Northern Territory Government

Geology and mineral resources of the Northern Territory

Ahmad M and Munson TJ (compilers)

Northern Territory Geological Survey
Special Publication 5

Chapter 8: Murphy Province

BIBLIOGRAPHIC REFERENCE: Ahmad M, Munson TJ and Wygralak AS, 2013. Chapter 8: Murphy Province: in Ahmad M and Munson TJ (compilers). *'Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publicatio*n 5.

Chapter 8: MURPHY PROVINCE

M Ahmad, TJ Munson and AS Wygralak

INTRODUCTION

The Murphy Province (new name) includes Palaeoproterozoic metasedimentary, volcanic and felsic intrusive rocks that underlie Palaeoproterozoic and younger sedimentary basins in the northeast of the Northern Territory and northwestern Queensland (**Figures 8.1**. **8.2**). The province is exposed in the Murphy and Carrara Range inliers, but otherwise, is largely in the subsurface. It forms an extensive east–west-trending basement high, previously colloquially called the 'Murphy Tectonic Ridge', that separates the unconformably overlying McArthur Basin succession in the north from the South Nicholson Basin and Lawn Hill Platform successions in the south. (**Figure 8.2**) This feature extends in the shallow subsurface for at least 50 km to the west of the exposed Murphy Inlier to the vicinity of the Coanjula microdiamond locality and probably extends for at least another 100 km further west-southwest at greater depths (Lee *et al* (1994, **Figure 8.2**). A basement high, consisting of Murphy Province rocks, is also inferred to extend for at least 100 km south of the exposed Murphy Inlier, beneath the South Nicholson Basin and Lawn Hill Platform successions, to the vicinity of the Carrara Range Inlier and possibly further south. Murphy Province basement is also likely to occur at much greater depths beneath younger basin successions and may be continuous with equivalent basement rocks of other provinces, such as the Pine Creek Orogen and Tennant Region.

Murphy Inlier

The most extensive exposures of the Murphy Province are in the Murphy Inlier. The northern boundary of the inlier is defined, in part, by the 'Tin Hole Hinge Line', which separates it from the Westmoreland Conglomerate (**Figure 8.3**). Ahmad and Wygralak (1989) described this structure as a probable thrust fault along which the Westmoreland Conglomerate has moved southward. A drillhole collared in the Cliffdale Volcanics south of the Namalangi uranium deposit intersected the Westermoreland Conglomerate at a depth of 200 m demonstrating the reverse faulted nature of the Tin Hole Hinge Line (Darby 1985). The southern boundary of the inlier is not well defined and probably coincides, in part, with the Fish River Fault Zone (Sweet and Slater 1975, Sweet *et al* 1981, Ahmad and Wygralak 1989, 1990, **Figure 8.1**). This is a series of east–west-trending faults along which mainly vertical movements have occurred. Sweet *et al* (1981) indicated that blocks to the north of the fault zone have been uplifted 500–1000 m relative to terranes to the south.

The Murphy Inlier consists of the Murphy Metamorphics, Nicholson Granite Complex, and the Cliffdale and Connellys volcanics. The Murphy Metamorphics was included in the P4 succession of Ahmad (2000) and comprises metasedimentary rocks that are possible stratigraphic equivalents of the Finniss River Group (Pine Creek Orogen) and the Warramunga Formation (Warramunga Province). The Nicholson Granite Complex, Cliffdale Volcanics and Connellys Volcanics are a suite of comagmatic felsic intrusive and volcanic rocks that was emplaced at 1855–1845 Ma (Page *et al* 2000). Minor alkaline igneous activity occurred in the inlier at ca 1830 Ma (Hanley 1996).

Carrara Range Inlier

The Carrara Range Inlier (new name) is a narrow elongate belt that incorporates a number of small outcrop areas of lower greenschist-facies metasedimentary rocks along the southern margin of the Lawn Hill Platform in MOUNT DRUMMOND[1] (**Figures 8.1**, **8.2**). The name Murphy Metamorphics has been used for these rocks, although they are separated from the main Murphy Inlier outcrops by about 110 km. However, they occupy an equivalent stratigraphic position beneath the Lawn Hill Platform succession and comprise similar lithologies to the main outcrop tract (Sweet 1984, Rawlings *et al* 2008).

[1] Names of 1:250 000 and 1:100 000 mapsheets are in large and small capital letters, respectively, eg MOUNT DRUMMOND, NICHOLSON RIVER.

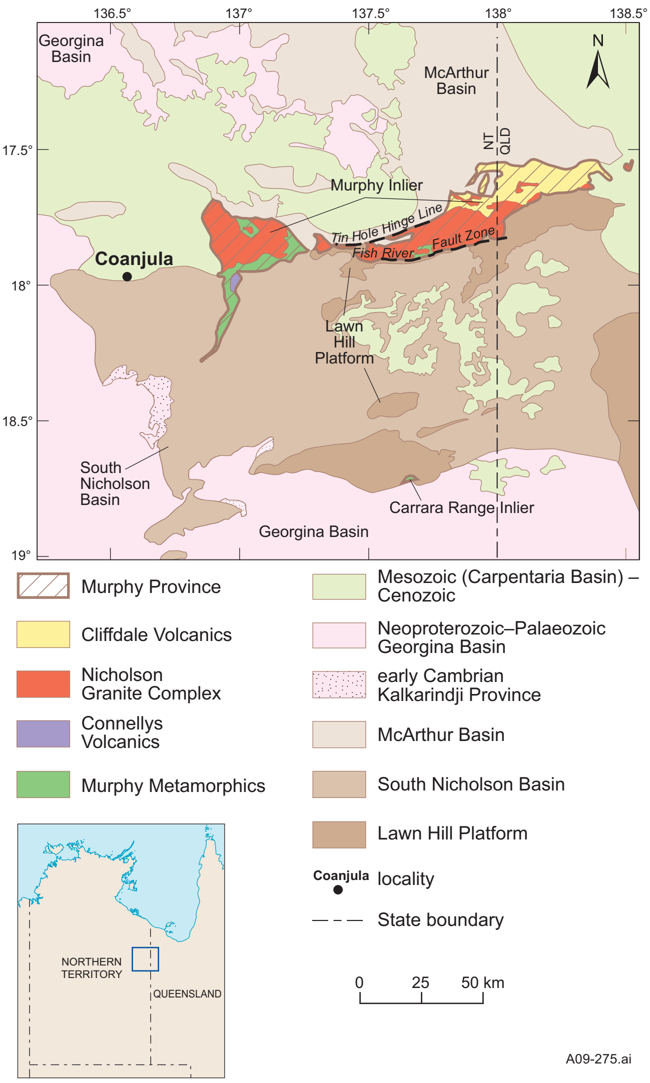

Figure 8.1. Simplified geological map of the Murphy Province and surrounding regions derived from 1:2 500 000-scale map of the Northern Territory (Ahmad and Scrimgeour 2006) and WESTMORELAND (Grimes and Sweet 1979).

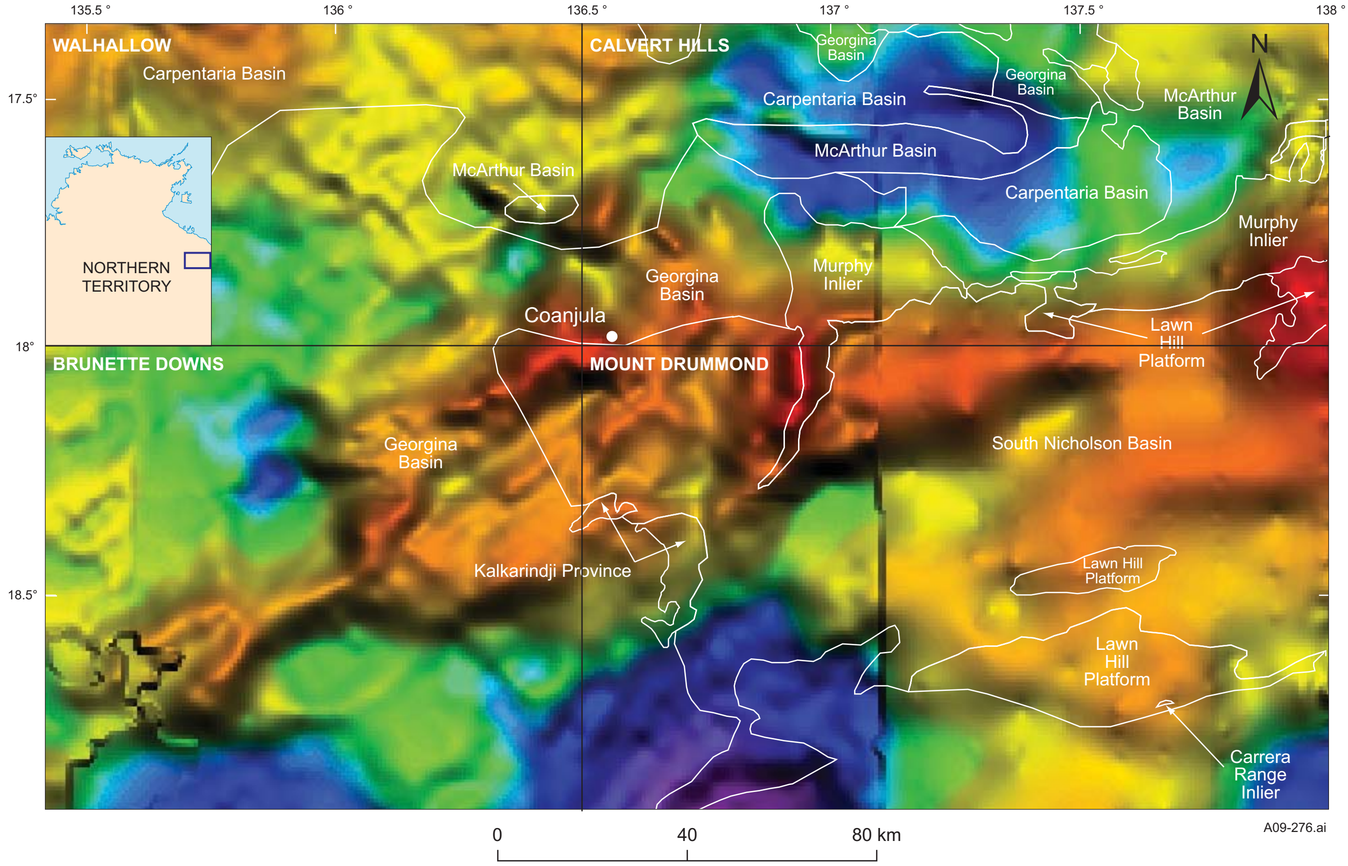

Figure 8.2. Gravity image overlain by outline of NT geological regions, showing subsurface extent of Murphy Province basement high to west-southwest and south of exposed Murphy Inlier. Gravity highs are likely to correspond to areas of relatively shallow basement. Data from NTGS 2009 4 km-spaced Barkley Gravity Survey (western two-thirds of image) and 11 km-spaced gravity readings acquired in 1960s and 1970s. Image processed by Clarke Petrick (NTGS).

PALAEOPROTEROZOIC

Murphy Metamorphics

The Murphy Metamorphics represents a succession of greenschist-facies metamorphosed shale and greywacke. A 5 m-thick interval of banded ironstone (**Figure 8.4**) is locally present (eg, at 53K 704350mE 7992200mN; Rawlings *et al* 2008). In the Murphy Inlier, the Murphy Metamorphics are isoclinally folded along east–west axes and are vertical or dip steeply north (**Figure 8.5**). They are unconformably overlain by the Cliffdale Volcanics and are intruded by the Nicholson Granite Complex.

The Murphy Metamorphics have been divided into two unnamed sub-units – Ƥlm$_1$ and Ƥlm$_2$ (Ahmad and Wygralak 1989), but the relationship between the two is not known. Ƥlm$_1$ predominantly consists of silty metapelite and shale, and contains quartz, muscovite, biotite and albite, with accessory zircon, tourmaline, leucoxene and opaques. Ƥlm$_2$ comprises immature meta-arenite, consisting of angular quartz, lithic fragments, muscovite, biotite and albite, with accessory tourmaline, zircon and opaques.

In the Carrara Range Inlier, the Murphy Metamorphics are composed of ferruginised outcrop and float of red-brown to purple or yellow, finely laminated micaceous metasiltstone (phyllite), metagreywacke, quartz-mica schist and quartzite. Numerous quartz veins are present. Orridge (1980) reported banded chert and haematitic ironstone, which is pyritic and graphitic at depth.

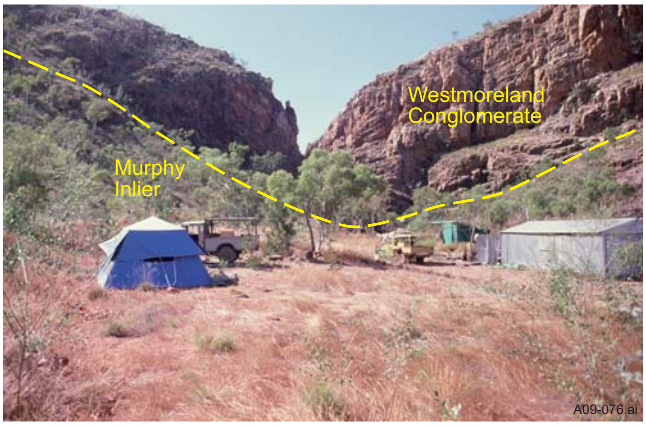

Figure 8.3. Westmoreland Conglomerate of the McArthur Basin overlying Nicholson Granite Complex rocks of the Murphy Inlier (Dry Creek Gorge looking north, 53K 787300mE, 8033100mN CALVERT HILLS).

SHRIMP U-Pb dating of detrital zircons from the Murphy Metamorphics by Hanley (1996) yielded ages ranging from 2968 Ma to 1867 Ma. The youngest and dominant population provided a maximum age of deposition of 1867 ± 7 Ma. LA-ICPMS dating of detrital zircons from a ferruginous metasandstone of the Murphy Metamorphics (Hollis *et al* 2010) has yielded a maximum deposition age of 1853 ± 4 Ma, based on the dominant youngest population. As the metamorphics are intruded by the Nicholson Granite Complex and unconformably overlain by the Cliffdale Volcanics (see below), a minimum depositional age of about 1850 Ma is indicated.

The Murphy Metamorphics are interpreted to have originally been deposited as a succession of turbidites. These sediments were deformed and metamorphosed prior to the extrusion of the Cliffdale Volcanics.

Nicholson Granite Complex

The Nicholson Granite Complex (Sweet and Slater 1975, Ahmad and Wygralak 1989) includes the Norris and Nicholson granites of Roberts *et al* (1963). Gardner (1978) identified eight lithological varieties, which were simplified into two groups by Ahmad (1987). Group A comprises inequigranular, coarse- to medium-grained hornblende- and/or biotite-bearing granite, quartz monzonite and granodiorite, emplaced into the mesozone. The unit is characterised by common mafic xenoliths and large K-feldspar phenocrysts, often up to 70 mm across. The groundmass includes quartz, plagioclase, perthite, hornblende and biotite, with accessory titanite, apatite, zircon and monazite. Group B comprises equigranular biotite- and/or muscovite-bearing quartz monzonite, granite and alkali granite, emplaced into the epizone. Hornblende is rare and mafic xenoliths are generally absent. Zircon, apatite and fluorite are common accessory minerals and titanite is rare (Ahmad and Wygralak 1989). Group B is more fractionated and has higher amounts of SiO_2, Al_2O_3, Rb and K, and lower Sr, Ca and Mg. Fe_2O_3/FeO ratios are also notably higher than in Group A.

Two samples of Nicholson Granite Complex have yielded SHRIMP U-Pb zircon ages of 1856 ± 3 and 1845 ± 3 Ma (Page *et al* 2000).

Cliffdale Volcanics

The Cliffdale Volcanics (**Figure 8.6**) are coeval with the Nicholson Granite Complex and unconformably overlie the Murphy Metamorphics. The succession is over 4 km thick and comprises rhyolite, alkali rhyolite and dacitic lavas, ignimbrites and intrusions. Minor andesite and sedimentary intervals also occur within the succession. It was divided into several members (Sweet *et al* 1981, Mitchell 1976), which were placed into two broader unnamed groups by Ahmad and Wygralak (1989). The lower succession is about 2 km thick and comprises coarse, poorly sorted ignimbrites of dacitic and rhyolitic composition. The upper succession consists essentially of flow-banded alkali rhyolite and minor tuff. Darby (1985) considered the contact between the lower and upper parts of the succession to be locally unconformable. Orth (2009) has described the complicated relationship between the Nicholson Granite Complex and Cliffdale Volcanics. At some localities, the Cliffdale Volcanics are intruded by granite and they even form roof pendants in the granite. East of Pandanus Creek, high-angle flow banding in rhyolite and the overall shape of a felsic body suggest that the volcanics could be intruding early phases of the granite. Abundant quartz+feldspar porphyry bodies and dykes intrude both the volcanics and the granite.

SHRIMP U-Pb dating of zircons from a sample of Cliffdale Volcanics has yielded an age of 1851 ± 3 Ma (Page *et al* 2000), which supports the notion that the unit is coeval with the Nicholson Granite Complex.

Figure 8.4. Banded ironstone of Murphy Metamorphics, showing intricate interlamination of iron-rich and silica-rich bands (53K 704550mE 7992150mN, after Rawlings *et al* 2008).

Figure 8.5. Steeply dipping foliated metasiltstone (phyllite) and metagreywacke of the Murphy Metamorphics (53K 704250mE 7992200mN, after Rawlings *et al* 2008).

Figure 8.6. Oxidised copper ore from unnamed diggings within Cliffdale Volcanics (53K 807028mE 8044259mN), photo A Wygralak, NTGS).

Connellys Volcanics

The Connellys Volcanics are exposed in a small area in the southwest of the Murphy Inlier and were previously included in the Murphy Metamorphics (Smith and Roberts 1963). However, they are now considered more likely to be stratigraphically equivalent to the Cliffdale Volcanics

(Rawlings *et al* 2008). The volcanics comprise weathered porphyritic rhyolite or rhyodacite, which generally has a mottled and highly weathered appearance. They are composed of equant and euhedral K-feldspar and subhedral to anhedral, embayed quartz phenocrysts up to 3 mm in diameter in a recrystallised, equigranular, ferruginous quartzofeldspathic groundmass. Outcrop is characterised by locally abundant, epithermal-style quartz veins and clay-rich slickenside surfaces, defining a crude foliation.

Alkaline magmatism

Minor alkaline igneous intrusive rocks under shallow cover were discovered in the western part of the Murphy Province in the Coanjula area as a result of diamond exploration programs in the 1980s (Ong 1991, Lee *et al* 1994, Hanley 1996, see **Diamonds**). Several varieties of igneous rocks are present (Ong 1991); these include alkali basalt, quench-textured high-K trachyandesite and rocks with shoshonitic affinities, shonkinite (mafic syenite) and kentallenite (olivine monzogabbro). Intrusive volcanic pipes have yielded abundant kaersutite xenocrysts, one of which was dated by the K-Ar method at ca 1665 Ma (Lee *et al* 1994). Hanley (1996) dated a trachyandesite which yielded a post-orogenic SHRIMP U-Pb age of 1830 ± 7 Ma, suggesting that this was the timing of alkaline magmatism in the area. Based on geochemical similarities with the trachyandesite, the kentallenite and shonkinite were interpreted by Hanley to be also post orogenic. A mica lamprophyre from the same area has returned an older pooled age of 1861 ± 10 Ma, similar to the age of the Murphy Metamorphics, but there is uncertainty as to whether this represents a magmatic age or whether it is due to xenocrystal zircons inherited from the Murphy Metamorphics (Hanley 1996).

MINERAL RESOURCES

The Murphy Inlier contains a variety of small occurrences of uranium, copper, tin and tungsten (Ahmad and Wygralak 1990, Wygralak *et al* 2009, **Figure 8.7**). A number of mineral ccurrences are within sedimentary and volcanic rocks of the immediately overlying McArthur Basin succession. A search of the NTGS MODAT database shows that there are a total of thirty-three mineral occurrences within the Northern Territory portion of the Murphy Inlier; these include nineteen copper, nine uranium and six tin-tungsten occurrences.

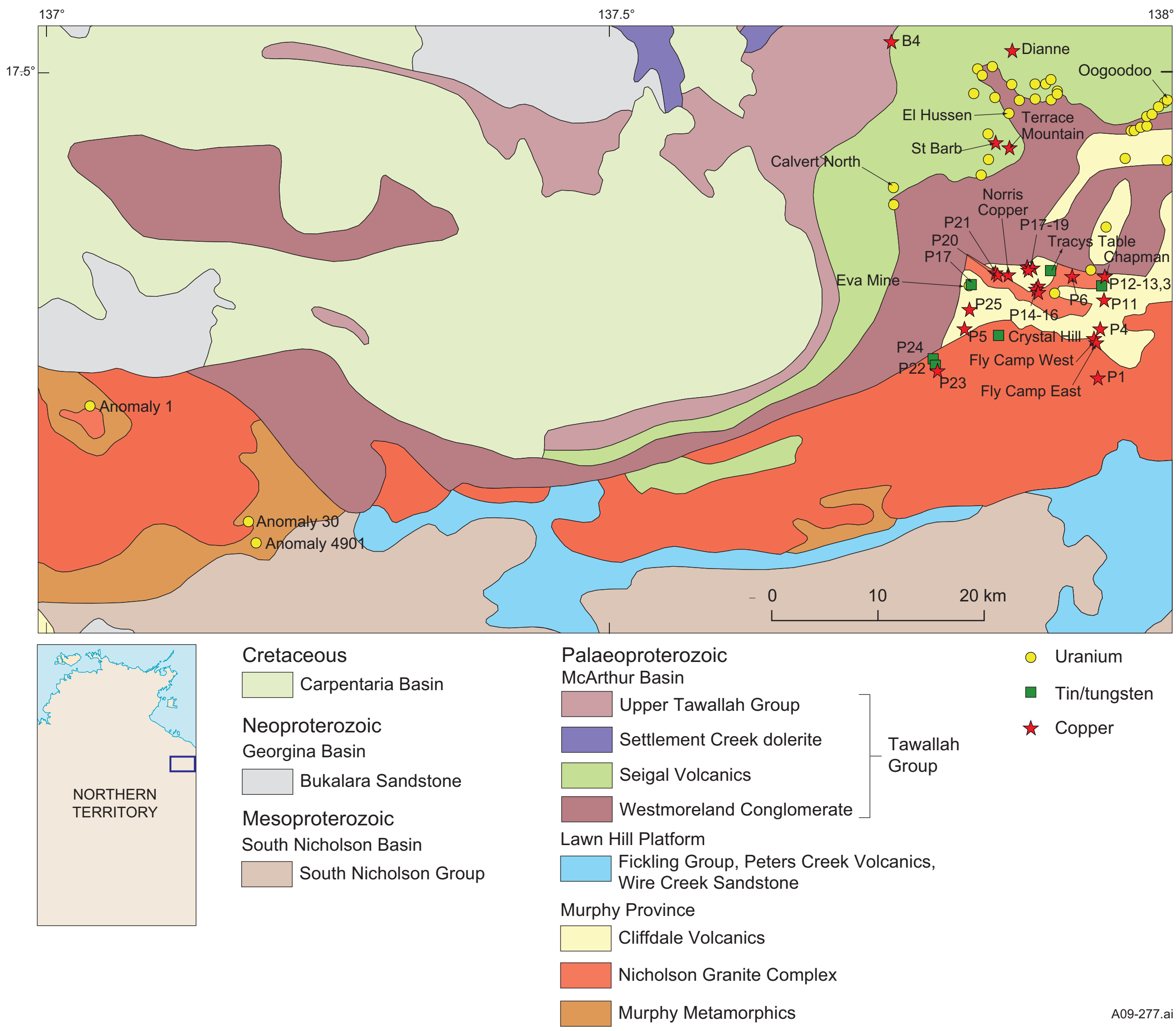

Figure 8.7. Locations of mineral occurrences, prospects and mines in Murphy Inlier and adjacent area of NT (from NTGS MODAT database) on geology basemap derived from NTGS 1:2 500 000-scale GIS dataset. See **Figure 8.8** for more detail of uranium occurrences in east of inlier.

In addition the Coanjula microdiamond occurrence occurs in the Murphy Metamorphics beneath shallow cover about 35 km west of the Murphy Inlier exposures. The Carrara Range Inlier is insignificantly explored and no significant mineral occurrences are recorded.

Copper

Copper occurrences are hosted within the Nicholson Granite Complex and Cliffdale Volcanics (**Figures 8.6**, **8.7**), and occur as fracture fillings, generally following faults or shear zones. In oxidised zones, malachite, azurite, chalcocite and chrysocolla are common, whereas in primary zones, chalcopyrite is the main mineral. Quartz is the principal gangue mineral. The *Norris Copper* mine is the only known significant deposit, where copper is associated with a northwest-trending fault parallel to the major Calvert Fault. The deposit is within the Cliffdale Volcanics in the form of a mineralised vein, extending over a strike length of over 1 km. The mine has produced about 150 t of concentrate, averaging about 14% Cu (Ahmad and Wygralak 1990).

Uranium

Uranium occurrences in the eastern Murphy Inlier near the Queensland border are hosted by the Cliffdale Volcanics, close to the unconformity with the overlying Westmoreland Conglomerate. Several uranium occurrences are also known from the overlying basal succession of the McArthur Basin (Westmoreland Conglomerate and Seigal Volcanics, **Figures 8.7**, **8.8**) and these are described in **McArthur Basin**.

The *Eva* (*Pandanus Creek*) mine is the only known significant uranium deposit within the Murphy Inlier succession. It was discovered in 1958 and was evaluated by BHP Ltd during 1958–1959 (Morgan 1965). During 1960–1962, South Alligator Uranium NL selectively mined 306 t of ore averaging 8.37% U_3O_8 to a depth of 28 m; this was trucked to Rum Jungle for processing. About 3000 t of ore averaging 1% U_3O_8 and 11 g/t Au was estimated to have remained in a spoil dump at the mine and 56 000 t of ore at 0.56% U_3O_8 remains *in situ* at the deposit (Morgan 1965, Ahmad 1982). A composite sample from the mine dump assayed at 11 g/t Au, with individual samples ranging from 1.5 to 103 g/t Au (Ahmad 1982). The Eva lease is currently being explored by NuPower Resources Ltd, who have announced a preliminary resource of up to 120 000 t at 0.32% U_3O_8, containing up to 380 t of U_3O_8 (NuPower Resources Ltd, ASX announcement, 7 April 2009). There is no account of the gold content, as reported previously, because drill core samples were not assayed for gold.

At the Eva mine, the Cliffdale Volcanics strike northeast, dip steeply northwest and are unconformably overlain by the moderately to steeply north-dipping Westmoreland Conglomerate. A local steepening of dips of the Westmoreland Conglomerate is attributed to thrust faulting. Most mineralisation at the Eva deposit is controlled by shears and fractures in intensely altered porphyritic acid volcanics. The orebody is lenticular, 60 m long and up to 10 m wide, strikes east–west and dips steeply to the north. A phase of the Nicholson Granite Complex underlies the deposit and is exposed to the west, but is not mineralised (Morgan 1965). Mineralisation is associated with sericite-epidote-quartz rock with rare haematite. Quartz-topaz rock is present 100 m along strike to the north of the ore zone, and quartz-cassiterite-topaz veins also occur to the east. Orth (2009) described a zoned alteration pattern in the rhyolite, varying with distance from the unconformity. White clay/ sericite±haematite alteration is closest to the unconformity and is associated with veinlets of yellow autunite. A zone of yellow-green illite/muscovite alteration in granophyre is 30 m from the unconformity and chlorite becomes more abundant at greater distances. An outer zone of chlorite+potassic alteration enhances primary textures, but it is uncertain whether this outer zone is related to mineralisation in the Eva Mine area, or to broader diagenesis/alteration of the Cliffdale Volcanics.

High-grade ore consists of a central core of remnant pitchblende and secondary uranium minerals, surrounded by massive uranium ochres replacing host rocks. Mineralised lenses pinch out laterally into barren quartz veins less than 15 cm wide. Low-grade ore, consisting of secondary uranium minerals coating joint and fracture surfaces, occurs to 8 m depth. The ore minerals at Eva comprise sklodowskite, boltwoodite, beta-uranophane and remnant pitchblende, with minor amounts of saleeite, autunite and torbernite. Gold and silver are distributed erratically, but are generally associated with high uranium grades. Small amounts of galena, manganese oxide and copper carbonate are also associated with the ore. Uranium deposits in the overlying Westmoreland Conglomerate have been subjected to detailed studies (eg Polito *et al* 2005), but little genetic information is available on the uranium occurrences in the Murphy Inlier, although these uranium systems are undoubtedly related. Geological setting (age, nature of volcanism, structural and stratigraphic settings) of the Eva mine is, in some respects, similar to the Coronation Hill Au-PGE deposit in the South Alligator Valley Region of the PCO. The area is under explored and has significant mineral potential.

Other minor uranium occurrences in the eastern part of the Murphy Inlier succession include *Crippled Horse*, which is associated with a subvertical, quartz-filled fault zone, and *Duccios*, which has no apparent structural control.

Minor uranium occurrences in the western part of the Murphy Inlier include Anomaly 1, Anomaly 30 and Anomaly 4901 (**Figure 8.7**). These small uneconomic occurrences differ from those in the eastern Murphy Inlier in that they are hosted by the Murphy Metamorphics, rather than the Cliffdale Volcanics, near the contact with the Nicholson Granite Complex (Pietsch and Tucker 1972, Mason 1980, Billington 1981).

Tin and tungsten

Several small tin ± tungsten occurrences are hosted by the Nicholson Granite Complex and Cliffdale Volcanics. The *Crystal Hill* occurrence is the largest amongst these and was described in detail by Ahmad (1989). This deposit is circular in shape and is contained within greisenised granite belonging to a late phase of the Nicholson Granite Complex. Muscovite from the greisen was dated by the Rb/Sr method at 1621 ± 28 Ma (Fanning and Webb 1986), although this is unlikely to represent a crystallisation age. Cassiterite is the main ore mineral and is associated with quartz, muscovite, phlogopite, fluorite, wolframite and pyrite. Ahmad (1989) provided data on fluid inclusion studies. Early primary fluid inclusions formed at a temperature range of 190–400ºC and have a salinity range of 0.3–12 wt% eq NaCl. Late secondary inclusions have a lower temperature (90–330ºC) and high salinity (up to 40 wt% eq NaCl). There is no visible CO_2 or CH_4. Co-existing liquid/vapour inclusions and vapour-phase homogenisation of some inclusions indicate fluid boiling. Oxidation and temperature decreases were suggested to be the main causes of cassiterite precipitation. Boiling also attests to the epizonal character of the intrusion.

Gold

Roberts *et al* (1963) reported the presence of gold in Tin Hole Creek. Gold also occurs in economic concentrations at the Eva uranium mine and at several other uranium occurrences hosted in the overlying Westmoreland Conglomerate and Seigal Volcanics. Ahmad *et al* (1984) examined heavy mineral concentrates from eight stream sediment and two conglomerate matrix samples and found gold grains ranging in size from 0.1 to 0.6 mm. All samples were from creeks draining the Westmoreland Conglomerate. Hitchman and Simpson (1991) reported the results of a stream-sediment survey in NICHOLSON RIVER. The initial stream sediment sampling program located several low-order (approximately 1 ppb) gold anomalies with a maximum assay of 50.8 ppb Au. Follow-up stream sediment sampling confirmed the anomaly; however, soil and rock chip sampling failed to locate any zones of mineralisation.

Diamonds

The Coanjula microdiamond occurrence is situated in a black soil-covered area, about 50 km west of Benmara

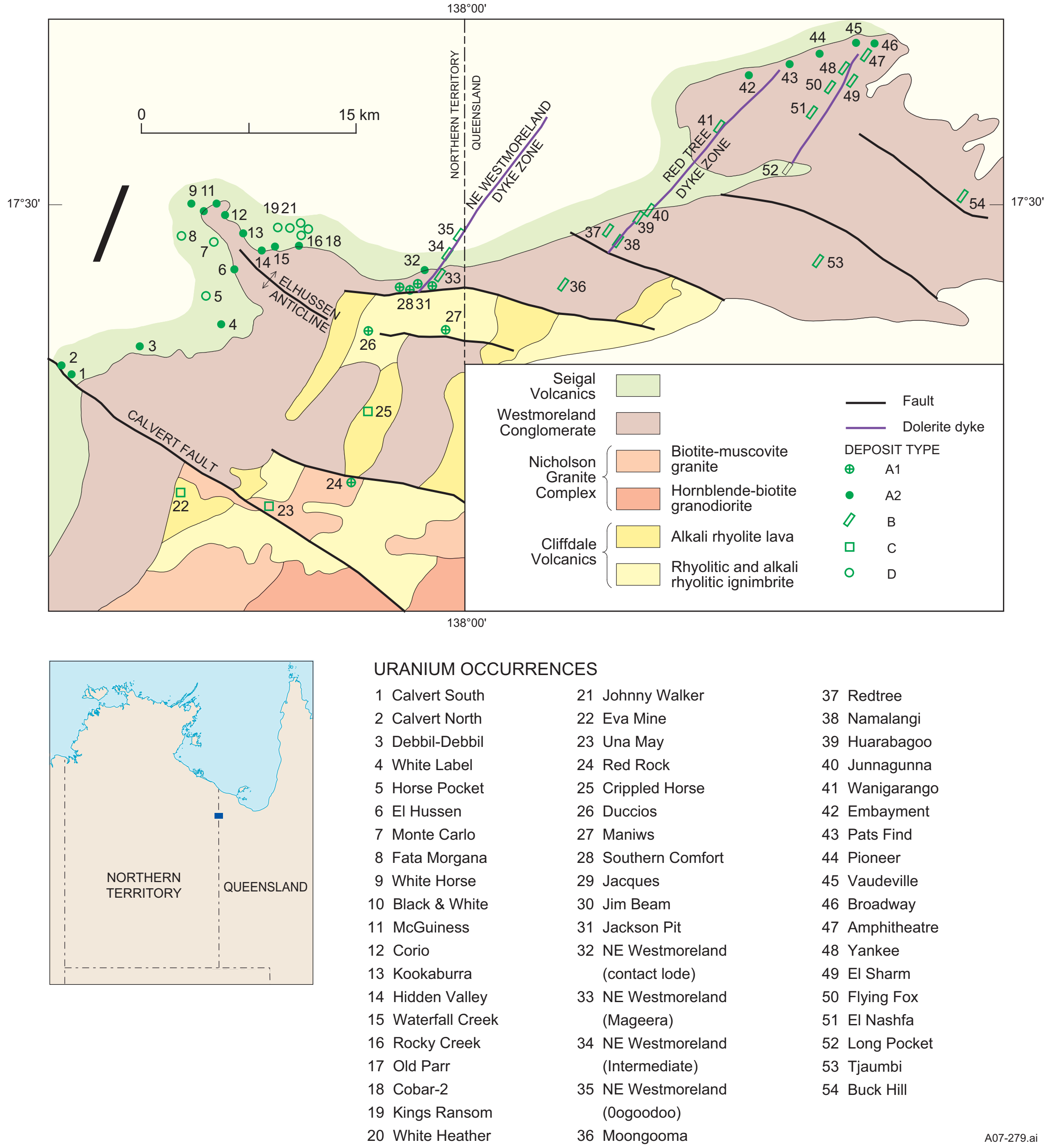

Figure 8.8. Regional geological setting of uranium deposits in the Murphy Inlier–Westmoreland area (modified from Ahmad and Wygralak 1989). Classification of uranium occurrences into five deposit types (A1, A2, B, C, D) is based on their hydrological and geological settings and is after Ahmad (1987); see **McArthur Basin** for more details.

homestead (**Figure 8.1**). It was delineated in the 1980s by contouring the regional distribution of microdiamonds and diamond indicator minerals in soil and stream samples (Lee *et al* 1994). Aeromagnetic surveys and follow-up drilling revealed 21 intrusive pipes with alkali basalt affinities (Ong 1991), but none was associated with diamonds (Lee *et al* 1994, Hanley 1996). The microdiamonds are instead hosted in metasedimentary rocks of the Murphy Metamorphics, which in this area, occur at very shallow depths (ca 10–50 m) beneath Cenozoic cover (**Figure 8.9**). The microdiamonds probably have not travelled far as populations are dominated by fibrous cube morphologies that abrade easily and would therefore not be likely to survive long transport distances (Lee *et al* 1994).

The source of the microdiamond anomaly at Coanjula is uncertain. A meteorite-impact was postulated as a possible source, but this was considered to be unlikely due to the absence of cryptocrystalline diamond (lonsdaleite), a high-pressure diamond that forms during shock metamorphism (Lee *et al* 1994). Hanley (1996) documented previously undiscovered mica lamprophyres in drillholes (see **Alkaline magmatism**, **Figure 8.9**), which also contained high microdiamond abundances in metasedimentary intervals, and by analogy with a recent discovery of a diamond-bearing mica lamprophyre in Canada (MacRae *et al* 1995), suggested that this rock may be a source of microdiamonds.

Models proposed for the emplacement of microdiamonds in metasedimentary rocks at Coanjula by Hanley (1996) include:

1. They are a detrital component eroded from a proximal primary igneous host rock.
2. The microdiamonds were transported in suspension during a shallow-marine incursion from a more distal source.
3. They were derived from pyroclastic or air-fall volcaniclastic activity, related to a highly volatile source rock of possible kimberlitic affinity.
4. An igneous intrusive rock entrained the microdiamonds at depth and intruded along pre-existing fractures, joints and bedding surfaces causing brecciation rather than a typical volcanic diatreme. These small dykelets of igneous material may not have been distinguished by routine drilling and bulk sampling methods during exploration in the area.

A commercial diamondiferous deposit has yet to be delineated in the Coanjula area.

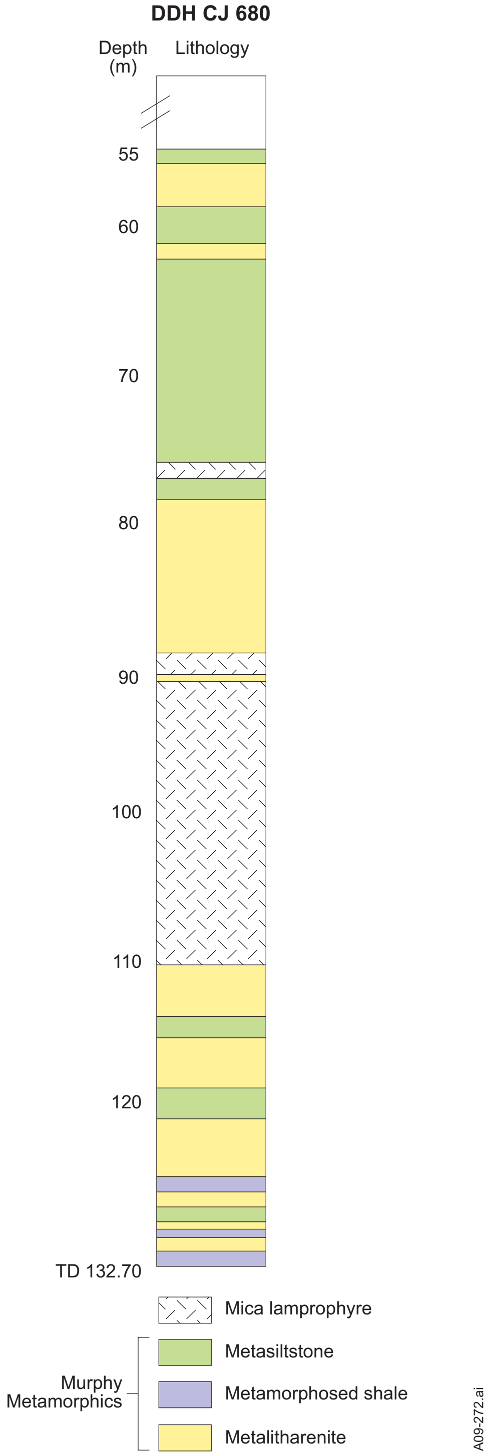

Figure 8.9. Ashton Mining Ltd drillhole DDHCJ680 (53K 663942mE 8011071mN): simplified log after Hanley (1996). Mica lamprophyre intrudes metasedimentary rocks of Murphy Metamorphics at relatively shallow depths beneath Cenozoic cover.

REFERENCES

Ahmad M, 1982. A report on the inspection of the Eva mine, Nicholson River, Northern Territory. *Northern Territory Geological Survey, Technical Report* GS1982-002.

Ahmad M, 1987. Uranium-gold occurrences of the Murphy Inlier and surrounding region. *Northern Territory Geological Survey, Technical Report* GS1987-002.

Ahmad M, 1989. Fluid inclusion study of greisens associated with the Nicholson Granite Complex, Murphy Inlier, Northern Territory. *Australian Journal of Earth Sciences* 36, 207–218.

Ahmad M, 2000. *Geological map of the Northern Territory. 1:2 500 000 scale.* Northern Territory Geological Survey, Darwin.

Ahmad M, Hallenstein CP and Wygralak AS, 1984. Palaeoplacer potential in the mid-Proterozoic of the Northern Territory: A study of the Westmoreland Conglomerate: in *Darwin Conference, 1984.* Australasian Institute of Mining and Metallurgy, Parkville, Victoria, 357–366.

Ahmad M and Scrimgeour IR, 2006. *Geological map of the Northern Territory. 1:2 500 000 scale*. Northern Territory Geological Survey, Darwin.

Ahmad M and Wygralak AS, 1989. *Calvert Hills, Northern Territory. 1:250 000 metallogenic map series explanatory notes, SE 53-08*. Northern Territory Geological Survey, Darwin.

Ahmad M and Wygralak AS, 1990. Murphy Inlier and environs: regional geology and mineralisation: in Hughes FE (editor) *'Geology of the mineral deposits of Australia and Papua New Guinea.' Australasian Institute of Mining and Metallurgy, Monograph* 14, 819–826.

Billington WG, 1981. Nicholson River EL 1319, NT. Annual and final report to August 1981. Esso Exploration and Production Australia Inc. *Northern Territory Geological Survey, Open File Company Report* CR1981-0227.

Darby PR, 1985. Results of government investigations in the Mary River Mining Reserve (MR 275). *Northern Territory Geological Survey, Technical Report* GS1985-010.

Fanning M and Webb AW, 1986. Rb-Sr dating of muscovite from sample 1780. *Australian Mineral Development Laboratories, Report* G 6459/86.

Gardner CM, 1978. Precambrian geology of the Westmoreland region. Part III. The Nicholson Granite Complex and Murphy Metamorphics. *Bureau of Mineral Resources, Australia, Record* 1978/32.

Grimes KG and Sweet IP, 1979. *Westmoreland, Queensland (Second Edition). 1:250 000 geological series, SE 54-05*. Bureau of Mineral Resources, Australia, Canberra.

Hanley LM, 1996. *Geochronology, mineral chemistry, geochemistry and petrography of diamond-associated rocks in the Coanjula Region, Northern Territory*. BSc Hons thesis, Geology Department, University of Western Australia, Perth.

Hitchman SP and Simpson PG, 1991. Final annual report EL6560, Benmarra, year ending 4 September 1991. *Northern Territory Geological Survey, Open File Company Report* CR1991-0607.

Hollis JA, Beyer EE, Whelan JA, Kemp AIS, Scherstén A, and Greig A, 2010. Summary of results. NTGS laser U-Pb and Hf geochronology project: Pine Creek Orogen, Murphy Inlier, McArthur Basin and Arunta Region, July 2007–June 2008. *Northern Territory Geological Survey, Record* 2010-001.

Lee DC, Boyd SR, Griffin BJ, Griffin WL and Reddicliffe TH, 1994. Coanjula diamonds, Northern Territory, Australia: in Meyer HOA and Leonardos OH (editors). *'Proceedings of the Fifth International Kimberlite Conference, Araxa, Brazil. June 1991. Volume 2. Diamonds: Characterisation, genesis and exploration.' Companhia de Pesquisa de Recursos Minerais, Special Publication* 1B, 51–68.

MacRae ND, Armitage AE and Jones AL, 1995. A diamondiferous lamprophyre dike, Gibson Lake area, Northwest Territories. *International Geology Review* 37, 212–229.

Mason AJ, 1980. Final report. Field investigations – EL 1235, NT. Benmara. Mines Administration Pty Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1980-0143.

Mitchell JE. 1976. Precambrian geology of the Westmoreland region, northern Australia. Part II. The Cliffdale Volcanics. *Bureau of Mineral Resources, Australia, Record* 1976/34.

Morgan DBD, 1965. Uranium ore deposit of Pandanus Creek: in McAndrew J (editor) *'Geology of Australian ore deposits, Second Edition'. Eighth Commonwealth Mining and Metallurgical Congress, Australia and New Zealand, 1965, volume* 1. The Australasian Institute of Mining and Metallurgy, Melbourne, 210–211.

Ong N, 1991. *The mineralogy, petrology and geochemistry of igneous rocks and metasediments from the Coanjula microdiamond deposit area, Northern Territory*. BSc Hons Thesis, Department of Geology, University of Western Australia, Perth.

Orridge GR, 1980. Carrara Range Project, Northern Territory, EL 2112, Annual Report. *Northern Territory Department of Mines and Energy, Open File Company Report* CR1981-0093.

Orth K, 2009. Insights into alteration and mineral potential of volcanic successions of the Murphy Inlier and surrounding areas: in *'Annual Geoscience Exploration Seminar (AGES) 2009. Record of abstracts.' Northern Territory Geological Survey, Record* 2009-002.

Page RW, Jackson MJ and Krassay AA, 2000. Constraining the sequence stratigraphy in northern Australian basins: SHRIMP U-Pb zircon geochronology between Mount Isa and McArthur River. *Australian Journal of Earth Sciences* 47(3), 431–460.

Pietsch G and Tucker D, 1972. Report on prospecting exploration licence No 122, Northern Territory 1972. Report No 188. Noranda Australia Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1972-0087.

Polito PA, Kyser KT, Rheinberger G and Southgate PN, 2005. A paragenetic and isotopic study of the Westmoreland Uranium deposits, southern McArthur Basin, Northern Territory, Australia. *Economic Geology* 100, 1243–1260.

Rawlings DJ, Sweet IP and Kruse PD, 2008. *Mount Drummond, Northern Territory. 1:250 000 geological map series explanatory notes, SE 53-12*. Northern Territory Geological Survey, Darwin.

Roberts HG, Rhodes JM and Yates KR, 1963. *Calvert Hills, Northern Territory (First Edition). 1:250 000 geological map series explanatory notes, SE 53-08*. Bureau of Mineral Resources, Australia, Canberra.

Smith JW and Roberts HG, 1963. *Mount Drummond, Northern Territory (First Edition). 1:250 000 geological map series explanatory notes, SE 53-12*. Bureau of Mineral Resources, Australia, Canberra.

Sweet IP, 1984. *Carrara Range Region, Northern Territory. 1:100 000 geological map commentary*. Bureau of Mineral Resources, Australia, Canberra.

Sweet IP and Slater, 1975. Precambrian geology of the Westmoreland region, northern Australia, Part 1: Regional setting and cover rocks. *Bureau of Mineral Resources, Australia, Record* 1975/88.

Sweet IP, Mock CM and Mitchell JE, 1981. *Siegal, Northern Territory and Hedleys Creek, Queensland. 1:100 000 geological map commentary*. Bureau of Mineral Resources, Australia, Canberra.

Wygralak AS, Mernagh TP, Hollis J and Carson C, 2009. Geology and mineral potential of the Murphy Inlier Region: in *'Annual Geoscience Exploration Seminar (AGES) 2009. Record of abstracts.' Northern Territory Geological Survey, Record* 2009-002.