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NEW U–Pb AGE CONSTRAINTS AND POTENTIAL IMPLICATIONS FOR THE GENESIS OF THE KITTS URANIUM DEPOSIT, CENTRAL MINERAL BELT, LABRADOR

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ABSTRACT

One of the earliest discoveries of uranium mineralization, within the Central Mineral Belt (CMB), still stands as the highest grade deposit found. The Kitts deposit represents a predominantly structurally controlled, vein-hosted style of uranium mineralization occurring within metasedimentary rocks of the Paleoproterozoic Post Hill Group. A new U–Pb SHRIMP age of 1881.8 ± 3.4 Ma, from a crosscutting quartz-feldspar porphyry dyke, now provides a minimum age limit on the primary mineralizing event within the deposit. Furthermore, a U–Pb TIMS date from an undeformed, crosscutting diorite dyke of 1662 ± 4 Ma provides a minimum age constraint on the deformation event(s) that postdate the intrusion of the quartz-feldspar porphyry dyke, and result in the local remobilization of the uranium mineralization. The inference, that the primary uranium mineralization is older than ca. *1882 Ma, highlights potential problems with previous models for the source(s) of the uranium. In conjunction with other geochronological data, the results indicate at least two discrete periods of uranium mineralization within the eastern portion of the CMB.*

INTRODUCTION

EXPLORATION HISTORY

Despite the intensive exploration effort for uranium mineralization within the Central Mineral Belt (CMB) of Labrador since the mid-1950s, some of the earliest mineralization discovered, in outcrop, still remains as the highest-grade deposit within the region, and represents the first potentially economic uranium deposit found within the CMB. Uranium mineralization was first noted along the eastern coastline of Kaipokok Bay in 1956 by Walter Kitts, after whom the deposit is named, while conducting regional reconnaissance exploration for British Newfoundland Exploration Ltd. (BRINEX). Initial reports on the prospect described a narrow intermittent zone of radioactivity over a mile in strike length, along which, local grab samples of up to 2.38% U_3O_8 were discovered (Morrison, 1956).

Due to the initial encouraging results, the area surrounding the Kitts deposit became the focus of a more detailed field program in 1957, which included geological mapping, stripping and trenching of mineralized outcrops and packsack drilling. Initial drillhole results demonstrated the continuity of the mineralization at depth and a systematic diamond-drilling program was initiated late in 1957. Encouraging drill results, combined with the favourable topographic location, led to preliminary underground development by the end of 1957. In April of 1958, a 30-ton bulk sample was collected from the exploration adit and shipped to the Radioactivity Division of the Mines Branch in Ottawa for metallurgical testing. A resource calculation done in 1959 indicated a potential resource of 203 000 tons of ore at an average grade of 0.883% U_3O_8 (Project Mine Planning Group, 1976). The development of the Kitts project failed to qualify for supply contracts with the Atomic Energy Commission of Canada and development was suspended in 1958 (Golder, 1977).

The Kitts deposit and surrounding region became the focus of renewed exploration in 1966 with the signing of a joint venture agreement between BRINEX and Urangesellschaft Ltd. The discovery of the larger, lower grade Michelin deposit was the major outcome of this, and Kitts was included as part of a joint feasibility study in 1977. The total development work up to 1979 included approximately 160 surface drillholes totalling some 12 150 m and approximately 118 underground holes totalling some 1900 m, from which about 1900 samples were collected. In 1977, the resource was calculated at 203 880 tons at a grade of 0.73% U_3O_8 (Golder, 1977). In 1979, a development proposal was put forth to the Government of Newfoundland and Labrador for both the Kitts and Michelin deposits; however, approval was withheld due to environmental concerns regarding waste disposal (Powell *et al.*, 1980). The development of the project was further hampered by a down turn in market prices in the early 1980s, and BRINEX finally relinquished rights to the area in 1985.

The Kitts deposit currently lies within exempt mineral lands and therefore has not benefitted from the resurgence in uranium exploration that began in the early 2000s. Several reports produced in the late 1970s, allude to the potential for expansion of the mineral resource, both along strike and at depth (*e.g.*, Golder, 1977), which has proven to be the case with other historical uranium deposits within the CMB that have seen a second stage of exploration (*e.g.*, Michelin deposit; Cunningham-Dunlop and Lee, 2008).

PREVIOUS WORK

The first descriptions of the mineralization in the vicinity of the Kitts deposit are summarized by Morrison (1956) and Hooper (1956). Hooper (1956) noted the development of radioactivity within gossan zones in finely laminated black slate along the contact with a mafic intrusion, but also recognized that not all gossan zones in the region were mineralized. He described the local occurrence of radioactive highs in association with the crests and troughs of minor folds, and concluded that the mineralization was both lithologically and structurally controlled. Beavan (1958) provided a detailed summary on the nature of the mineralization within the Kitts deposit, in which he noted the radioactivity to be preferentially concentrated along shear zones developed at or very close to the intrusive contact between the gabbro and argillite units. These mineralized structures were interpreted to be the result of regional folding. He also proposed the subdivision of the mineralization into the A, B and C zones, with the A and B zones hosting the bulk of the mineralization (Beavan, 1958).

Gandhi (1969, 1970) conducted regional mapping in the area of the Kitts deposit and noted the strong spatial controls on the mineralization within the 'Kitts-Post Hill Belt' (Figure 1). He noted evidence for the localized concentration of uranium within particular stratigraphic horizons of the metasedimentary package hosting the mineralization, and the local concentration of radioactivity at crests of minor drag folds. This led him to conclude that the uranium was of a syngenetic sedimentary origin, and was later remobilized into dilatant structures (Gandhi, 1970). He also postulated that the Kitts A, B and C zones occurred along the same stratigraphic unit that was part of a large synclinal structure, noting that the fold hinge would potentially be a very prospective setting for further high-grade mineralization (Gandhi, 1976a). Gandhi (1978) furthered this model by placing the various uranium occurrences along the Kitts-Post Hill Belt into a stratigraphic context and drawing parallels between this mineralization and that found in the Rum Jungle district of northern Australia.

More detailed work in the region of the Kitts deposit was carried out by Marten (1977), who examined basement–cover contact relationships along the region of the Kitts-Post Hill Belt. The resultant interpretation on the development of the uranium mineralization was that the mineralization was remobilized into structurally dilatant zones during early syntectonic processes. In the vicinity of the Kitts deposit, Marten (1977) noted that uranium mineralization was primarily developed within the sulphidic semipelite or 'iron formation', which he interpreted to occur as discontinuous layers within the Kitts Pillow Lava Formation, and to form the loci for early D_1–D_2 shear zones (Regional D_1 of Culshaw *et al.*, 2000). He also noted that the uraninite was incorporated into fine-grained metamorphic amphibole and biotite, which he inferred as evidence for the pre- to syn-D_2 timing for the mineralization. The mineralization within these shear zones was noted to be concentrated along the S_1–S_2 schistosity planes and locally within quartz-carbonate veins (Marten, 1977). Later remobilization of the mineralization was recognized along small-scale shear zones related to D_3 (Regional D_4 of Culshaw *et al.*, 2000); these structures also result in the remobilization of the uranium into the surrounding country rock (Marten, 1977).

Evans (1980) conducted a detailed examination of the uranium mineralization along the Kitts-Post Hill Belt. He identified two distinct shear zones within the Kitts deposit, the first of which was essentially conformable with the schistosity in the volcaniclastic rocks (~320° strike/45-90° NE dip). This structure is dominant within the deposit as it is host to most of the mineralization, and is termed the 'Main Shear Zone'. The second shear zone is developed roughly parallel to the regional schistosity (010–020° strike/55-65° SE dip) but is discordant to the lithological contacts within the deposit; this structure is referred to as the 'Cross Shear Zone' (Evans, 1980). The intrusion of quartz-feldspar porphyry dykes, which are generally developed subparallel to the Cross Shear Zone but are also locally transposed by the same structures, are inferred to predate the main D_3 event (Evans, 1980; Regional D_4 of Culshaw *et al.*, 2000).

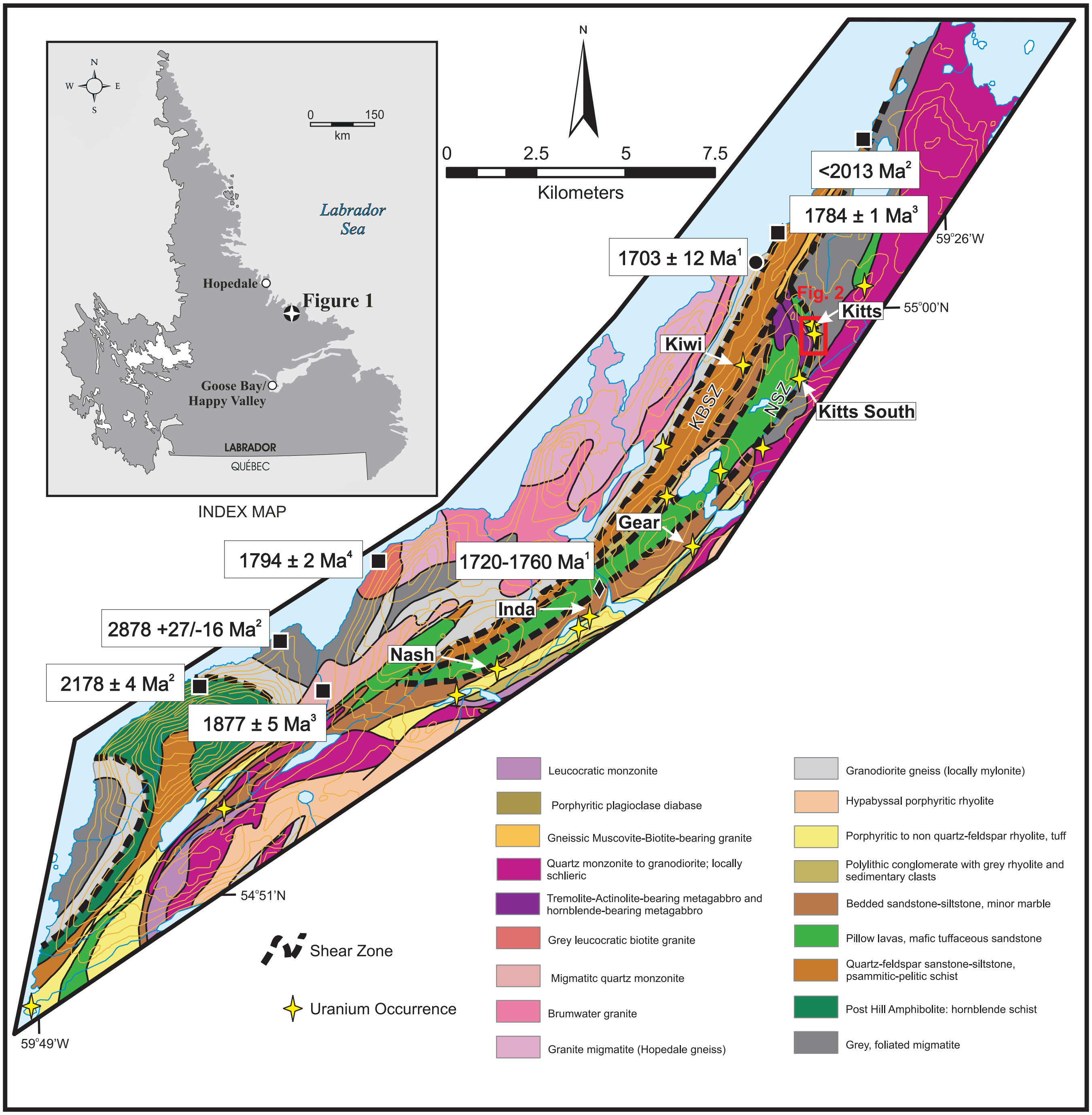

Figure 1. *Geological map of the Kitts-Post Hill Belt, showing the location of significant uranium occurrences and the distribution of known geochronological data. Solid diamonds (amphibole) and circles (muscovite) represent Ar–Ar determinations, the solid squares represent U–Pb data. Age sources: (1) Culshaw* et al.*, 2002; (2) Ketchum* et al.*, 2001; (3) Ketchum* et al.*, 1997; (4) Schärer* et al.*, 1988. Abbreviated structures include KBSZ - Kaipokok Bay Shear Zone and NSZ - Nakit Shear Zone. Modified after Marten, 1977; Gower* et al.*, 1982; and Culshaw* et al.*, 2002. Box shows location of Figure 2.*

REGIONAL GEOLOGY

The Kitts deposit is situated along the eastern coast of Kaipokok Bay, within a structurally complex region that has been the focus of numerous scientific studies (Figure 1; Gandhi, 1969, 1970, 1978; Marten, 1977; Gower *et al.*, 1982; Schärer *et al.*, 1988; Culshaw *et al.*, 2000, 2002; Ketchum *et al.*, 2001, 2002). Within this region, remobilized Archean basement rocks are structurally overlain by amphibolite-facies supracrustal rocks of the Post Hill Group

(Ketchum *et al.*, 2002). The Post Hill Group comprises psammite, schistose mafic metavolcanic rocks and minor pelite, which are interpreted to have been deposited within a continental-margin-type environment (Culshaw and Ketchum, 1995). Quartzites from the base of the Post Hill sequence contain Archean detrital zircons and were deposited after 2235 Ma, as the rocks postdate the intrusion of the Kikkertavak dyke swarm (Ketchum *et al.*, 2002). Tuff layers contained within the overlying Post Hill amphibolite have produced a U–Pb age of 2178 ± 4 Ma, which is interpreted to be the formational age of the amphibolite (Ketchum *et al.*, 2001). The amphibolite unit is, in turn, overlain by the Metasedimentary Formation of Marten (1977), which includes thin-bedded psammite and minor pelite. Based on the mineralogy of these units, Marten (1977) interpreted them to have originally been deposited as greywackes. A micaceous psammite sample from within this sequence was found to contain both Archean and Paleoproterozoic detrital zircons and was deposited after 2013 ± 3 Ma (Ketchum *et al.*, 2001). The Kitts Pillow Lava overlies the Metasedimentary Formation and forms the upper most unit of the Post Hill Group stratigraphy (Marten, 1977; Evans, 1980). This unit consists of massive metavolcanic pillow basalt with minor discontinuous beds of argillite and iron formation, which is the host to most of the uranium mineralization at the Kitts deposit.

To the east, the Post Hill Group is tectonically juxtaposed with the Aillik Group, which is composed of an upper greenschist- to lower amphibolite-facies volcano-sedimentary sequence consisting predominantly of felsic volcanic rocks and related volcaniclastic equivalents (Gower *et al.*, 1982; Hinchey, 2007). The original nature of this contact has been the focus of much debate; it has been interpreted as both conformable (Evans, 1980) and unconformable (Marten, 1977). Regardless of the original relationship, the structurally complex zone now separating the Post Hill and Aillik groups is a region of significant uranium mineralization, defining the Kitts-Post Hill Belt (Gandhi, 1978). This region includes the Kitts, Gear, Inda and Nash deposits, as well as several other significant occurrences of uranium mineralization (Gandhi, 1978; Gower *et al.*, 1982; Evans, 1980; Cunningham-Dunlop and Lee, 2008). Much of this mineralization is developed at or very near the inferred top of the Post Hill Group.

The Post Hill Group has undergone considerable deformation and upper greenschist- to lower amphibolite-facies metamorphism (Gandhi, 1978; Gower *et al.*, 1982). Marten (1977) subdivided the deformation within the region into five events and early deformation was restricted to the basement–cover interfaces with the motion inferred to be largely subhorizontal. As part of his work, Marten (1977) identified four D_1–D_2 high strain zones termed 'tectonic slides', which he recognized as possible shear zones associated with this subhorizontal motion (D_1) later reactivated during D_2; these were the Post Hill, Fiace Lake, Nakit and Witch Lake 'slides'. This region of transpressive ductile shearing was later termed the Kaipokok Bay Shear Zone (KBSZ) by Culshaw *et al.* (2000; Figure 1). Culshaw *et al.* (*op. cit.*) subdivided the KBSZ into four components, namely the Postville, Drunken Harbour, Julies Harbour and Witch Lake shear zones, of which the Julies Harbour component is the most proximal to the Kitts deposit. The Julies Harbour Shear Zone is assigned to D_4 by Culshaw *et al.* (2000), but may have been active during earlier (D_2) deformation.

Early amphibolite-facies metamorphism has been dated at *ca.* 1896 within the Kaipokok domain northeast of the KBSZ, and it has been postulated that the Post Hill Group may have experienced some of this early deformation (Ketchum *et al.*, 1997, 2002). On the basis of a crosscutting quartz monzonite in the area of Post Hill (Figure 1; Culshaw *et al.*, 2000; Ketchum *et al.*, 1997, 2002), thrusting associated with D_1 along the KBSZ occurred prior to 1877 ± 5 Ma. The KBSZ was subsequently reactivated (D_4 of Culshaw *et al.*, 2000) between 1840–1784 Ma (Ketchum et al., 1997, 2002), during which time regional dextral shearing was contemporaneous with amphibolite metamorphism (Culshaw *et al.*, 2002). The deformational history of the region is punctuated by the intrusion of multiple felsic to mafic intrusions that include both foliated and non-foliated varieties. These magmatic pulses have been broadly subdivided into three separate events by Culshaw *et al.* (2000); they are: 1) 1895–1870 Ma, 2) 1802–1784 Ma and 3) 1720 Ma and younger plutons.

GEOLOGY OF THE KITTS DEPOSIT

LOCAL GEOLOGY

The Kitts uranium deposit occurs within a north-northwest-trending shear zone, which is developed proximal to, and parallels, the northern portion of the Nakit shear zone, where it becomes deflected to the northwest and is truncated along the Julies Harbour shear zone (Figure 1). Within this region, a large body of deformed and metamorphosed gabbro, known as the Kitts Metagabbro, intrudes the Kitts Pillow Lava Formation and associated interbedded iron formation (Figure 2). Uranium mineralization is predominantly hosted within a deformed northeasterly dipping sequence of iron formation, which comprises sulphidic argillite, albitic greywacke and mafic tuff; these units form the 'Mine Volcaniclastic Sequence' (MVS) of Evans (1980). Within the deposit, Evans (1980) subdivided the sequence into four main units: 1) a mafic tuff to argillite transition zone (~5 m), 2) argillite zone (5–20 m), 3) albitic greywacke (5–30 m) and 4) mafic tuff (Figure 3). A detailed description of the

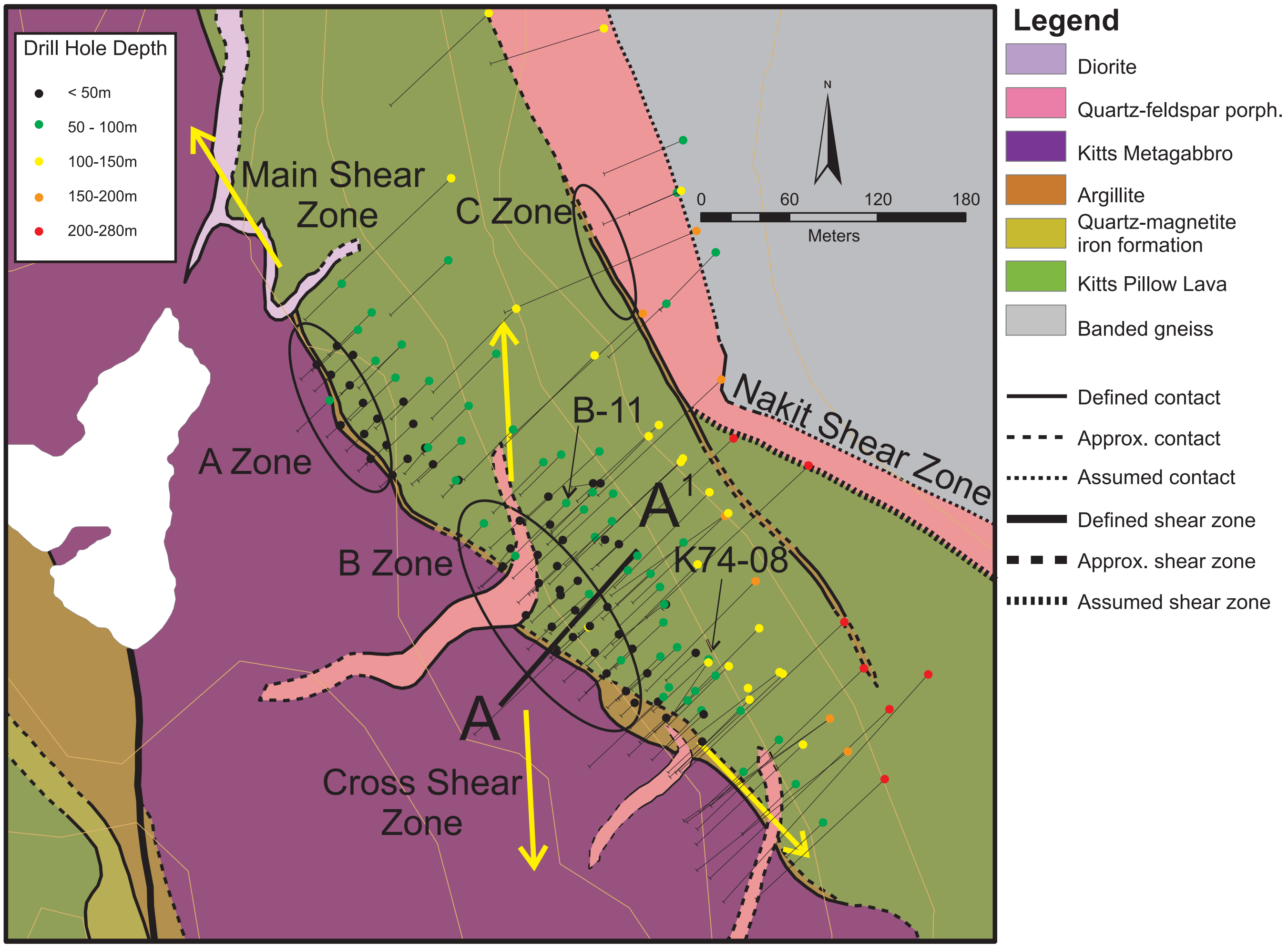

Figure 2. *Detailed geological map of the area surrounding the Kitts deposit showing the location of A, B and C zones and the distribution of surface drilling. Modified after Marten (1977). Note the location of cross-section shown in Figure 5.*

host rocks can be found in Evans (1980) and Gandhi (1978), and is only briefly summarized herein.

The uranium mineralization within the deposit is mostly located at the northern margin of the Kitts Metagabbro intrusion, where it intrudes the adjacent MVS. The gabbro intrusion is interpreted to predate deformation and mineralization, and is assumed to represent a co-magmatic intrusion related to the formation of the metavolcanic rocks within the sequence (Marten, 1977; Evans, 1980). At surface, the mineralization is moderately to well exposed along the northeastern slope of a northerly trending ridge, and is associated with a well-developed radiometric anomaly. Minor occurrences of anomalous radioactive gossans are noted within metasedimentary rocks along the southwestern margin of the metagabbro; however, none of these have proven to be of economic interest (Beavan, 1958; Piloski, 1968). The stratigraphy of the Kitts deposit has been inferred to be structurally overturned (Evans, 1980), however, Gandhi (1978) interprets the stratigraphy to be right way up and part of a larger scale synclinal structure.

The Kitts deposit, which is situated within the regional KBSZ, occurs in a structurally complex region. Evans (1980) subdivided the structural elements of the Kitts deposit into two main shear zones. Mineralization along the northern margin of the metagabbro is interpreted to be hosted within the Main Shear Zone, which is developed roughly subparallel to the margin of the metagabbro intrusion (Evans, 1980). This structure ranges from 3–50 m in width and is developed roughly subparallel to the regional Nakit shear zone and is inferred to be related to D_1–D_2 (Marten 1977; Evans, 1980). The Main Shear Zone is best developed in the MVS as seen by the contrast in the intensity of the foliation within this sequence, in comparison to the adjacent metagabbro and mafic volcanic units (Marten, 1977). A pronounced penetrative linear fabric within the MVS plunges 46° toward 135°, which is also roughly mimicked by the ore

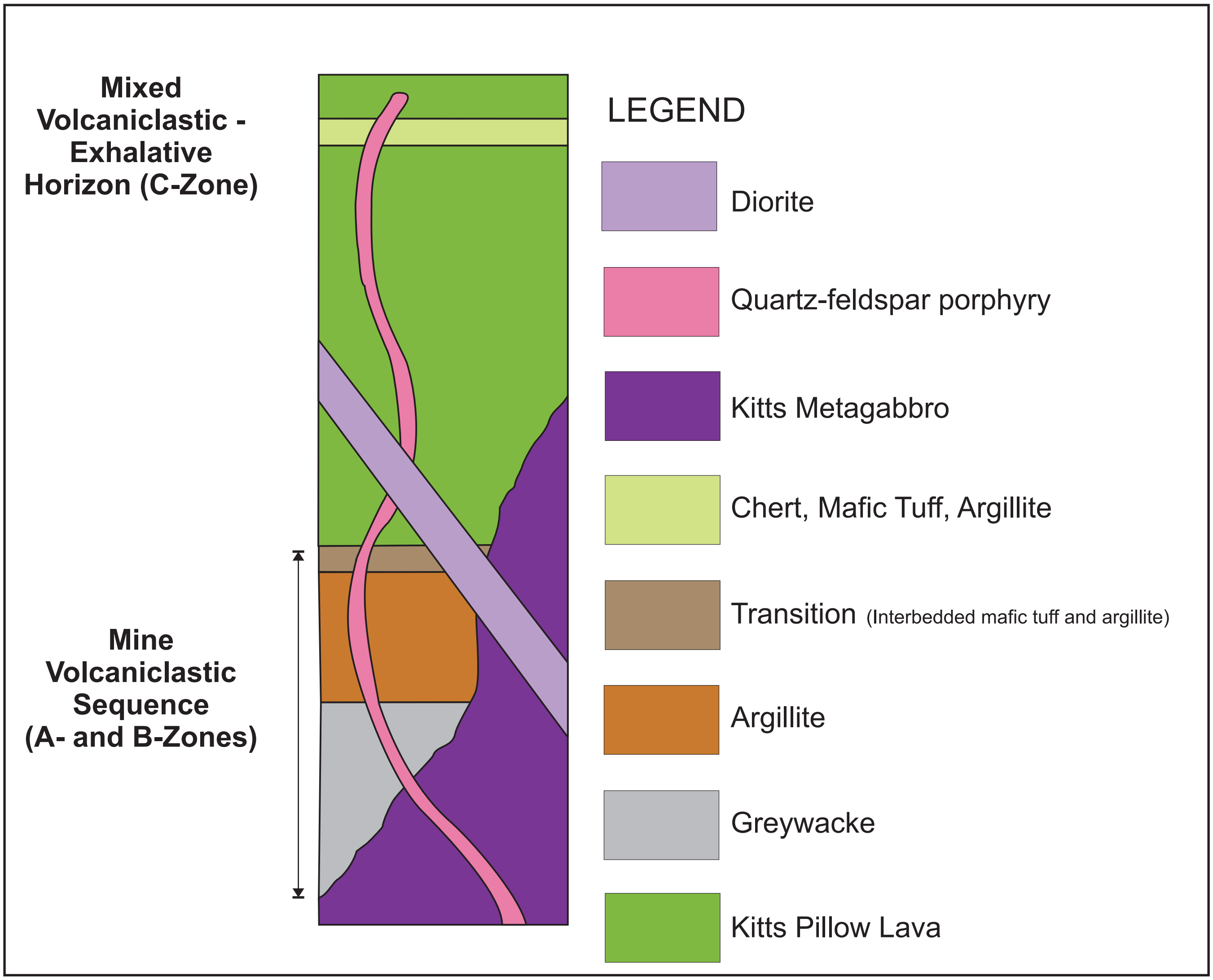

Figure 3. *Schematic stratigraphic section of the representative rock types within the Kitts deposit; modified after Evans (1980).*

shoots within the deposit (Evans, 1980). The Main Shear Zone is affected by the younger Cross Shear Zone, which ranges from 60–80 m in width, and results in a dextral offset of the MVS between the A and B zones within the deposit (Figure 2; Evans, 1980). The Cross Shear Zone trends approximately north–south and is developed roughly parallel to the regionally extensive Julies Harbour Shear Zone of Culshaw *et al.* (2000), along which the Nakit Shear Zone is truncated. Evans (1980) interpreted the development of the Cross Shear Zone to be related to D_3 of Marten (1977; Regional D_4 of Culshaw *et al.*, 2000).

The region of the Cross Shear Zone is also highlighted by the intrusion of quartz-feldspar porphyry dykes, which are generally developed subparallel to the structure. These dykes range from 2–8 m in width where they crosscut the MVS, but locally reach up to 20 m in width within the Cross Shear Zone. The unit consists of mm-scale white feldspar phenocrysts and lesser grey subrounded quartz phenocrysts within a pale-grey fine-grained biotite–chlorite-bearing groundmass (Plate 1). A single well-developed foliation is observed in both outcrop and drillcore and is developed roughly subparallel to the Cross Shear Zone. The quartz-feldspar porphyry dykes are generally observed to crosscut the mineralization hosted within the MVS (Plate 2); however, locally remobilized uranium mineralization is observed along discrete fractures and sheared margins of the dykes. Mineralization within the porphyry dykes is attributed to the local remobilization of the uranium during subsequent deformation along the Main Shear Zone that locally results in a sinistral offset of the dykes. This later sinistral motion is possibly related to the narrow sinistral greenschist-facies zones assigned to D_6 by Culshaw *et al.* (2000).

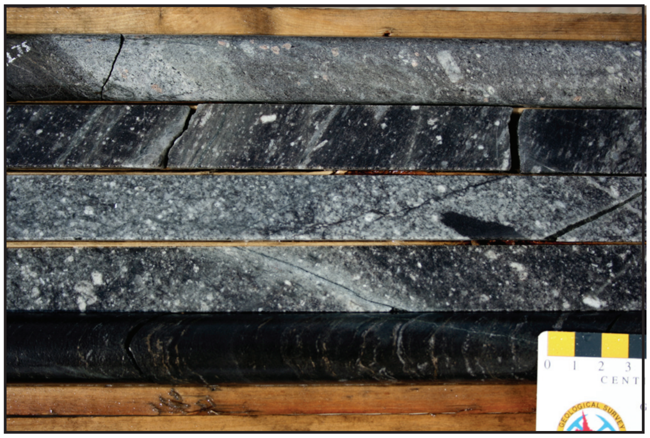

Plate 1. *Dated quartz-feldspar porphyry dyke displaying a weakly to moderately developed foliation and a locally developed chilled margin at its upper contact with the metasedimentary unit (upper left hand corner).*

Plate 2. *Mineralized metasedimentary rocks (left) containing up to 0.09%* U_3O_8 *as well as 0.3% Mo and 1.31 ppm Re are crosscut by a quartz-feldspar porphyry dyke (right) containing an anomalous value of 0.04%* U_3O_8*.*

The entire deposit is crosscut by a relatively flat-lying to gently southwesterly dipping unfoliated diorite dyke, which consists of dark-green euhedral amphibole phenocrysts within a white plagioclase-rich groundmass (Plate 3). Petrographic examination of the unit displays well-developed igneous growth zoning preserved within the euhedral amphibole, which demonstrates the posttectonic origin of the intrusion. This intrusion is interpreted to be relatively late with respect to the development of the uranium mineralization and deformation along the structures within the deposit, as it is unaffected by the Main or Cross Shear zones. Thus, this intrusion is assumed to postdate the D_6 sinistral shearing and is inferred to be the youngest event within the deposit.

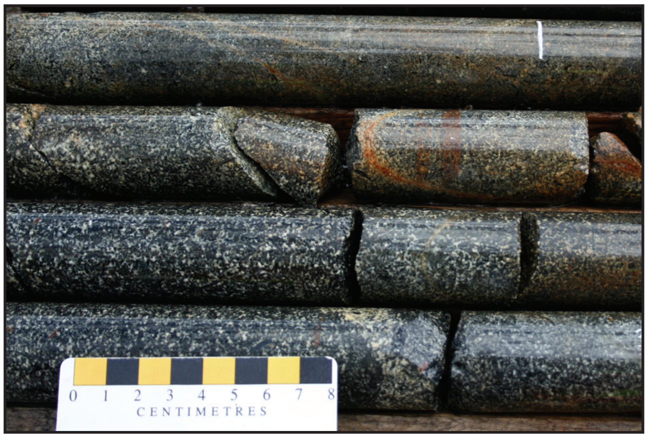

Plate 3. *Undeformed, fine- to medium-grained amphibole-rich diorite dyke.*

The somewhat removed C Zone occurs in mainly mafic tuff and chert along with minor argillite and greywacke, approximately 180 m to the north-northeast of the main deposit (Figure 2). This zone is interpreted by Evans (1980) as a second volcaniclastic unit within the stratigraphic sequence (Figure 3); however, Gandhi (1978) assumes the mineralization to occur within the same sequence but located on the opposite side of a major synclinal structure. Drilling within the C Zone has shown the mineralization to be of narrow widths and of limited extent (Piloski, 1968).

MINERALIZATION

The uranium mineralization within the Kitts deposit is unequally distributed between the three zones. The bulk of the mineralization is contained within the B Zone, which is interpreted to be the result of a higher degree of folding and the effect of the Cross Shear Zone (Beavan, 1958; Gandhi, 1978). The exact nature of this folding is unknown, but the regionally extensive fold structures mapped by Martin (1977) were interpreted to be related to D_3 (D_4 of Culshaw *et al.*, 2000). Within the A and B zones, the mineralization has been subdivided into six separate ore shoots, each of which displays significant variation in both dimension and grade with respect to depth; these shoots plunge toward the southeast along the Main Shear Zone (Figure 4; Evans, 1980). The ore zone comprises a group of narrow shear zones ranging in width from 1 to 2 m and forming an en-echelon-like pattern, within a zone 380 m long and up to 36 m wide; however the zone is more commonly 5 m or less in width and is known to extend at least to a depth of 150 m (Evans, 1980). Local evidence for sinistral motion exists within the Main Shear Zone, however, because this offset affects the quartz-feldspar porphyry dykes, the motion must be due to later reactivation of the structure.

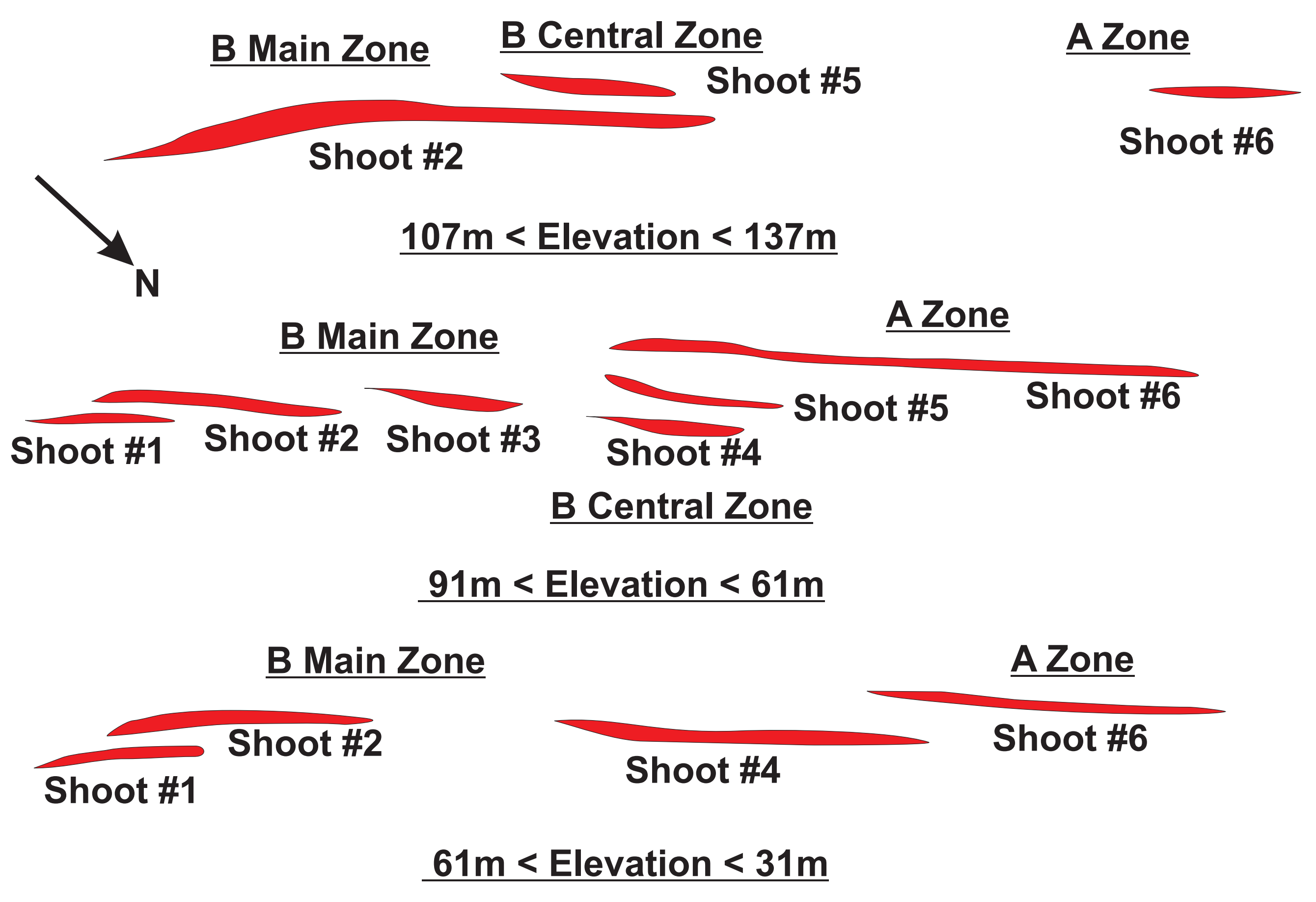

Figure 4. *Stacked slices through the Kitts deposit showing the distribution of uranium mineralization at various elevations relative to sea level; modified from Evans (1980).*

In the B Main Zone (Figure 4), there are four such shoots which vary in thickness from 2.0 to 2.6 m; here the mineralization is predominantly hosted within the graphite and pyrrhotite-bearing argillite with both mafic tuff and quartz-feldspar porphyry locally hosting significant mineralization (Figure 4; Evans, 1980). In the B Central Zone (Figure 4), a number of individual mineralized structures trend between 320 to 285°; the transposition of these structures from a northwest to a more westerly trend is inferred to be the result of the overprinting Cross Shear Zone (Evans, 1980). In this zone, the mineralization is again predominantly hosted within the argillite, mafic tuff, greywacke and quartz-feldspar porphyry. Within the A Zone, the mineralized zone is narrower, with an average width of 1.5 m. Here mineralization occurs within mafic tuff, argillite and mafic dykes; mineralization in this region also has a closer association with the development of carbonate veins than in other zones (Evans, 1980). The greatest thickening of the MVS within the B Zone, and the best drillhole intersections, occur where folding coincides with embayments within the metagabbro contact along the southern portion of the zone (Beavan, 1958).

Within the mineralized ore shoots, uranium mineralization is most commonly present as high-grade veins along narrow shear zones (Plate 4), however, lower grade, finely disseminated material is also locally developed (Plate 5). Gandhi (1970) highlighted the fact that mineralization preferentially occurred along certain stratigraphic horizons within the MVS, particularly those enriched in pyrrhotite, and inferred the mineralization to be primarily stratigraphically controlled. Most of the high-grade vein mineralization is hosted within both argillite and mafic tuff and also includes rare occurrences within mafic dykes (Evans, 1980). The host rock commonly consists of hornblende, sericitized plagioclase, chlorite, muscovite and minor garnet (Evans, 1980). The development of white to pink calcite veining locally shares a close spatial association with mineralization, which is most notable within the A Zone portion of the deposit. Evans (1980) noted that the uranium generally

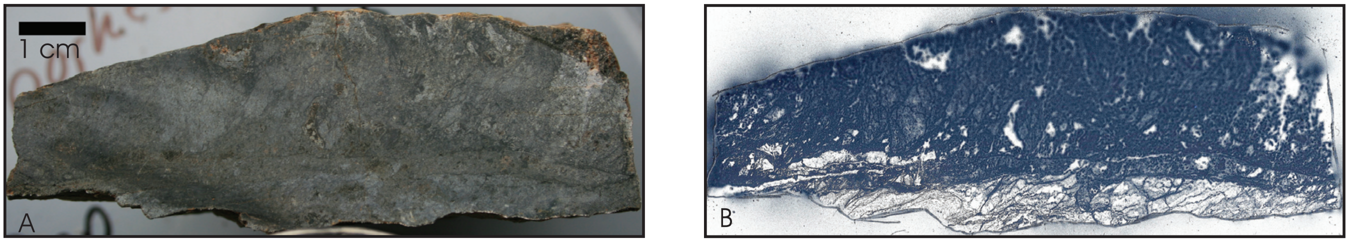

Plate 4. *A) Hand sample of vein-hosted uranium mineralization that produced up to 60 000 counts per second in outcrop and assayed >1% U; B) Corresponding autoradiograph of the uranium mineralization (dark areas) within the hand sample. The autoradiograph procedure is summarized in Appendix A.*

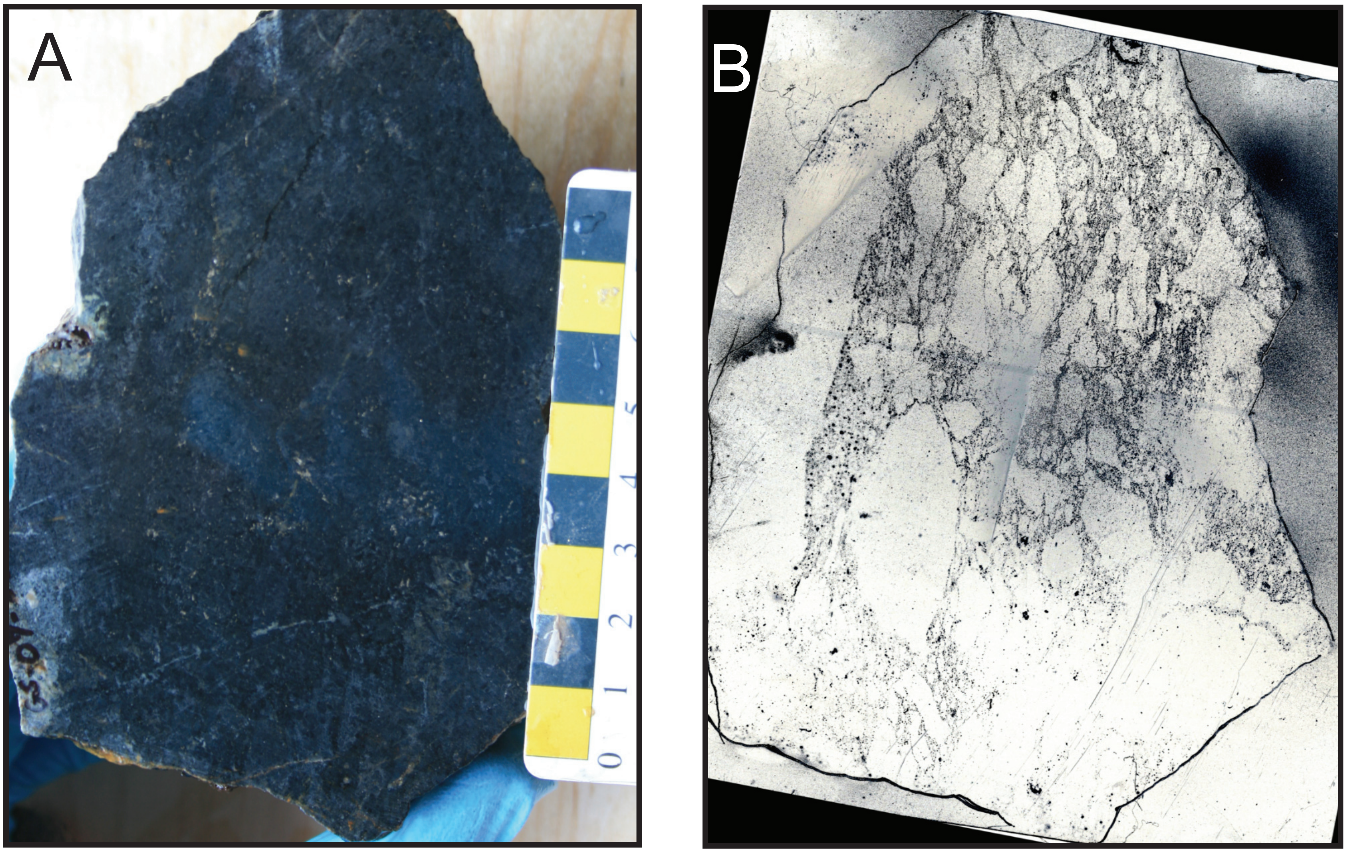

Plate 5. *A) Hand sample of disseminated uranium mineralization that assayed 0.11%* U_3O_8*; B) Corresponding autoradiograph of the uranium mineralization (dark areas) within the hand sample. The autoradiograph procedure is summarized in Appendix A.*

occurred as 1–3 mm microcrystalline clots or veinlets that were either rimmed by Fe-rich chlorite and/or were incorporated within amphibole crystals or inter-grown with calcite, graphite and pyrrhotite. The incorporation of uraninite within amphibole crystals was interpreted by Marten (1977) as supporting evidence for the development of the uranium mineralization during D_1–D_2 deformation. Alteration surrounding the mineralization is very subtle and it is often hard to distinguish mineralized core from unmineralized core. Evans (1980) noted chemical evidence for a very narrow halo (generally <1 m) of sodic alteration developed within the greywacke and argillite units adjacent to mineralization, however, there is no visible evidence of the alteration.

Although the quartz-feldspar porphyry dykes that crosscut the deposit are interpreted to postdate the formation of the primary uranium mineralization, they locally host discrete zones of mineralization. This mineralization is hosted within fractures and localized shear zones, which crosscut the dykes (see above), and are interpreted to represent remobilization of the primary uranium mineralization. Locally,

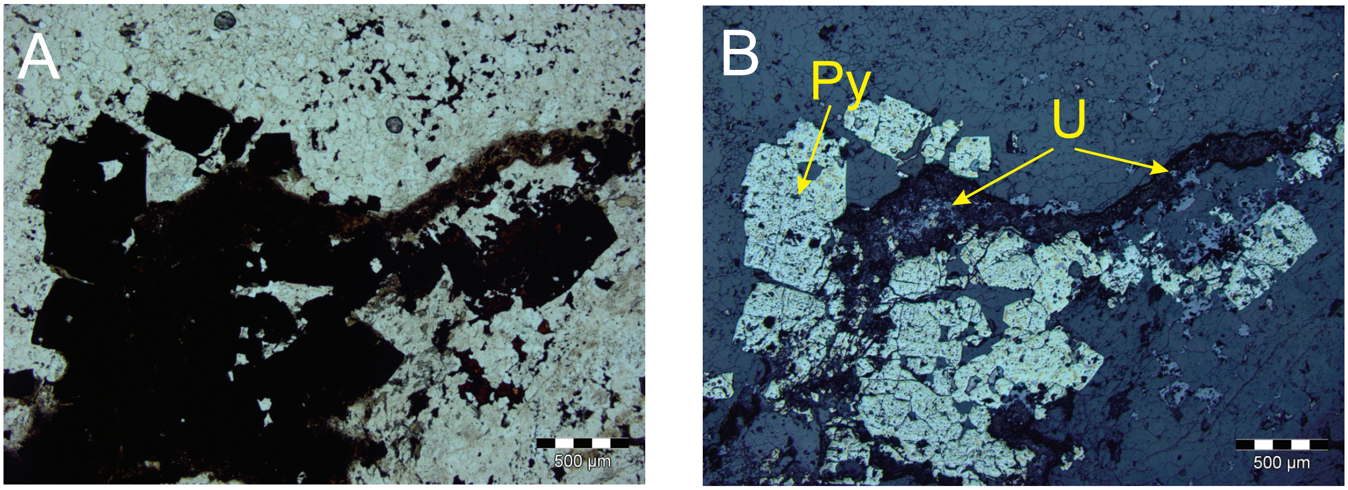

Plate 6. *Photomicrograph of a mineralized fracture developed within the quartz-feldspar porphyry, containing early uraninite and late pyrite; A) Plane-polarized light; B) Reflected light image of A showing the distribution of uraninite (U) and pyrite (Py) within the fracture.*

assays of up to 0.24% U_3O_8 occur within these quartz-feldspar porphyry dykes (Evans, 1980). Within these mineralized fractures, uranium mineralization is often accompanied by hematization of the surrounding host rock, and the mineralized fractures are generally in-filled with calcite and or quartz (Plate 6). These dykes have locally undergone alteration where they occur within the MVS; this alteration results in the enrichment of Ca and Na. Altered porphyries contain an average of 16.8 ppm U, whereas the unaltered equivalents contain an average of 10.2 ppm U (Evans, 1980).

GEOCHRONOLOGICAL CONSTRAINTS

Numerous geochronological studies have been carried out within the Kaipokok Bay region utilizing both U–Pb and Ar–Ar dating methods to constrain the timing of deposition and deformation within the region; results from these studies are summarized in Figure 1. The direct dating of uranium mineralization is often problematic given the high mobility of the uranium in fluids, especially in regions where the mineralization is subsequently overprinted by deformation, such as the Kitts deposit. Previous attempts to constrain the age of mineralization at the Kitts deposit through U–Pb dating of uraninite produced ages ranging from 1777 to 1730 Ma (Gandhi, 1976b, 1978; Wilton and Longerich, 1993). The work reported herein focuses on the crosscutting intrusive units within the deposit in order to constrain the age of the mineralization. For this reason, both a sheared quartz-feldspar porphyry dyke (Plate 2), which is locally reported to crosscut uranium mineralization, and an undeformed diorite dyke (Plate 3) were chosen for geochronological study.

A sample of the quartz-feldspar porphyry was collected from drillhole K74-08, between 93.10 and 98.48 m, and was submitted to the Geological Survey of Canada for Sensitive High Resolution Ion MicroProbe (SHRIMP) dating (Figure 5). Analytical techniques used for this procedure are as described in Stern (1997) and Stern and Amelin (2003). Results are reported in Table 1 and presented in concordia diagrams in Figure 6, with errors at the 2σ level. The sample produced an abundant population of high-quality zircon, from which a selection of grains were mounted and analyzed. The majority of the analyses are interpreted to be magmatic in origin. A weighted average of the ^{207}Pb/^{206}Pb ages of these analyses gave an age of 1881.8 ± 3.4 Ma (MSWD = 0.88; prob. of fit = 0.66; n = 34) and is assumed to represent the crystallization age of the unit. Analysis of several grains also revealed the presence of inherited zircon that had significantly older ages, ranging from *ca.* 2835 to 2703 Ma (Table 1); these zircons are inferred to have been assimilated from the adjacent argillite unit, which is known to contain detrital zircon from the Archean basement rocks (Ketchum *et al.*, 2001). The age provided by the quartz-feldspar porphyry is interpreted as a minimum age limit on the formation of the primary uranium mineralization and also provides constraints for the development of early D_1–D_2 deformation within the Kitts deposit.

The diorite dyke, which crosscuts the deposit, is interpreted to postdate the $D_{4\text{-}6}$ of Culshaw *et al.* (2000). This unit was sampled for geochronological study to provide a minimum age limit on the timing of the deformational events that postdated the intrusion of the quartz-feldspar porphyry. A sample of coarse-grained amphibole-rich diorite was collected from drillhole B-11, between 25.21 and 30.48 m and

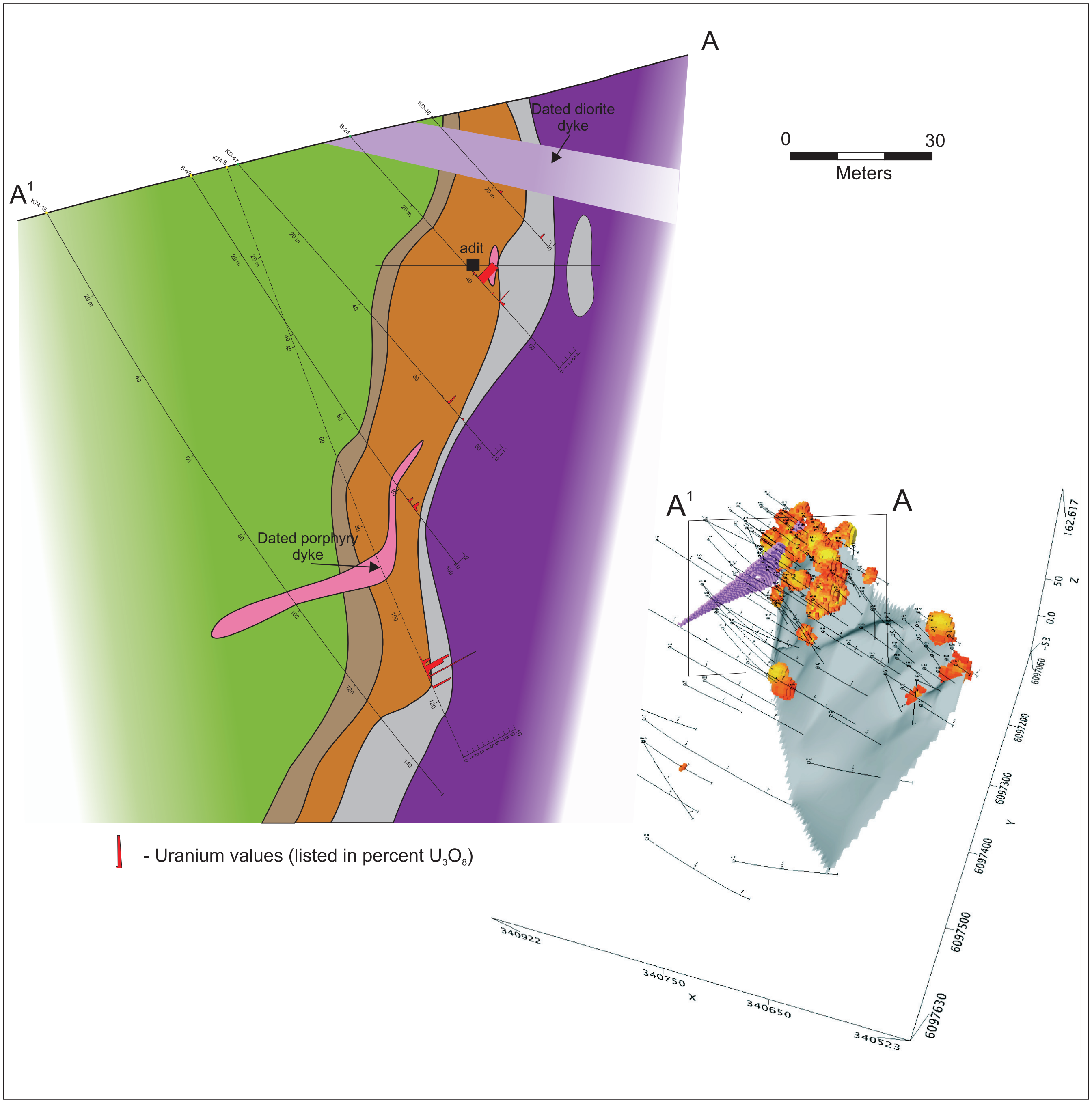

Figure 5. *Schematic cross-section through the Kitts deposit showing the distribution of the main rock types in association with uranium mineralization; modified from Evans (1980). Inset shows a 3D image of the surface of the metagabbro unit (grey) in association with uranium mineralization (orange-yellow) intersected in drillcore, and the relationship and attitude of the crosscutting quartz-feldspar porphyry (pink) with respect to the mineralization. Refer to Figure 3 for legend. Note K74-08 is located 30 m NW of the section and is projected onto the current plane.*

submitted to Memorial University for Thermal Ionization Mass Spectrometry (TIMS) analysis. Analytical techniques and sample preparation used in the TIMS analyses are described in Sanchez-Garcia *et al.* (2008). The sample yielded an abundant population of titanite, which, from petrographic examination, are observed to occur within late quartz-rich segregations within a predominantly quartz–amphibole-rich groundmass (Plate 7). Results are reported in Table 2 and presented in Figure 7. Four, single-grain analyses were carried out on strongly abraded titanite. The

Table 1: U/Pb SHRIMP analytical data for sample number GS-07-298; Quartz feldspar porphyry, Kitts deposit, Labrador (z9537)

																	Ages (Ma) ± 1				
Spot name	U (ppm)	Th (ppm)	Th/U	Pb (ppm)	^{204}Pb (ppb)	^{204}Pb/ ^{206}Pb	f206	^{208}Pb/ ^{206}Pb	±^{208}Pb/ ^{206}Pb	^{207}Pb/ ^{235}U	±^{207}Pb/ ^{235}U	^{206}Pb/ ^{238}U	±^{206}Pb/ ^{238}U	Corr Coeff	^{207}Pb/ ^{206}Pb	±^{207}Pb/ ^{206}Pb	^{206}Pb/ ^{238}U	±^{206}Pb/ ^{238}U	^{207}Pb/ ^{206}Pb	±^{207}Pb/ ^{206}Pb	% DISC
9537-2.1	105	74	0.730	38	0	0.00001	0.00017	0.1708	0.0089	5.27229	0.09537	0.33235	0.00461	0.835	0.11505	0.00115	1849.8	22.3	1880.7	18.2	1.6
9537-3.1	300	383	1.318	112	8	0.00010	0.00165	0.2754	0.0060	4.89752	0.06911	0.31052	0.00336	0.837	0.11439	0.00089	1743.3	16.6	1870.3	14.1	6.8
9537-4.1	896	428	0.494	312	4	0.00001	0.00026	0.1270	0.0026	5.19885	0.06414	0.32600	0.00359	0.937	0.11566	0.00050	1819.0	17.5	1890.2	7.8	3.8
9537-5.1	149	193	1.340	62	1	0.00003	0.00050	0.3377	0.0075	5.30449	0.07842	0.33339	0.00385	0.848	0.11539	0.00091	1854.8	18.7	1886.1	14.3	1.7
9537-6.1	181	116	0.661	65	6	0.00011	0.00192	0.1468	0.0089	5.23532	0.08534	0.32888	0.00387	0.799	0.11545	0.00114	1833.0	18.8	1887.0	17.9	2.9
9537-8.1	280	335	1.235	92	13	0.00017	0.00296	0.1372	0.0057	4.87720	0.06462	0.30610	0.00333	0.881	0.11556	0.00073	1721.5	16.5	1888.6	11.4	8.9
9537-16.1	137	162	1.226	42	5	0.00015	0.00252	0.2032	0.0068	4.35256	0.07905	0.27031	0.00334	0.761	0.11678	0.00139	1542.4	17.0	1907.6	21.5	19.1
9537-14.1	86	71	0.854	33	5	0.00019	0.00322	0.2108	0.0074	5.33075	0.11730	0.33508	0.00427	0.673	0.11538	0.00189	1863.0	20.7	1885.9	29.8	1.2
9537-13.1	504	622	1.275	216	9	0.00006	0.00105	0.3211	0.0095	5.52282	0.07398	0.34699	0.00394	0.903	0.11544	0.00067	1920.2	18.9	1886.7	10.5	-1.8
9537-12.1	126	82	0.672	47	2	0.00005	0.00086	0.1712	0.0048	5.32291	0.08730	0.33527	0.00405	0.810	0.11515	0.00112	1863.9	19.6	1882.2	17.6	1.0
9537-11.1	108	86	0.817	41	2	0.00006	0.00100	0.2029	0.0101	5.29381	0.09027	0.33429	0.00369	0.733	0.11485	0.00134	1859.1	17.9	1877.6	21.2	1.0
9537-18.1	124	64	0.530	44	1	0.00003	0.00044	0.1223	0.0257	5.30999	0.07623	0.33587	0.00366	0.829	0.11466	0.00093	1866.8	17.7	1874.6	14.7	0.4
9537-19.1	88	63	0.732	33	1	0.00002	0.00042	0.1907	0.0064	5.30610	0.10392	0.33195	0.00375	0.671	0.11593	0.00170	1847.8	18.2	1894.4	26.6	2.5
9537-22.1	76	57	0.768	28	3	0.00014	0.00246	0.1930	0.0063	5.18550	0.09395	0.33135	0.00415	0.772	0.11350	0.00132	1844.9	20.1	1856.2	21.1	0.6
9537-28.1	143	84	0.608	50	7	0.00017	0.00296	0.1314	0.0046	5.13345	0.07852	0.32906	0.00357	0.786	0.11314	0.00108	1833.9	17.3	1850.5	17.3	0.9
9537-27.1	137	104	0.788	51	0	0.00001	0.00017	0.1854	0.0043	5.31623	0.07979	0.33092	0.00422	0.904	0.11651	0.00076	1842.8	20.5	1903.4	11.7	3.2
9537-25.1	75	57	0.787	45	1	0.00004	0.00070	0.1867	0.0070	13.08511	0.20186	0.51146	0.00679	0.912	0.18555	0.00118	2662.9	29.0	2703.1	10.6	1.5
9537-32.1	118	70	0.613	42	2	0.00006	0.00112	0.1464	0.0072	5.12602	0.07492	0.32597	0.00365	0.836	0.11405	0.00092	1818.8	17.8	1865.0	14.7	2.5
9537-34.1	382	239	0.648	139	6	0.00006	0.00101	0.1567	0.0030	5.32932	0.06744	0.33320	0.00348	0.884	0.11600	0.00069	1853.9	16.9	1895.5	10.8	2.2
9537-35.1	98	94	0.988	38	1	0.00005	0.00084	0.2507	0.0127	5.32419	0.09050	0.33316	0.00443	0.850	0.11590	0.00105	1853.7	21.5	1894.0	16.4	2.1
9537-37.1	609	842	1.428	267	9	0.00005	0.00092	0.3824	0.0037	5.39689	0.06005	0.33922	0.00354	0.969	0.11539	0.00032	1882.9	17.1	1886.0	5.0	0.2
9537-44.1	132	97	0.757	49	0	0.00000	0.00000	0.1891	0.0078	5.29632	0.06976	0.33187	0.00355	0.874	0.11574	0.00075	1847.5	17.2	1891.5	11.7	2.3
9537-43.1	384	383	1.032	154	3	0.00002	0.00043	0.2528	0.0058	5.38799	0.07324	0.34052	0.00394	0.906	0.11476	0.00067	1889.2	19.0	1876.1	10.5	-0.7
9537-41.1	197	134	0.701	73	1	0.00002	0.00037	0.1728	0.0065	5.32336	0.07537	0.33574	0.00380	0.863	0.11500	0.00083	1866.1	18.4	1879.8	13.0	0.7
9537-39.1	197	129	0.676	72	1	0.00002	0.00037	0.1668	0.0038	5.27770	0.06391	0.33419	0.00360	0.935	0.11454	0.00050	1858.7	17.4	1872.6	7.8	0.7
9537-46.1	421	403	0.988	167	4	0.00003	0.00050	0.2492	0.0062	5.36370	0.06165	0.33718	0.00360	0.964	0.11537	0.00036	1873.1	17.4	1885.7	5.6	0.7
9537-48.1	122	90	0.764	45	0	0.00001	0.00017	0.1736	0.0064	5.25084	0.07944	0.32990	0.00379	0.830	0.11544	0.00098	1837.9	18.4	1886.7	15.4	2.6
9537-49.1	535	356	0.688	199	2	0.00001	0.00025	0.1641	0.0051	5.35567	0.07595	0.33751	0.00374	0.848	0.11509	0.00087	1874.7	18.0	1881.2	13.7	0.3
9537-55.1	303	304	1.034	121	1	0.00001	0.00017	0.2631	0.0037	5.31920	0.06112	0.33697	0.00353	0.950	0.11449	0.00041	1872.1	17.0	1871.8	6.6	0.0
9537-54.1	215	136	0.651	81	2	0.00003	0.00051	0.1653	0.0090	5.36005	0.07025	0.34008	0.00382	0.910	0.11431	0.00063	1887.0	18.4	1869.1	9.9	-1.0
9537-60.1	463	388	0.867	181	1	0.00001	0.00017	0.2243	0.0027	5.36889	0.06742	0.33929	0.00371	0.921	0.11477	0.00057	1883.2	17.9	1876.2	8.9	-0.4
9537-84.1	628	101	0.167	209	3	0.00002	0.00030	0.0382	0.0010	5.30487	0.06026	0.33541	0.00354	0.962	0.11471	0.00036	1864.6	17.1	1875.3	5.6	0.6
9537-82.1	52	21	0.418	31	4	0.00016	0.00284	0.0900	0.0058	14.92858	0.21217	0.53822	0.00622	0.875	0.20117	0.00140	2776.0	26.1	2835.7	11.4	2.1
9537-83.1	165	162	1.016	65	3	0.00006	0.00097	0.2765	0.0060	5.26340	0.07546	0.33016	0.00372	0.852	0.11562	0.00087	1839.2	18.1	1889.6	13.7	2.7
9537-73.1	55	46	0.866	35	3	0.00011	0.00184	0.2153	0.0064	13.80253	0.22586	0.52502	0.00694	0.870	0.19067	0.00155	2720.4	29.4	2748.0	13.4	1.0
9537-74.1	105	55	0.541	38	1	0.00003	0.00045	0.1287	0.0059	5.30549	0.08333	0.33752	0.00433	0.877	0.11400	0.00087	1874.7	20.9	1864.2	13.8	-0.6
9537-71.1	513	367	0.740	183	6	0.00004	0.00071	0.1394	0.0049	5.26796	0.05937	0.32995	0.00340	0.954	0.11580	0.00040	1838.1	16.5	1892.3	6.2	2.9
9537-70.1	64	39	0.628	23	3	0.00018	0.00317	0.1488	0.0066	5.23495	0.09925	0.33122	0.00475	0.828	0.11463	0.00123	1844.3	23.1	1874.1	19.5	1.6

Notes: Uncertainties reported at one sigma and are calculated by numerical propagation of all known sources of error (Stern, 1997). f206 refers to mole fraction of total 206Pb that is due to common Pb based on 204Pb; data have been corrected for common Pb according to procedures outlined in Stern (1997). GSC mount IP470. Spot size for analysis = 16 x 23 µm. GSC laboratory zircon standard z6266 zircon, with 206Pb/238U age = 559 Ma. Common-Pb corrected ratios and ages are reported with 1σ analytical errors, which incorporate an external uncertainty of 1.0% in calibrating the standard zircon (see Stern and Amelin, 2003). Sample collected from drill hole number K74-08 (UTM coordinates; NAD 27, Zone 21; 340829/6097189) between 93.10 and 98.48m.

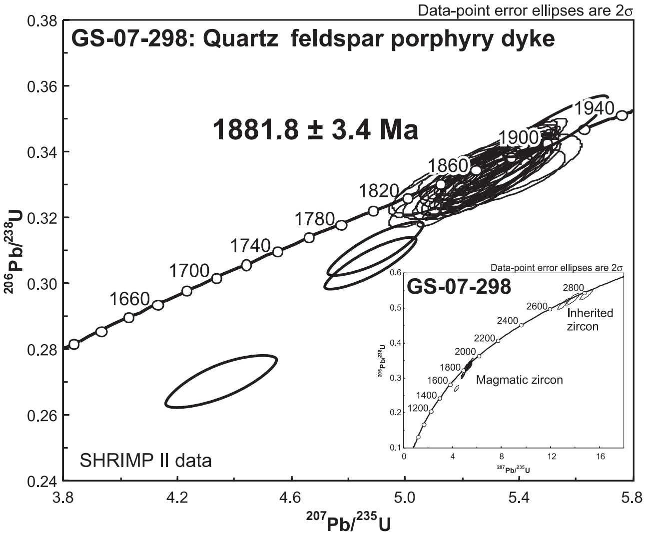

Figure 6. *Concordia diagram of zircon from sample GS-07-298, a quartz-feldspar porphyry dyke. Error ellipses are at the 2σ level.*

results of these analyses produced a weighted average $^{206}Pb/^{238}U$ age of 1662 ± 4 Ma (95% confidence interval, MSWD = 0.50; prob. of fit = 0.68). This age provides an upper limit on the deformation within the Kitts deposit and therefore provides a minimum age limit on the uranium mineralization that is remobilized subsequent to the intrusion of the quartz-feldspar porphyry dykes.

Preliminary investigations of uraninite dating using the SHRIMP have thus far duplicated the relatively young ages of earlier work (*e.g.*, Gandhi, 1978; Wilton and Longerich, 1993). Initial samples were collected from relatively high-grade vein material, which may represent the younger remobilized portion of the mineralization. Further work is required to isolate grains of uraninite incorporated into the early metamorphic silicate minerals, which may be shielded from the effects of the post-mineralization deformation.

DISCUSSION

The importance of structural control on the uranium mineralization within the Kitts deposit has long been recognized, but the source of the uranium has been a matter of much debate. Beavan (1958) considered the deposit to be hydrothermal in origin, but he did not speculate on the actual source of the uranium. Gandhi (1970) proposed a syngenetic sedimentary origin for the mineralization based on what he interpreted to be finely disseminated uraninite parallel to the lamination within the metasedimentary units and the apparent stratigraphic control on the mineralization. Marten (1977) suggested that the overlying felsic volcanic rocks of the Aillik Group were the primary source for mineralizing fluids, which migrated down through the stratigraphy into dilational zones at the base of the sequence during early deformational events. This model was also favoured by Evans (1980) who examined the background uranium content of rock types within the Post Hill and Aillik groups and concluded that the felsic volcanic rocks represented a more likely source for the uranium. Evans (1980) postulated that the uranium was leached from the regionally enriched felsic volcanic succession by neutral to weakly alkaline oxidizing groundwater and transported as uranyl carbonate and/or hydroxyl complexes. Gower *et al.* (1982) reviewed both the syngenetic and epigenetic models for the uranium mineralization within the eastern portion of the CMB and again concluded that the felsic volcanic rocks of the Aillik Group were the most likely source for uranium concentrated at Kitts and other similar deposits.

Models attributing the Aillik Group as the source of uranium were in part supported by U–Pb ages obtained from

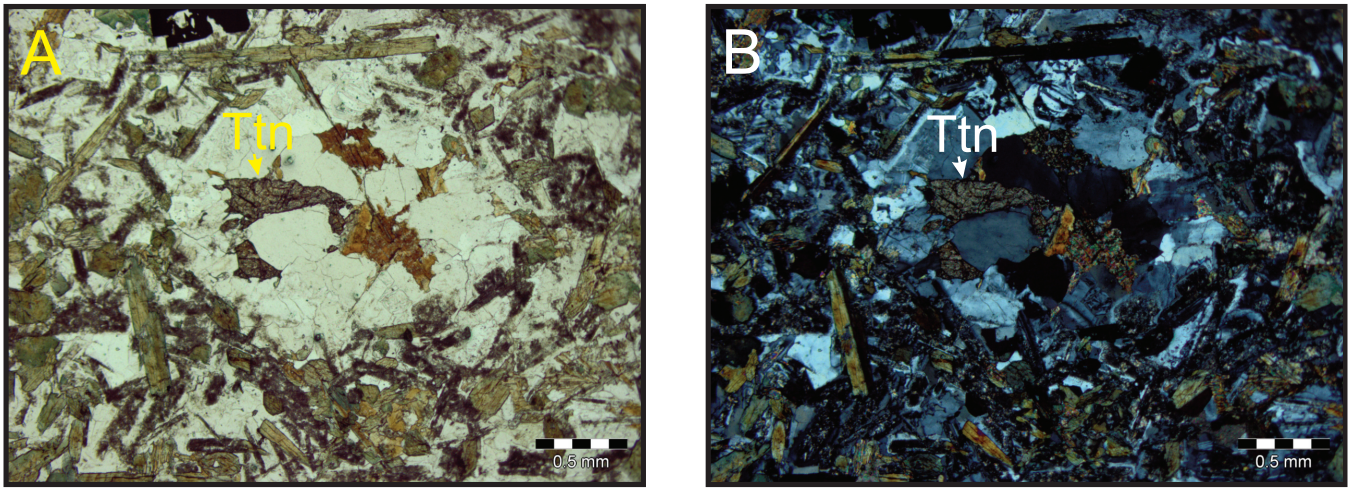

Plate 7. P*hotomicrograph of late quartz-rich segregations containing titanite (Ttn); A) Plane-polarized light; B) Cross-polarized light.*

Table 2: U-Pb data for the post-tectonic diorite dyke, sample number GS-07-170

		Concentration		Measured		Corrected Atomic Ratios (c)							Age [Ma]		
Fraction	Weight [mg] (a)	U [ppm]	Pb rad [ppm] (b)	total common Pb [pg]	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	+/-	$^{207}Pb/^{235}U$	+/-	$^{207}Pb/^{206}Pb$	+/-	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
T1 1 lrg dk xtal	0.003	281	90.2	22	720	0.1678	0.2937	12	4.105	19	0.10138	32	1660	1655	1649
T2 1 lrg dk xtal	0.003	266	95.5	20	770	0.3090	0.2950	34	4.158	55	0.10222	84	1666	1666	1665
T3 1 lrg dk xtal	0.003	316	117.3	29	614	0.3624	0.2947	14	4.093	33	0.10075	68	1665	1653	1638
T4 1 lrg dk brn	0.003	108	42.4	5	1239	0.4456	0.2938	20	4.107	25	0.10138	50	1660	1656	1650

Notes:

All grains were abraded (Krogh 1982) prior to dissolution. T, titanite; 1= number of grains in the analysis; brn, brown; xtal, crystal; lrg, large. Sample was collected from drill hole B-11 between 25.21 and 30.48m (UTM coordinates; NAD 27, Zone 21; 340732/ 6097296)

a. weights of grains were estimated, with potential uncertainties of 25-50% for small samples.

b. radiogenic lead

c. Atomic ratios corrected for fractionation, spike, laboratory blank of 2 picograms (pg) common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 0.3 pg U blank. Two sigma uncertainties are reported after the ratios and refer to the final digits.

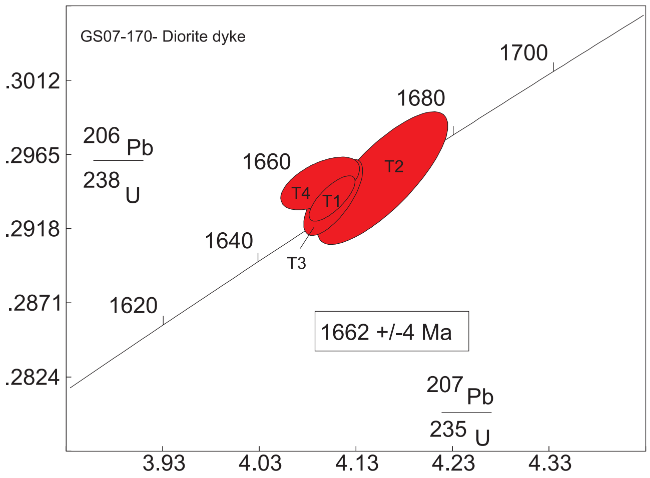

Figure 7. *Concordia diagram of titanite from sample GS-07-170, a diorite dyke. Error ellipses are at the 2σ level.*

uraninites at the Kitts deposit, most of which were younger than the assumed age of the Aillik Group. The new U–Pb data presented herein demonstrate that the age of the quartz-feldspar porphyry dyke is significantly older than the previously defined *ca.* 1777 to 1730 Ma age bracket defined by the uraninite ages. The mineralization has been interpreted to have utilized the D_1–D_2 structures (*e.g.*, Marten, 1977; Evans, 1980); these early structures have been demonstrated to predate *ca.* 1877 Ma elsewhere within the Kitts-Post Hill Belt (Ketchum *et al.*, 1997). An age for initial amphibolite-facies metamorphism related to D_1 in the region northeast of the KBSZ is provided by the *ca.* 1896 Ma metamorphic zircons dated from Kikkertavak dykes hosted within the Archean basement rocks (Ketchum *et al.*, 1997). Regional amphibolite-facies metamorphism affecting the Post Hill and Aillik group rocks occurred during D_3 (D_4 of Culshaw *et al.*, 2000), between *ca.* 1840–1790 Ma (Ketchum *et al.*, 2002: Culshaw *et al.*, 2000; Culshaw *et al.*, 2002); however older deformational events are known to have affected the Post Hill Group, the exact age and degree of which are not fully understood. The younger age limit for the remobilization of the uranium mineralization within the Kitts deposit is provided by the *ca.* 1662 Ma diorite dyke.

The 1881.8 ± 3.4 Ma age for the quartz-feldspar porphyry dyke suggests that primary uranium mineralization is at least this old. Although the age of *ca.* 1882 overlaps the oldest known ages of the Aillik Group within analytical error (Hinchey and Rayner, 2008), the new age limit for the mineralization makes the Aillik Group a less plausible source. An older source, such as the Archean basement rocks or the Post Hill Group itself, may be more likely. The regional distribution of the Post Hill Group in association with known occurrences of uranium mineralization (*e.g.*, Gear, Inda, Nash, and Anna Lake) provides supporting evidence for the Post Hill Group being a more likely source for the uranium. As noted by Evans (1980), background uranium contents for the argillite unit range from 2.9 to 11.0 ppm U, which is typical for black shale units within the CMB and for such rock types worldwide (Dahlkamp, 1993). Black shales, given their formation in a reducing environment are also generally enriched in Cu, Ni, Co, Mo and Ag (Dahlkamp, 1993). This corresponds well with recent drilling along the Kitts-Post Hill Belt, in which anomalous enrichments of Ag, Cu and Au were locally noted in association with uranium mineralization (Aurora Energy, Press Release, January 22, 2008). Anomalous enrichment in Mo is also reported in the bulk sample obtained from within the adit at the Kitts deposit (Beavan, 1958).

The age provided by the quartz-feldspar porphyry dyke demonstrates that the primary mineralization within the Kitts deposit is part of an older mineralization event. This event is separate from that identified farther east in the region of the Jacques Lake and Michelin deposits, which are inferred to be hosted within *ca.* 1856 Ma metavolcanic rocks of the Aillik Group (Schärer *et al.*, 1988). In the region of the Jacques Lake deposit, a minimum age limit on the uranium mineralization is provided by the *ca.* 1801 Ma quartz-feldspar porphyry dyke, which locally crosscuts the mineralization (Sparkes and Dunning, 2009). These new age data within the region show that previous deposit models linking the formation of the Kitts and Michelin mineralization to a single mineralizing event require some rethinking.

CONCLUSIONS

The Kitts deposit still stands as the highest grade uranium deposit discovered within the CMB to date. This deposit has undergone significant exploration, including limited underground development, but has not benefited from the recent resurgence in uranium exploration due to the fact that it currently lies within exempt mineral lands. Several detailed studies have been carried out on the region surrounding the Kitts deposit, but little work has been done since the early 1980s. Recent examination of archived drillcore, integrated with 3D modelling of the mineralization, provides some new insights as to the nature and timing of the mineralization. However, historical drill logs and reports written on the setting and style of the mineralization, particularly those by Marten (1977), Gandhi (1978) and Evans (1980), remain the main sources of technical information.

Mineralization of the Kitts deposit developed within a prominent D_1–D_2 shear zone, along the margin of a large mafic intrusion. This mineralization is hosted within metasedimentary rocks of the Post Hill Group and is locally crosscut by quartz-feldspar porphyry dykes, which are subsequently affected by later deformational events (*e.g.*, D_4 of Culshaw *et al.*, 2000). New U–Pb zircon data from the quartz-feldspar porphyry dyke provide a crystallization age of 1881.8 ± 3.4 Ma. This dyke is interpreted to crosscut the primary mineralization thus providing a minimum age limit on uranium mineralization. The dyke is affected by D_3 of Marten (1977; D_4 of Culshaw *et al.*, 2000) and thus provides a maximum age for this deformation event. The intrusion of an undeformed, non-metamorphosed diorite dyke yielded a U–Pb titanite age of 1662 ± 4 Ma, providing an lower age constraint on the D_4–D_6 deformation of Culshaw *et al.* (2000), which overprints both the quartz-feldspar porphyry and the primary uranium mineralization. If the relationship between the quartz-feldspar porphyry dyke and the uranium mineralization is correct, then this suggests that the mineralization is older then most of the Aillik Group and as such, previously developed models require some revision with respect to the source of the uranium. Notably, there may be a closer genetic link between the mineralization and the Post Hill Group, although the mineralization likely still postdates the formation of the host rocks. More geochronological data are required to further evaluate the nature of this relationship.

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APPENDIX A

The autoradiographs for the mineralized samples are produced using a specialized clear plastic monomer known as CR-39. The plastic is exposed to the gamma radiation present within the geological samples and then etched in a NaOH solution, which only affects the material that has been altered due to the gamma radiation. For a more detailed description of the technique the reader is referred to Basham (1981).