Chapter 1 Introduction

The environmental management of active and abandoned mines is a contentious issue. Mine sites have a variety of contamination sources and dispersal mechanisms that make it difficult to predict the amount and types of environmental problems that may occur at any particular mine. Australia has a number of decommissioned mines where, for example, acid drainage causes major contamination problems (e.g. Brukunga in South Australia, Mt. Lyell in Tasmania, and Rum Jungle in the Northern Territory). The key landforms of mining, including uranium mines, are mine workings, waste rock piles and tailings areas. Such landforms can represent sites of elevated metal or even radioactive pollutants and have the potential to generate saline, acidic or alkaline and/or metal rich drainage waters which may adversely affect the surrounding environment. Uranium tailings have special containment requirements because of their radioactivity, emanating from residual long-lived U isotopes, and U daughter products, Th^{230} and Ra^{226} with half lives of 80 000 y and 1600 y, respectively (Noller et al., 1997).

An environmental assessment of mine sites includes discussions on deposit type, deposit size, host rocks, regional geology, nature of ore, mining and ore processing methods, deposit trace element geochemistry, primary mineralogy and zonation, secondary mineralogy, soil and sediment signatures, topography, hydrology, drainage signatures, climatic effects and potential environmental concerns (Plumlee 1999; Plumlee et al., 1999). The Mary Kathleen uranium mine site is assessed by determining the above mentioned characteristics and by comparing them with previously determined relationships. Hence their potential for adverse impacts can be determined (Plumlee et al., 1999).

The Mary Kathleen uranium mine in north-west Queensland was one of the first uranium mines in Australia to undergo comprehensive rehabilitation. This study documents the current environmental status of the Mary Kathleen mine site by reporting on its key areas including the open pit, waste rock piles, tailings dam, evaporation dam and Cameron Creek.

1.1 Mine site description, location, physiography, climate and hydrology

The historic Mary Kathleen uranium mine site is located 70km west of Cloncurry, northwest Queensland at latitude 20°45.1'S, longitude 140°0.6'E (Figure 1.1). The mine site area is surrounded by ranges and ridges up to 600 m above sea level and undulating low lands with an average elevation 300 m above sea level. Mary Kathleen has a semi-arid/tropical savanna type climate with an annual rainfall of approximately 497 mm. The annual rainfall has exceeded 700 mm ten times in the last 50 years (Figure 1.2). The wet season (summer months) monthly rainfall can exceed 400 mm (Figure 1.3). Annual evaporation rates can exceed 2600 mm per year. Average maximum temperatures for Cloncurry during summer and winter are 31.8 °C and 26 °C, respectively; average minimum temperatures are 20 °C and 9 °C, respectively.

The mine site is located within the Flinders River catchment system. Drainage patterns of Cameron Creek and nearby Corella River flow in a northerly direction toward the Gulf of Carpentaria. Flood conditions can develop from cyclonic influences in the Gulf. Semipermanent waterholes and billabongs are common in Cameron Creek year round.

The area surrounding the rehabilitated mine site characterised by open to low-open woodlands with eucalypts, acacia and red river gums closer to Cameron Creek. Hummock grasslands and less wooded areas are utilised for grazing. Vegetation at the minesite includes; *Acacia chisholmii* (wattle), *Aerva javanica* (kapok bush), *Triodia longiceps* (porcupine spinifex) and various grass species. Excluding the void, the immediate mine site area and surrounding region are currently used for grazing cattle and tourism.

Figure 1.1 Location Map

(Reference: Derrick G.M., 1980. Marraba, Queensland. 1:100 000 scale Geologic Series, Sheet 6956 explanatory notes. BMR Geology and Geophysics. Australian Government Publishing Service, Canberra.)

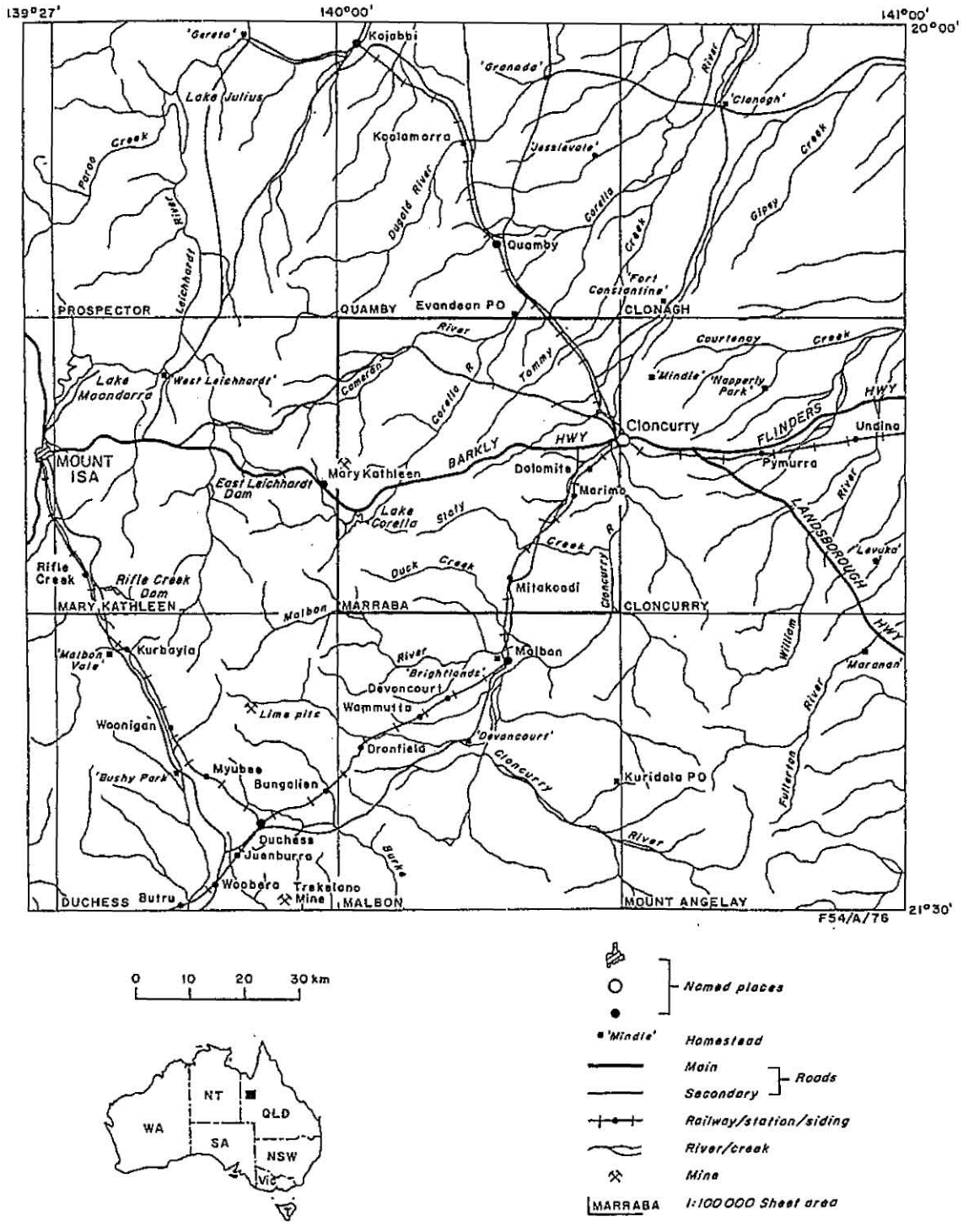


Figure 1.2

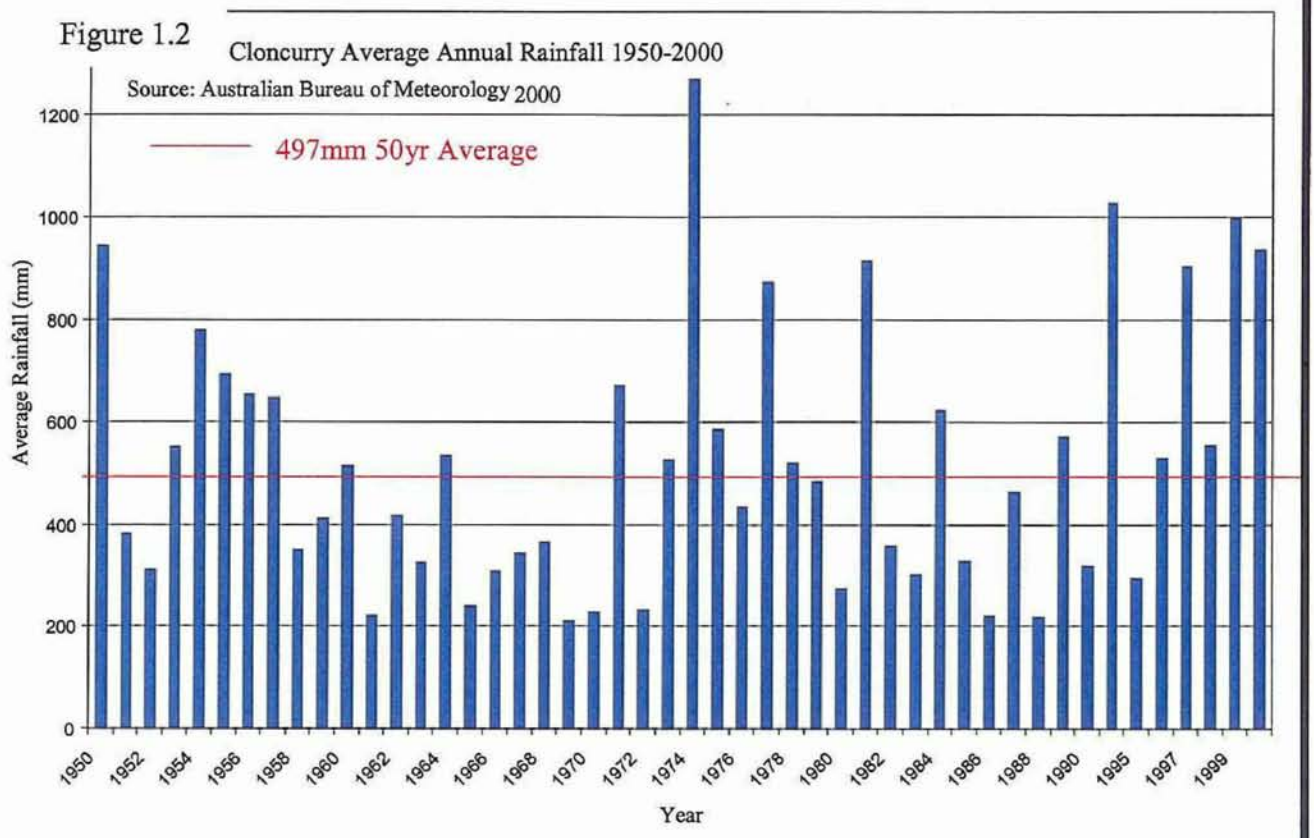
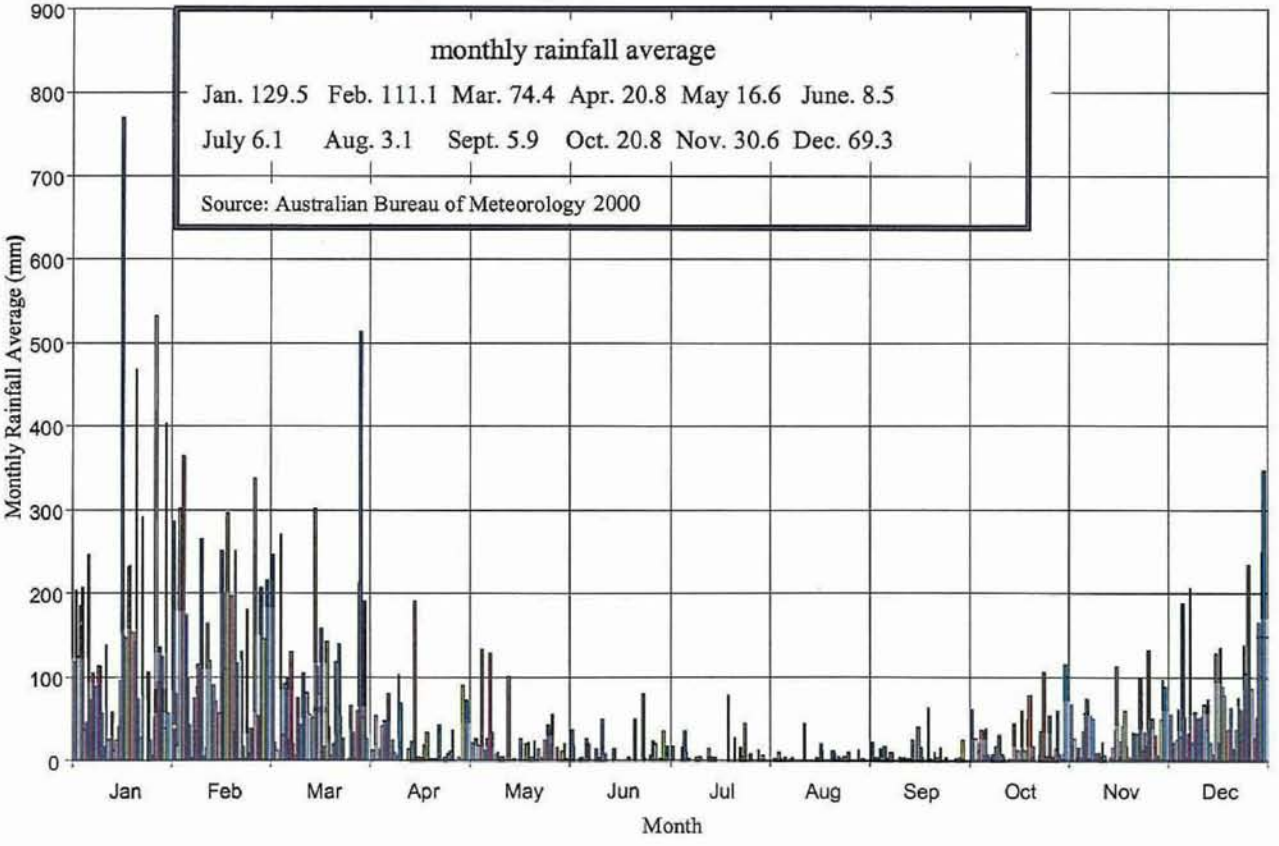
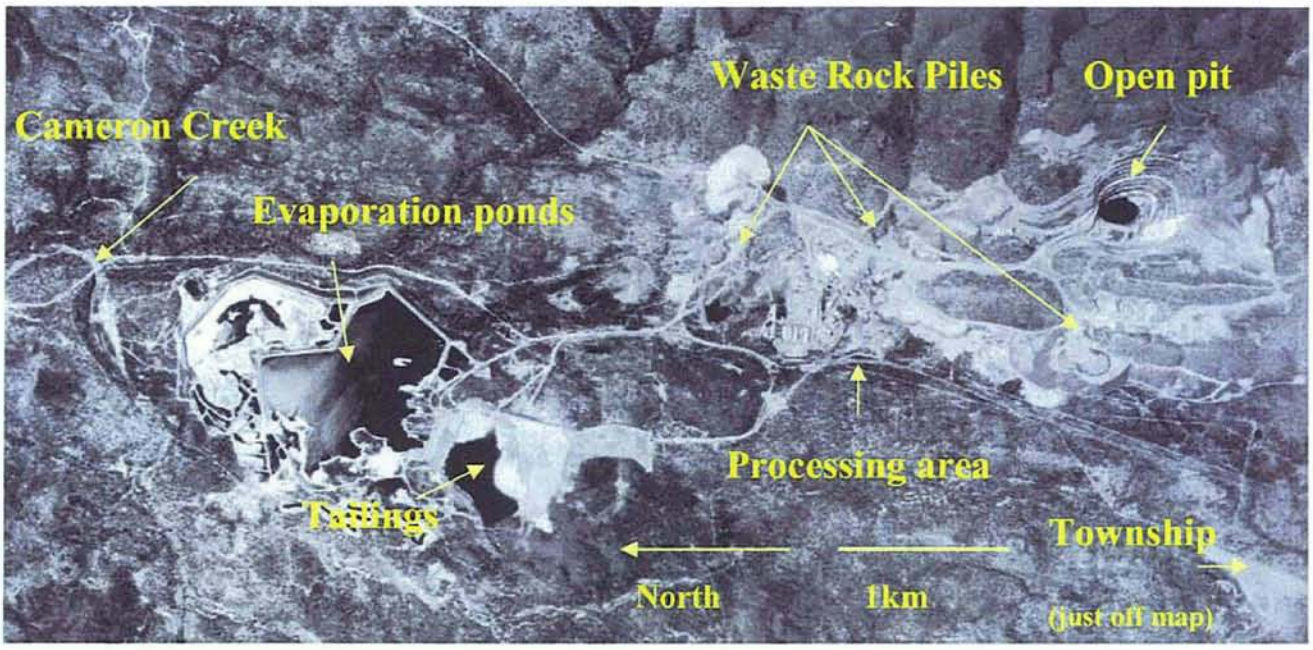


Figure 1.3. Cloncurry monthly rainfall average (mm) 1950-2000



The key landforms of the Mary Kathleen mine site (Figure 1.4) are the open pit, D stock pile, Goldings West and Crusher waste rock piles, the evaporation ponds and tailings dam areas, the township remnants and Cameron Creek.

Figure 1.4 Aerial photograph of the Mary Kathleen mine site (taken from Run 7, 198-228, 6856, photograph taken 1983. Department of Natural Resources.)

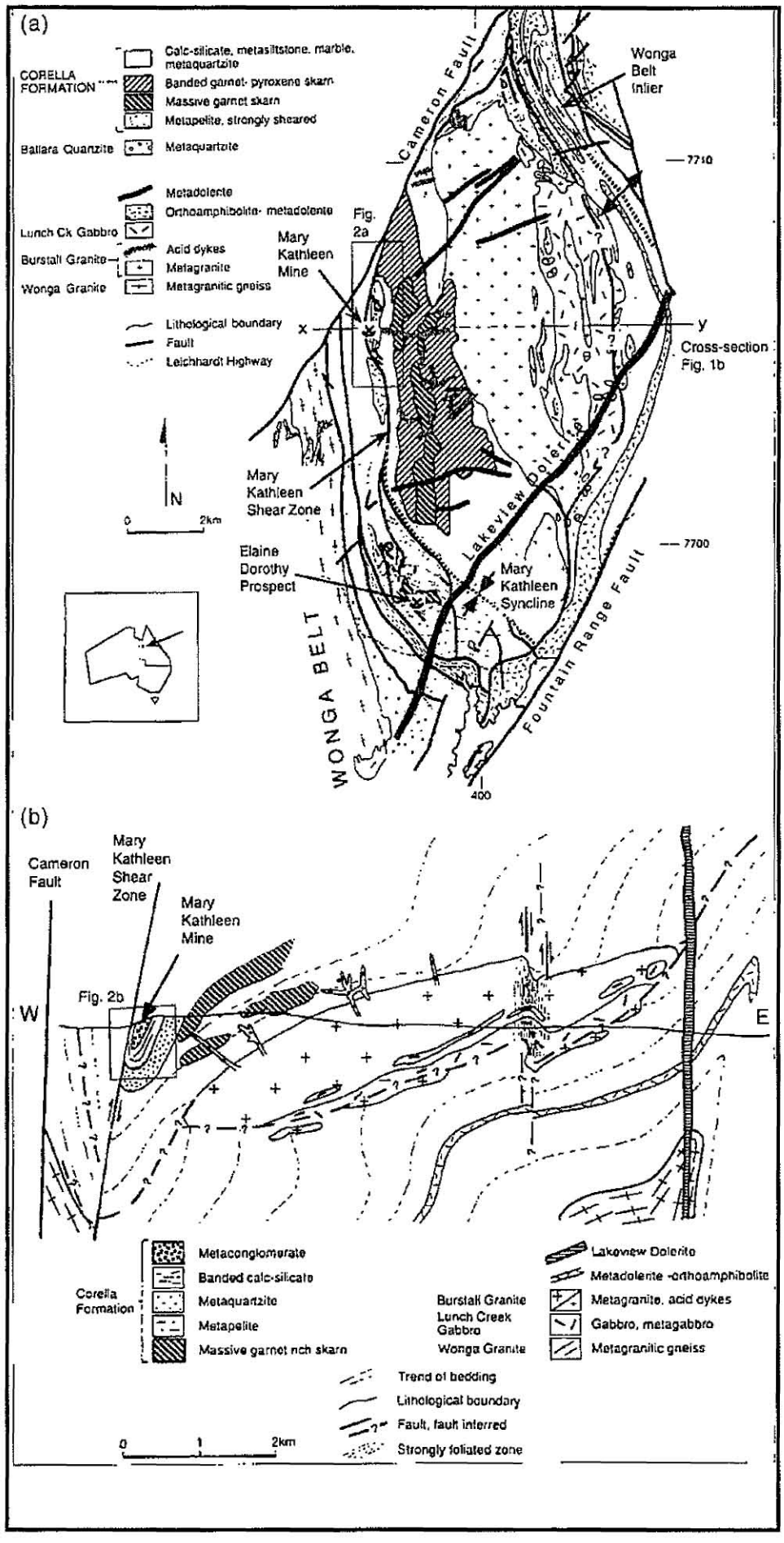


The Mary Kathleen mine site and sample map (Figure 1.4b) located in the back pocket of this thesis, is an A3 sized map detailing mine site landforms, topography and key sample locations.

1.2 Regional geology

Uranium and rare earth element (REE) mineralisation is hosted within the Mary Kathleen Group in the Proterozoic terrane of north-west Queensland (Hughes and Munro, 1965; Derrick, 1977; Oliver et al., 1999). The mineralisation occurs within the Mary Kathleen Fold Belt (Figure 1.5), which defines a belt of amphibolite facies rocks within the Mt Isa Inlier (Holcombe et al., 1992; Oliver et al., 1999). The Mary Kathleen Group is composed chiefly of the Corella Formation and the underlying Ballara Quartzite (Scott and Scott, 1985). At the mine site the Mary Kathleen Group unconformably overlies the Tewinga Group (Derrick, 1980). The uranium ore body has been described as a syn-metamorphic deposit (Dahlkamp, 1993; Plant et al., 1999) and is considered a type-area for structurally controlled fluid focusing during regional metamorphism (Oliver and Wall, 1987).

Figure 1.5 Geology of the Mary Kathleen Syncline. a) Map showing ore deposit along Mary Kathleen Shear Zone. b) Cross-section along X-Y (Oliver et al., 1999)

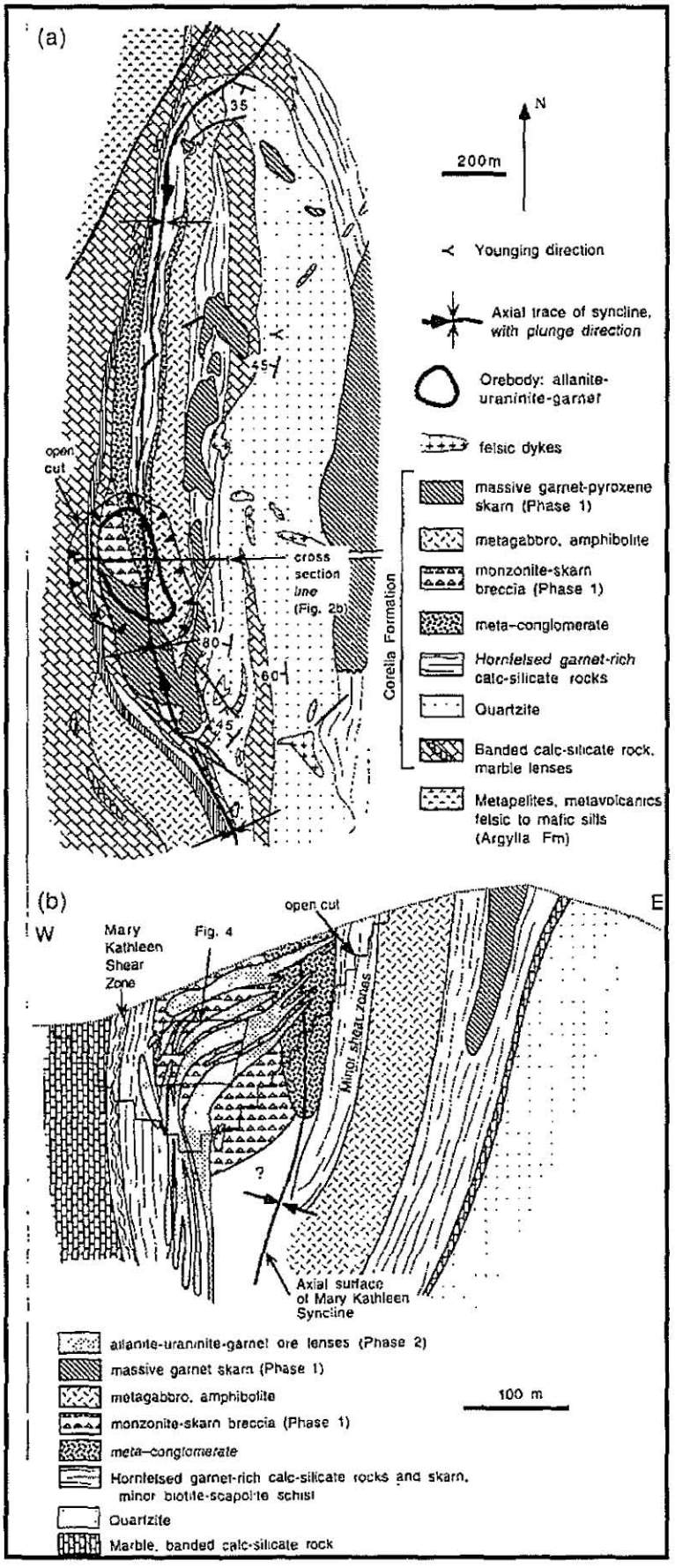


The skarn type U-Th-REE mineralisation is hosted by amphibolite grade metamorphosed calc-silicate, mafic to intermediate igneous and sedimentary rocks of the Corella Formation. The high grade mineralisation formed narrow, irregular patches and networks of generally west-dipping ore shoots (Hawkins, 1975; Oliver et al., 1999). Remnant ore zones are composed of medium to coarse grained garnet (andradite-grossular) and clinopyroxene (diopside), with accessory allanite, plagioclase, pyrrhotite, chalcopyrite and uraninite (Derrick, 1980). Later retrograde alteration to chlorite, calcite, sericite, epidote and scapolite occurs. Fine grained uraninite (0.01-0.1 mm across), enclosed in allanite, is partly replaced by metamict products and quartz, pyrite or galena (Derrick, 1980). The average sulphide content of the ore body was approximately 2%. The total REE concentration amounted to approximately 2.6% with light REE (LREE) lanthanum and cerium accounting for 85% of the total REE load (MKU, 1982).

Two major structural features (Figure 1.6) within the mineralised zone are the Mary Kathleen Syncline and the Mary Kathleen Shear Zone. Mary Kathleen Syncline (a D_2 structure) is a tight doubly plunging synform (Page and Bell, 1986; Connors and Page, 1995; Oliver et al., 1999). The ore body lies within the axial zone and western limb of the syncline. Ore shoots cut the Mary Kathleen Syncline (Oliver et al., 1999). The Mary Kathleen Shear zone is a curvilinear fault, which is subparallel to but locally truncates the axis of the Mary Kathleen Syncline (Battey et al., 1987; Oliver, 1995). The shear is up to 30 m wide, and weathering along it extends to a depth of about 150 m (Oliver, 1995). Ore shoots steepen towards the Shear Zone (Oliver et al., 1999). A lack of garnet and uranium mineralisation in the shear adjacent to the Mary Kathleen open cut suggests that the normal faulting postdates ore formation, and hence postdates intrusion of the Burstall Granite (Oliver, 1995).

The catchment area surrounding the mine and treatment plant is underlain by the Burstall Granite (Scott and Scott, 1985) and the Corella Formation which consists of schists, and calc-silicates as well as metamorphosed dolomites and lavas (Ward and Cox, 1986). Quartz-feldspar porphyry dykes transgress the Corella Formation at the east limb of the Mary Kathleen syncline (Scott and Scott, 1985).

Figure 1.6 *Detailed local geology map.* a) map showing localisation of ore deposit. b) cross-section along section marked on (a) showing the general distribution of ore shoots relative to the syncline axis and the Mary Kathleen Shear Zone. (Oliver et al., 1999)



1.4 Mary Kathleen mining history

The Mary Kathleen uranium deposit was discovered in 1954. Total average ore grade U_3O_8 at Mary Kathleen prior to mining was 0.116%. Rare earth element grades up to 7.6% were identified (Cruikshank et al., 1980). Phase one open cut mining started in 1956 and continued until 1963. The drop in U_3O_8 prices forced the mine into a care and maintenance period. Phase two mining commenced in 1976 and ceased in 1982. At that time 9.2 million tonnes total ore had been processed (MKU, 1982). The total material removed from the mine was about 31 million tonnes. Rare earth elements and thorium were not extracted. Total uranium production was 7532 t U (8882 t U_3O_8) (McKay and Miezitis, 2001).

The following is a summary taken from the MKU operation report 1982 (MKU 1982). The shallowness of the ore body allowed open cut mining of oxidised and sulphidic uranium ores. Selective mining and grade control were important factors at Mary Kathleen due to the nature of the ore lenses. Mining blast holes were radiometrically probed to determine ore-waste separation. Waste rock was deposited in neighbouring valleys and on the slopes of adjacent hills close to the mine. The total area occupied by the waste rock is approximately 64 hectares. Ore was transported to the discriminator. At the discriminator 10% of each truck's load was measured for radioactivity, and based on these results, each load was directed to either high grade, low grade or waste piles. Ore was then crushed. The beneficiation process then sorted crushed rock to 40mm and 150mm sized particles as well as ore grade and waste products. The ore refining process continued with fine crushing, grinding then leaching with sulphuric acid (95%). A liquid-solid separation circuit fed to a solvent extraction plant for purification. Locally mined pyrolusite was added to the mill feed to maintain the redox potential at about 450mV. Gaseous ammonia was added to the liquor achieving a final pH of 7.5 from which uranium was precipitated as ammonium diuranate. The concentrated precipitate was then dried in a furnace, crushed, cooled and fed into 200kg drums.

The 12 hectare tailings dam was contained in a small valley west of the plant. The total evaporation area of 80 hectares was divided into two areas for both solid wastes and for acidic liquid wastes.

Employees were accommodated in a self-contained town of approximately one thousand people, six kilometres from the mine. Other mine site facilities during the operation phase include a laboratory, workshops, stores, offices, electric power and water supply from Lake Corella.

1.5 Rehabilitation of the Mary Kathleen mine site

When operations at Mary Kathleen recommenced in 1976, the company undertook to operate in accordance with the 1975 Environmental Code and later with the Environment Protection (Nuclear Codes) Act 1978 (Ward and Cox, 1984). Towards the end of mining, the Department of Mines acted as the administering authority and discussed plans for decommissioning and rehabilitation with relevant state and federal government departments. The aim of rehabilitation was to leave the mine site and surrounds in a safe and satisfactory condition, consistent with future land use in the area, requiring no foreseeable on-going maintenance and minimal monitoring (Ward et al., 1983; Ward and Cox, 1984; MKU, 1986).

The methods used to rehabilitate Mary Kathleen are well documented in numerous published (Flannagan et al., 1983; Ward and Cox, 1985; Ward et al., 1983; UIC, 1998) and unpublished rehabilitation reports (e.g. MINENCO, 1986; MKU, 1982; MKU, 1986). The object of the rehabilitation phase was to: make all areas safe for public access; remove all structures which could deteriorate and become unsightly or unsafe with time; and encourage natural re-vegetation on erosion resistant surfaces (Ward and Cox, 1985). The principal site considerations included; climate, vegetation, water, soil, land use (cattle grazing), nearby population, social, economic and monitoring requirements.

During rehabilitation the main contaminants monitored were radon, radon daughters, direct radiation and radioactive contamination in the soil. Surface and subsurface water quality measurements (particularly in the tailings dam and Cameron Creek) focused on SO_4, Cl, Mn, total dissolved solids and pH, since there was no indication for the mobilisation of uranium and other elements from the tailings dam (Flanagan et al., 1983).

1.5.1 Rehabilitation techniques and studies

Open pit

Safety measures included smooth wall blasting and cable bolting on bench crests, wide catch-benches to hold falling rock and the blocking of access roads into the void. Gamma radiation in the pit area was considered safe in 1985 (Ward and Cox, 1985). Rainwater and some recovered groundwater containing salts from boreholes around the tailings/evaporation ponds area were stored in the open pit. It was expected that the pit water would deteriorate with respect to sulphate content and total dissolved solids over the long term (MINENCO, 1986).

Waste rock piles

The stability of the waste dumps was studied and predictions indicated a low chance of massive failure (Ward and Cox, 1984). The upper surfaces of the dumps were surveyed for gamma radiation and radon emanation. Areas exhibiting elevated levels were covered with 300 mm to 500 mm weathered waste rock and soil. The piles were contoured, ripped and seeded with local seeds with the view to establishing natural vegetation growth on the upper surfaces and controlling erosion on the slopes. Investigation into the leaching of dump materials by rainwater concluded that the heavy metal content of water draining from the dumps was very low and would fall over time and that the seepage waters would continue to be slightly alkaline (MINENCO, 1986).

Treatment plant and township area

The treatment plant was decontaminated using low and high pressure water jets, washing with acid solution, scrubbing and sandblasting (Ward and Cox, 1985). The product dryer and associated equipment, the dryer building, solvent extraction tanks and pipework, product thickeners, leaching section, tailings pipeline and general pipework were demolished and buried in the tailings dam. Contaminated surface soils were trucked to the tailings dam for burial. The treatment plant area was contoured and re-vegetated with local seeds (MKU, 1986). Buildings from the township were offered for sale and removed at an auction held in April 1983. It was not intended to remove all traces of the operation as this would deny future generations the opportunity to visit and identify the site of an important phase of Australia's mining history (Ward and Cox, 1985).

Tailings and evaporation ponds

The tailings disposal system was designed for total confinement of all effluents but seepage to the creek bed downstream from the pond wall was detected early in the mine's history. The dam was rehabilitated using a multi-barrier system (0.5 m layer of rolled soil/loam/clay; 1 m of waste rock; filter zone 2 m compacted waste material covered by large boulders at the toe of the dam) (Ward and Cox, 1985; MKU, 1986). The surface was contoured to slopes of 1:200 leading to spillways in the perimeter of the capped dam. Piezometers were installed on the tailings dam and their installation caused minor tailings spills. Natural vegetation was established on the rock cover.

Tailings seepage

At the base of the tailings dam wall, seepage flow was recorded at 67 m^3/day on the 26th May 1986 and was predicted to fall to less than 5 m^3/day by the year 2000 (MINENCO, 1986). Piezometers were installed and samples were tested for pH, total dissolved solids

(TDS), SO_4, Cl, CO_3, HCO_3 Na, Ca, Mg, K, Al, Mn, and Fe. In 1986, during final testing, SO_4 and Mn (SO_4 9030 mg/L, Mn 525 mg/L) were the only analytical parameters considered to have elevated levels (MINENCO, 1985). Closure reports, including the Mary Kathleen uranium mine rehabilitation water quality prediction studies final report (MINENCO, 1985), conclude that the movement of heavy metals and radionuclides from the tailings would be significantly retarded by hydrolysis effects, cation adsorption and co-precipitation reactions within the soil, and the high buffering capacity of the soils in the area. Also radionuclide or heavy metal contamination of surface waters in Cameron Creek would not occur in the short or long term from tailings seepage or surface water flows (MKU, 1986).

Cameron Creek

Pre-closure and closure reports on Cameron Creek concluded that there would not be any long term accumulation of salts in stream beds (MINENCO, 1985; MKU, 1986). The salts should be effectively flushed out of the drainage system during the normal surface flow (MKU 1986). Iron and manganese were not present in significant concentrations in the sediments (MKU 1986). In November 1985 a sample from piezometer EP8, recorded low SO_4 (4300 mg/L) and Cl (1009 mg/L) concentrations.

Rehabilitation of the site was completed in 1985 and the work won an award for environmental excellence from the Institution of Engineers Australia. At Mary Kathleen the current and long-term land use include cattle grazing and tourism.

1.6 Research objectives

1.6.1 Aims

The Mary Kathleen mine site was chosen as it provided an opportunity to study a rehabilitated uranium minesite, which has well documented scientific predictions and data sets for comparison.

The major aim of this project has been to investigate the current environmental status of the historic Mary Kathleen mine site including the open pit; D Stockpile, Crusher, Goldings West, West Tip, Southern Tip and North Waste Tip pile; evaporation ponds and tailings dams area; and Cameron Creek. This study will provide data for an integrated assessment and suggests appropriate environmental management responses.

Major objectives are:

1. Detecting and measuring the levels and causes of radiation in the open pit, on and near selected waste rock piles, on the tailings dam surface, at the tailings dam seepage point, and in Cameron Creek.

2. Determining characteristics of contamination from existing waste repositories such as waste rock piles and the tailings dam.

3. Investigating the dispersal of contaminants into the local soils as well as Cameron Creek sediments and waters.

Minor objectives are:

1. Biogeochemical characterisation of vegetation species providing limited information on the bioavailability of uranium at the mine site.

2. Defining significant problems, which may warrant future attention and additional rehabilitation or the planning of long-term remediation strategies.

1.6.2 Sampling and methods

Appendix 1 describes detailed sampling and methods of analysis. For convenience, a brief description is given here. Field surveying and sampling of the Mary Kathleen mine site was conducted in July 1998 and August and October 1999 (dry season). Prior sampling by Drs Lottermoser and Ashley at Mary Kathleen in June 1999 of 145 samples covering all media types and radiometric data of the open pit and 7 other traverses were supplied to the candidate (listed in Appendix 4). Gamma-ray data as well as stream sediment, soil, wall rock, waste rock, mineral efflorescence, iron rich precipitates, tailings, vegetation and water samples were collected (Appendix 2). GPS positions were recorded for all samples except for those taken within the open pit. Open pit samples were located by using a base map, as GPS recordings were erroneous within the pit.

A portable GR-320 Spectrometer and a Scintrex BGS-1SL scintillometer were used for radiometric surveys (Appendix 3). Environmental data (μR/hr, nSv/hr) and geophysical data (concentrations in equivalent %K and equivalent ppm of U and Th) were recorded as point readings (60 seconds) and traverses (approximately 0.16 m/s and a height of 1m over dry ground).

Pulverised soil, stream sediment, tailings, waste rock, mineral efflorescence and pit wall samples were submitted to Australian Laboratory Services (ALS) Townsville for chemical analysis (Appendix 4). Mineral constituents in selected mineral efflorescences, soils and tailings were identified by X-ray diffraction. Water samples were analysed by the Australian Centre for Tropical Freshwater Research for major ionic composition and trace metals (Appendix 5). Water temperature, pH, salinity, dissolved oxygen and conductivity were measured in the field. Vegetation samples were identified (by the Queensland Herbarium), then ashed and submitted for chemical analysis (Appendix 6).

Quality control procedures required all samples to be labelled, logged, stored in separate paper or cloth bags and covered in plastic to prevent cross contamination. All samples were re-homogenised prior to sub-sampling for analysis. Duplicate samples, quartz blanks and the geochemical reference material GXR-2 were submitted to ALS Townsville for quality control (Appendix 4). Deviations from GXR-2 for the listed elements are <5% for all components. All remaining, non-hazardous samples have been archived at JCU (Appendix 7). For personal safety a thermoluminescent dosemeter was worn at all times.

1.6.3 Study constraints

It was the intent of this investigation to gain an overview of the rehabilitated mine site to gain data on potential problems so later research or detailed monitoring could be put into place.

This data set presents a robust and thorough dataset for the assessment of the environment at Mary Kathleen however it is not exhaustive. Time restrictions, field access and budget constraints limited the number of samples that could be processed and analysed.

Sampling was not conducted during the wet season due to access problems, limiting the evaluation potential of seasonal fluctuations in contamination and dispersal at this site.

The behaviour of radionuclides has not been studied, as such investigations were conducted by Dr Bernd Lottermoser.

At radiometric survey points where uranium concentrations exceeded 150 ppm, accurate readings could not be recorded as GR-320 spectrometer specifications did not allow such analysis. Therefore, some geophysical measurements (equivalent %K, ppm U, ppm Th) are missing on traverses of high radioactivity.

1.6.4 Relevant guidelines

Environmental guidelines aim to protect ecosystems and humans through the management of goals that focus on concerns or potential problems within given areas. Water, soil and radiation limits are the tools that are used to evaluate this mine site. These limits are contained within the regulatory guidelines listed in Table 1.1 and current limits pertinent to this study are listed in Appendix 8.

Table 1.1. Summary of guidelines used in this thesis.

Sample Medium	Guidelines
Water	Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000) National Health and Medical Research Council & Agricultural and Resource Management Council of Australia and New Zealand Australian drinking water guidelines (NH&MRC 1995)
Radiation	United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000) National Health and Medical Research Council. Recommendations for limiting exposure to ionizing radiation and national standard for limiting occupational exposure to ionizing radiation. (NH&MRC 1995)
Soil	Australian and New Zealand Guidelines for the Assessment and Management of Contaminated Sites (ANZECC 1999)
Sediment	Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000)

1.7 Definitions

Acid Mine Drainage

A process generating low pH (<6) drainage waters derived from materials with an insufficient capacity to neutralise the acidic products of sulfide oxidation reactions (e.g. pyrite (FeS_2) and pyrrhotite (FeS)) (Plumlee, 1999).

Indirect oxidation of pyrite may be considered to take place in three major steps: (1) oxidation of pyrite to generate ferrous iron; (2) oxidation of ferrous iron to ferric iron; and (3) oxidation of pyrite by ferric iron (Jambor and Blowes, 1994; Alpers and Blowes, 1994; Morin and Hutt, 1997; Jambor and Blowes, 1998; Nordstrom and Alpers, 1999). As the pH of the seepage drops, the reactions become catalysed by bacteria (*Thiobacillus ferrooxidans*) and metal dissolution increases (Morin and Hutt, 1997; Nordstrom, 1977, 1982; Nordstrom et al., 1979).

Attenuation

A loss of intensity suffered by sound, radiation, etc., as it passes through a medium. It may be caused by absorption or scattering (Isaac et al., 1999).

Background radiation

The radiation from cosmic sources as well as naturally occurring radioactive materials, and global fallout as it exists in the environment from the testing of nuclear explosive devices according to the U.S. Nuclear Regulatory Commission. The global average for the individual dose of radiation from natural sources has been estimated to be 2.4 mSv per year (UNSCEAR, 2000).

Contamination

Undesirable substances present in the environment, but not causing noticable harm (Alloway and Ayres, 1997). The main sources of contamination in the study site are: the open pit, mine waters, tailing ponds, ore storage piles, low-grade ore piles, waste rock piles and processing areas.

Decontamination

The reduction or removal of contaminating material from a structure, area, object, or person. Decontamination may be accomplished by treating the surface to remove or decrease the contamination, or covering the contamination to shield or attenuate any radiation emitted (Isaac et al., 1999).

Hardness-modified trigger value (HMTV)

The Hardness-modified trigger value (HMTV) (ug/L) is calculated for Cu, Pb, Ni and Zn (Appendix 4) by using the hardness- dependent algorithms given

Copper $HMTV = TV\ (H/30)^{0.85}$ Lead $HMTV = TV\ (H/30)^{1.27}$

Nickel $HMTV = TV\ (H/30)^{0.85}$ Zinc $HMTV = TV\ (H/30)^{0.85}$

Where TV is the trigger value (ug/L) at a hardness of 30 mg/L as $CaCO_3$

H is measured hardness (mg/L as $CaCO_3$) of a fresh surface water (<2.5 $^{o}/_{oo}$).

The guideline trigger values represent the best current estimates of the concentrations of chemicals that should have no significant adverse effects on the aquatic system and give water managers a system to assess water quality at a particular site. (ANZECC 2000)*Iron rich precipitate*

The term is used to describe the red sludge produced from the tailings seepage solution. It consists mainly of amorphous Fe-oxyhydroxides.

Mineral efflorescence

Efflorescent salts are highly soluble, hydrated, heavy-metal sulphate compounds that have been shown to be very important for storing heavy metals and acid during dry periods in acid mine drainage settings. During seasonal rain these salts dissolve and release heavy metal and acid to the environment. Mineral efflorescences accumulate under oxidising conditions and high evaporation rates at exposed surfaces, they include melanterite ($FeSO_4.7H_2O$) and chalcanthite ($Cu(SO_4)\cdot 5(H_2O)$) (Clugston, 1998).

Piper diagram

Piper diagrams can be used to show the chemical character of water. Selected cations (positively charged ions; calcium, magnesium, and sodium plus potassium) and anions (negatively charged ions; bicarbonate plus carbonate, sulphate, and chloride) for each analysis are shown as a percentage of the total cations and anions. A water type can be described depending on the location of the projected point in the central diamond. The Piper type of diagram can be used to determine whether particular water is (1) chemically similar to some other water, or (2) a simple mixture of two chemically different water types (Helsel and Hirsch, 1992). The freeware GW_Chart (Version 1.1.2) program, was used to generate the Piper diagrams in this thesis.

Pollution

The introduction by humans into the environment, substances that are liable to cause a hazard to human health, living resources, the surrounding ecological systems or limits the legitimate use of the environment (Holdgate, 1979; Alloway and Ayres, 1997).

Radionuclide (or Radioisotope)

An unstable nuclide or isotope of an element that decays or disintegrates spontaneously, emitting radiation (Isaac et al., 1999).

Rare Earth Elements

Elements of atomic number between 57 to 71 are known as the rare earth elements (REE). Light Rare Earth Elements (LREE) include the elements lanthanum to europium. Cerium and lanthanum (La) are found in a number of minerals including allanite, monazite, and bastnasite (Alloway and Ayres, 1997).

Total dose

Measured in sieverts (millisieverts - mSv, microsieverts - μSv, nanosieverts - nSv). The rate of dose is generally reported as milli sieverts per year (Table 1. 2) (UIC, 2000).

Table 1.2. Comparative radiation doses (UIC, 2000)

Dose (mSv/yr)	Comment
2	**Typical background radiation to Australian public.**
3	Typical background radiation to North American public.
2.9	Average occupational dose to US nuclear industry employees.
5.0	Average occupational dose to Australian uranium miners.
1.5	Average incremental dose for aircrew.
10	Maximum actual dose to Australian uranium miners.
20	Current limit for nuclear industry employees (5 year average).
50	Former limit for nuclear industry employees and U miners
50	Current maximum limit in a single year.
350	in lifetime Criterion for relocating people after Chernobyl accident.
1000	as short term dose: would probably cause (temporary) radiation sickness.
5000	short term dose: would kill about half those receiving it within a month.
10,000	as short term dose: fatal within days or weeks.

Total alkalinity

Measured in milligrams per litre as calcium carbonate (mg/L $CaCO_3$) it is the measure of the capacity of water to accept H^+ ions (protons). The species primarily responsible for alkalinity in water are bicarbonate ion (HCO^{3-}), carbonate ion (CO_3^{2-}) and hydroxide ion (OH^-). It is important to distinguish between high basicity, i.e. an elevated pH, and high alkalinity, i.e. the capacity to accept H^+. Alkalinity measures the quantity of weak acids and the cations balanced against these weak acids in a sample of water (Manahan, 1994).

Total hardness

Measured in milligrams per litre as calcium carbonate (mg/L $CaCO_3$). Calcium carbonate is a general term that indicates the total quantity of divalent salts present in water (however, does not specifically identify whether calcium, magnesium and/or some other divalent salt is causing water hardness).

The decomposition of hydrogen carbonate (bicarbonate) salts, can be explained in the following equation (depositing precipitate of calcium carbonate) (Clugston, 1998).

$Ca(HCO_3)_2(aq) \rightarrow CaCO_3(s) + H_2O(l) + CO_2(g)$.

Uranium

Uranium is a radioactive element (atomic number 92). Three isotopes of uranium exist (Figure 1.3) with an average natural composition of 0.0057% U-234, 0.719% U-235 and 99.275% U-238 (Rosler and Lange, 1972). The average crustal abundance of uranium is 2-3 ppm (Plant et al., 1985). Uranium is known to have several oxidation states; U(III), U(IV), U(V), and U(VI). In aqueous fluids U(III) and U(IV) exist as the aqua ions U^{3+} and U^{4+} whereas U(VI) forms the oxyanion UO_2^{2+} (uranyl ion). The predominant species in weathering systems and hydrothermal solutions are the U(IV) and U(VI) species (Langmuir, 1997; Grenthe et al., 1995).

Table 1.3. Uranium-238 decay chain (Burns and Finch, 1999).

URANIUM DECAY CHAIN -- Main Branch Read from left to right. Arrows indicate decay.		
Uranium-238 ==> (*half-life: 4.468 billion years) alpha decay	Thorium-234 ==> (half-life: 24.1 days) beta decay	Protactinium-234 ==> (half-life: 1.17 minutes) beta decay
Uranium-234 ==> (half-life: 246,000 years) alpha decay	Thorium-230 ==> (half-life: 75,400 years) alpha decay	Radium-226 ==> (half-life: 1,600 years) alpha decay
Radon-222 ==> (half-life: 3.82 days) alpha decay	Polonium-218 ==> (half-life: 3.11 minutes) alpha decay	Lead-214 ==> (half-life: 26.8 minutes) beta decay
Bismuth-214 ==> (half-life: 19.9 minutes) beta decay	Polonium-214 ==> (half-life: 163 microseconds) alpha decay	Lead-210 ==> (half-life: 22.3 years) beta decay
Bismuth-210 ==> (half-life: 5.01 days) beta decay	Polonium-210 ==> (half-life: 138 days) alpha decay	Lead-206 (stable)

* The half-life is the time taken for half the original, parent isotopes to decay.

Uranium mill tailings

Radioactive residue from the crushing and leaching of uranium ore. Tailings are commonly pumped into a waste repository known as a tailings dam. This residue contains several radioactive elements including uranium-238, thorium-230, radium-226 and lead-210 (Alloway and Ayres, 1997).

For the description of the tailings mineralogy, the classification proposed by Jambor (1994) is used. The term "primary" is used to describe ore mineralogy. Secondary minerals are minerals formed within the tailings impoundment as the products of chemical and physical processes.