived from Uwet granodiorite. This is a syn-tectonic granitoid with a very long cooling history. The veins are mainly high angle structures emplaced mostly in pre-existing discontinuities under the panAfrican stress regime. For this reason the veins developed according to the law Y = MX, where Y and X are length and width respectively and M is a material constant with values of approximately 2.24 for schistose host rock and 5.16 for granodiorite. The difference between these values of slope is interpreted as the difference in fracture toughness between the two rock types, and introduces the idea of lithological control on vein dimensions. Although finite pegmatite veins up to 20 m in length were measured, the most frequently occurring lengths are between 2.0 and 3.0 m (approximately 2.5 m). Also veins oriented in the ESE - WNW (111º - 120º from N) were, on the average, longer than veins of other orientations. This is within the zone of tensile (extension) or mode I fractures. The strong presence of E-W veins (tensile fractures) at the level of the schist and disappearance of the same in the granodiorite is an indication of the changing role of confining pressure on fracture/vein orientation. The general preference of the veins for pre-existing discontinuities is understandable in view of the low to zero tensile strength along such structures. For this reason the driving pressure for vein initiation is greater along such structures than outside them and this explains the structural control on pegmatite vein orientations. The most frequently occurring vein width in schistose host rock is approximately 1.75 m, while that in granodiorite is about 1.25 m, and the frequency distribution of vein width is more exponential in granodiorite than schist.

Pegmatite veins in granodiorite host rock appear more radial or ubiquitous than those in schist for the simple reason that near the magmatic source, the volume and pressure of the magma are so high that the stress field is modified to an almost isotropic, hydrostatic condition. This condition produces mainly radial veins with ubiquitous distribution.

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