1. PREPARATION OF AN ENVIRONMENTAL IMPACT STATEMENT

1.1 Introduction and Background Information

In recent years, the public awareness of environmental issues has escalated rapidly to such an extent that legislation in many countries is now being adapted to reflect this concern. In particular, considerable attention is being paid to the consequences of developments, especially where these are perceived to negatively impact ecological and social issues.

In this context, the negative response of most people to issues relating to radio-activity and atomic energy require particularly careful handling. The irrational fear of these issues shown by many ill-informed people has had, and will undoubtedly continue to have, a considerable impact on the public's perception of all facets of nuclear energy.

In the past, negative public perceptions have adversely affected the mining and use of uranium and other radio-active materials. Uranium mining operations in Australia, Canada and the United States of America have been the focus of considerable public debate in the past. Mines are now required to operate according to strict codes of conduct so as to minimize environmental impacts and allay public fears surrounding radio-activity.

1.2 The Need for an Assessment of Environmental Impacts

Currently, a detailed Environmental Impact Assessment (EIA) is still not a legal pre-requisite for development in South Africa or Namibia (Fuggle, 1979). However, it is probable that legislation in many southern African countries will soon be adapted to incorporate escalating public concern for the environment. The statutory changes will probably include a requirement to assess the environmental impacts of each proposed development before permission is granted for the development to proceed. The incorporation of appropriate remedial or ameliorative measures, and the initiation of long-term monitoring to assess the efficacy of these actions, are an integral part of this process. It is therefore appropriate that Rössing Uranium anticipate these developments and draw up a detailed and comprehensive assessment of the environmental impacts that have already occurred as well as those that are likely to occur in future.

1.3 The Level of Investigation Required

In common with many mines that started operations before formal assessment of environmental impacts became customary, the Rössing Uranium Mine does not have an established baseline describing the conditions that prevailed prior to start-up. It is therefore necessary to establish such a baseline from current conditions and interpolation from adjacent and similar, but undisturbed, areas. This will then serve as a reference document against which the impacts of both current operations and future developments, as well as the effectiveness of environmental protection and reclamation measures, can be assessed (Robertson & McPhail, 1989).

When uranium mining started at Rössing, due care and attention was taken to ensure that all mining operations were conducted in a manner that minimized the influences of radio-activity on both the human and other environmental components. In addition, detailed studies were initiated to monitor changes in dust levels, ground-water flows and ambient levels of radio- activity. These studies will therefore form the nucleus of any assessment of environmental impacts.

Studies conducted at the Ranger uranium mining operations in the Alligator Rivers Region of Australia (A.R.R.R.I., 1987) provide a useful basis for comparison with Rössing. At the Ranger Uranium Mine, the dominant environmental risks both in the short- and long-term were those associated with the dispersion of mine-derived material into the environment. Similar environmental risks will also attend the mining operations conducted at Rössing Uranium, despite the great dissimilarity in climatic conditions.

The Ranger studies (A.R.R.R.I., 1987) concluded that sufficient information must be obtained to ensure that potential environmental impacts can be controlled and limited to some specified and acceptable level. However, even a basic assessment of the environmental consequences of uranium mining operations and the development of appropriate measures for their control, requires scientific and technical information from a wide variety of sources. This is particularly true of mining operations conducted in complex ecological regions, such as the tropical monsoon and dry desert regions where the Ranger and Rössing Uranium mines are located, respectively.

In the case of the Ranger operation, the scope of the study was geared to satisfy the legal requirement ".. that the environment does not undergo significant short- or long-term changes as a result of the project" (A.R.R.R.I., 1987). Most environmental regulations require mining companies to conduct their operations, not on the basis of zero environmental damage, but rather with the minimum environmental degradation and pollution that can reasonably be achieved, with due regard to a number of factors including cost and practicability.

This report presents a compilation of all the relevant environmental information relating to the Rössing Uranium Mine and details the environmental impacts that have so far been recorded, as well as those that are likely to occur with future developments. The report is based substantially on information received from mine personnel, as well as data and information obtained from the published literature and discussions with scientists in South Africa and Namibia. Undoubtedly, there will be considerable changes in both predictive technology and mining developments at Rössing during the remainder of the mine's life. Thus it is anticipated that there will be a continual need for revision of impact predictions and assessment of alternative decommissioning approaches.

2. A PRE-MINING BASELINE

2.1 Location and Topography

The geographical location of the Rössing Uranium Mine is 15° 2' 30" East longitude and 22° 27' 50" South latitude, near the inland edge of the central Namib Desert and close to the Khan River. This is approximately 60 kilometres east-north-east of the town of Swakopmund which is located on the Atlantic coast of Namibia (Figure 2.1).

The mining grants and accessory works cover an area of approximately 123 km^2, 91 % of which is on the north bank of the Khan River. The mine area has a mean altitude of 575 m above sea level, and the area to the west, north and north-east of the mine property is characterized by broad peneplains with low relief. These are traversed by shallow south to south- west trending drainage lines and storm-wash gullies, which drain towards the Khan River, and are interspersed with ridges of resistant rock and isolated inselbergs. The terrain rapidly becomes more hilly and rugged the closer one approaches the Khan River and the drainage lines coalesce and deepen to form gorges. Four of these gorges - Khan Gorge to the west, followed by Panner, Pinnacle and Dome Gorges to the east, traverse the mine property and discharge into the Khan River. Additional gorges drain into the Khan River before it discharges into the Swakop River approximately 15 km to the south-west of the mine property (Figure 2.1).

The relatively hilly mine site is divided into two sections by a steep- sided north-easterly trending ridge of hills between Pinnacle and Dome Gorges, rising to an altitude of 707 m at Westdome Hill. The areas north and west of this ridge consist of rolling hills with an average altitude of 600 m whilst the area to the east of the ridge is more rugged, with jagged- crested, steep-sided hills ranging in elevation from 550 to 600 m.

The south bank of the Khan River is demarcated by a range of north-east trending, steep-sided hills. Further south, these hills give way abruptly to the almost flat gravel plains of the Welwitschia Flats. This area covers virtually the entire area between the Khan and Swakop Rivers and lies within the Namib-Naukluft Park.

2.2 Climate

Diurnal, seasonal and long-term variations of climatic conditions interact to regulate the occurrence and distribution of organisms in an area and determine the diffusion and transport of atmospheric properties and pollutants. An understanding of climatic features and their variability is therefore essential for any evaluation of environmental impacts caused by mine-related activities and the development of pollution control measures.

Detailed meteorological data is collected by Rössing Uranium staff from weather stations located at three sites, namely: Arandis airport, Point Bill and the visitors lookout point at the open pit. All the data is stored on the mine's environmental data base. Since mining operations at Rössing are unlikely to have had a major effect on the climate, it is appropriate that the current climatic data be used to describe features of the regional climate. A generalized climatogram for the Rössing Uranium Mine is shown in Figure 2.2.

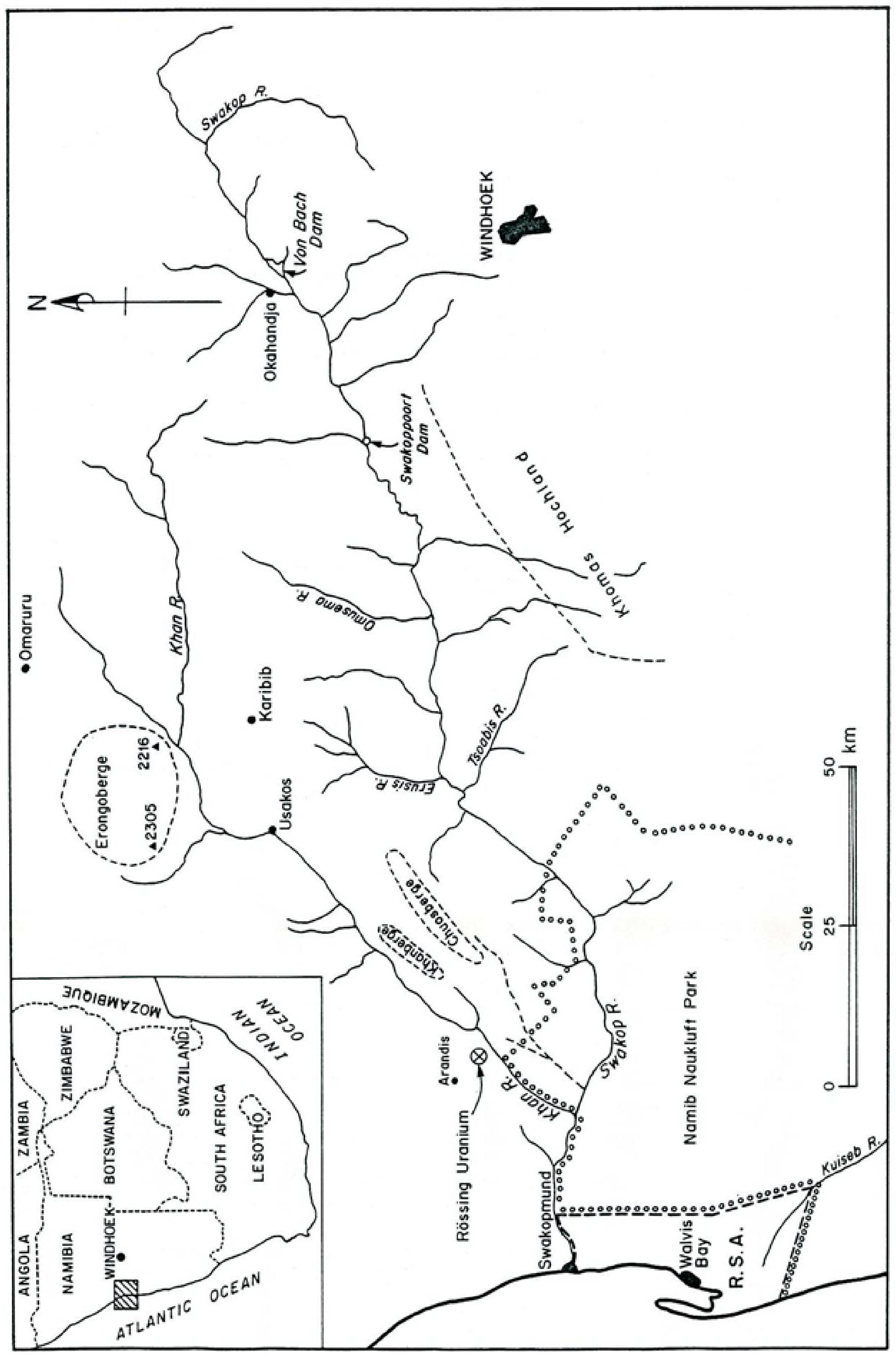


Figure 2.1: Diagrammatic map showing the position of the Rössing Uranium Mine in relation to the Khan and Swakop rivers, major towns and local mountain formations. Inset shows the location of this area within Namibia and southern Africa.

2.2.1 Winds

Winds are a very important component of any desert environment, though their effects are modified by a variety of local geographical features (Goudie, 1972; Huntley, 1985). Site characteristics such as latitude, altitude, location within a land mass, slope of ground, soil type, the nature and degree of vegetation cover, and proximity to areas of different geographical properties determine the meteorological conditions at a given location in response to the large scale meteorological conditions to which that location is exposed. This local response results in turbulent fluctuations of air motions.

Three meso-scale thermotopographic wind systems characterize the Rössing environment. Each of these has been described in detail elsewhere (Earth Science Services, 1987) and will thus only be briefly discussed here. The three main systems are:

i) A sea breeze/land breeze system induced by the interface between the cold sea and warm desert;
ii) A mountain - valley wind system induced by the Khan and other rivers which drain from the escarpment towards the coast; and
iii) A mountain - plain system induced by the existence of the desert and plateau surfaces, separated by the escarpment.

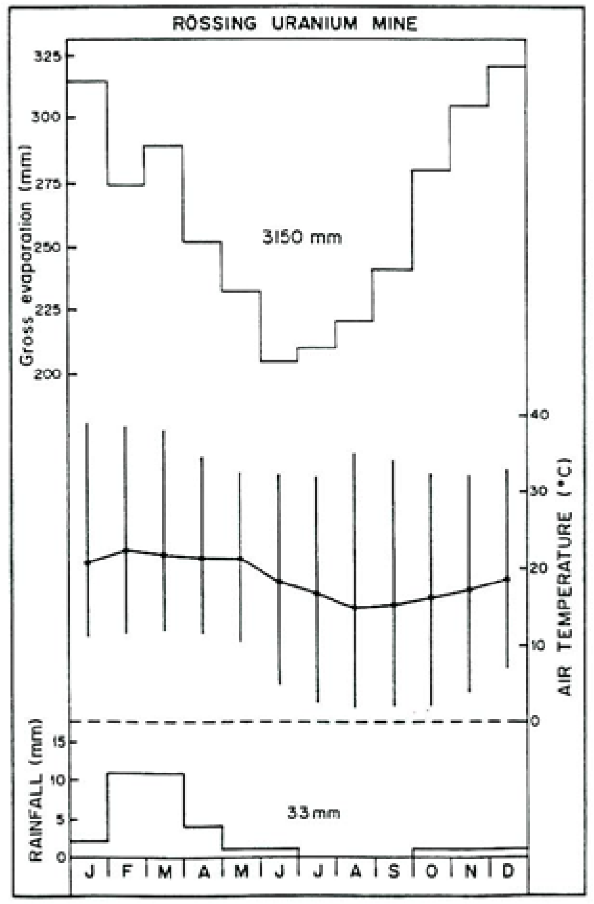


Figure 2.2: Generalized climatogram for the Rössing Uranium Mine, showing monthly variations in rainfall, gross evaporation and minimum, mean and maximum air temperatures. (Data derived from Earth Science Services (1987) and Hydrology Division (1988)).

The distinguishing features of these local winds are the strength of the near-surface circulation and the interactions between winds of the interior desert with the sea breeze regime and with regional winds. When synoptic pressure gradients are strong, local and regional winds may be obliterated by continental circulation systems. However, this happens on surprisingly few occasions each month. Local effects are dominant and frequently modify the near-surface winds of the general circulation pattern. The strength of these local winds is sufficient to mobilize fine sand and mica particles from the ground surface and this gives rise to the dusty conditions that are frequently recorded at Rössing.

Although they are not part of the thermotopographic wind family, berg winds are the only other wind system that is of importance at Rössing. These are formed when air displaced from the plateau to the coast becomes heated adiabatically due to a drop in altitude. Berg winds occur approximately 50 times per year, mainly from April to September, and give rise to the curious anomaly that the coastal areas frequently experience their highest temperatures during the winter months. They can prevail from a few hours to a few days depending on the synoptic pressure gradients. During berg winds, the air is normally unstable with monthly average wind velocities of 27 km hr^{-1} and average hourly velocities of 43 km hr^{-1} recorded. Peak velocities can exceed 125 km hr^{-1} (W. Jooste, personal communication). The strength of these winds allows them to carry great quantities of dust, sand and fine gravel; they are therefore a very important mechanism in wind erosion and the development of the dust storms so characteristic of the Namib Desert.

Normally, two macro-scale systems are associated with the berg winds, namely: 1) a strongly developed high pressure cell over the eastern parts of southern Africa, and 2) a coastal low along the west coast of Namibia. This synoptic arrangement induces north-east to easterly flows from the western escarpment to the coastal areas and will prevail until the high pressure cell moves eastwards or weakens. As the pressure gradient weakens, the low pressure cell moves southwards causing the wind direction to change from north-east to north-west with a dramatic decrease in temperature.

At Rössing the southwest - northeast trending Khan River valley exhibits a diurnal variation that is as striking as, but different from, that pertaining at the coast. Instead of being controlled primarily from by the land-sea interface, the dominant control is the variation of thermal regimes in the Khan valley. In addition, the flat stony desert to the north, the plateau to the south, the escarpment and the cold sea to the west all act to modify the valley effect. Despite these complicating factors, the diurnal cycle of winds experienced at Rössing is simple, particularly in winter.

As is to be expected with winds exhibiting a strong thermotopographically- induced component, an inverse correlation exists between monthly frequencies of occurrence of north-westerlies and east-north-easterlies. East-north-easterlies are an autumn phenomenon with a maximum occurrence during May - July and decreasing to near zero between October and February. In contrast, the north-westerlies occur throughout the year but are most marked during the summer months of January and February. The wind showing the least month-to-month variation in occurrence is the late afternoon south-westerly sea breeze.

The seasonal variation in the diurnal cycle of winds at Rössing has been reported in detail (Earth Science Services, 1987) and is summarized here. During the winter months (April to September), a cool down-valley wind sets in after midnight and prevails until 10h00 to 12h00. The period between 11h00 and 14h00 is a transition period, during which general winds are strong and unmodified by local conditions. By 14h00 the local thermal and pressure gradients have reversed and a south-westerly up-valley wind prevails. From 15h00 onwards to 18h00-19h00, the wind speed increases under the influence of the sea breeze. By 19h00 the sea breeze influence dissipates, with another transition period between 22h00 and 24h00, after which the cycle is repeated.

During the summer months (October to March), those parts of the cycle which are dependent on the cool air drainage are absent and the parts dependent on the heating process are more pronounced. Down-valley north-easterlies are weak whilst the thermal north-westerlies prevail during the day from 08h00 to 14h00. These are interrupted by the inland penetration of afternoon sea breezes until approximately 20h00 when they are replaced by north-north-westerly winds. These are relatively weak during the night but strengthen during the day and veer to become north-westerly.

The wind systems recorded at Rössing are somewhat different to the conditions reported from the Namib Desert Ecological Research Station at Gobabeb, some 100 kilometres south-southwest of Rössing (Goudie, 1972; Harmse, 1982; Ward & von Brunn, 1985). At Gobabeb, the winds are dominated by a bi-modal system comprising south-southwesterly to southwesterly and north to north-westerly winds during summer. Both of these winds decrease in frequency and intensity during winter when high-velocity, low-frequency easterly berg winds are experienced.

2.2.2 Precipitation

2.2.2.1 *Rainfall*

In Namibia, mean annual rainfall decreases from east to west and from north to south. In the central Namib Desert, rainfall is low and its distribution is highly erratic; the long-term average for the entire region is less than 100 mm, with much of the area receiving less than 50 mm per year. In addition, the reliability of rainfall varies greatly and variability increases sharply to the west (Logan, 1960; Tyson, 1978).

This pattern of decreasing rainfall from east to west is clearly shown in the catchment of the Khan River, where annual rainfall varies from 400 mm in the head-waters to 200 mm at Usakos and 35 mm at the Khan Mine (Hydrology Division, 1988). Rainfall measurements at the Rössing Uranium Mine indicate that the mine receives on average some 30-35 mm per year (Figure 2.2). Much of this rainfall occurs as late summer and autumn showers or thunderstorms of high intensity and short duration. Virtually no rainfall is recorded during the winter months, though occasional falls of up to 1 mm per month have been recorded (Richardson & Midgeley, 1979; Brown & Gubb, 1986; Craven, 1986; Earth Science Services, 1987; SWA DWA, 1987).

2.2.2.2 *Fog*

Fog is a highly significant source of water for the coastal vegetation of the Namib Desert but the quantity of water derived from fog is difficult to measure (Louw & Seely, 1982). Brown & Gubb (1986) report that fog precipitation amounts to approximately 35-45 mm yr^{-1} at the coast (three times the annual rainfall) and decreases to about 20 mm yr^{-1} some 40 km inland, on the open gravel plains. However, very much higher quantities of fog precipitation have been measured along the Kuiseb River to the south (up to 184 mm yr^{-1} at Swartbank; Ward & von Brunn, 1985).

Robinson (1976) noted that fog is probably an effective source of moisture for plants up to approximately 35 km inland from the coast. However, the distribution of some well-known "fog-dependent" plants such as *Arthraeura leubnitziae* corresponds largely to that of the fog zone. Since this species is represented by a few scattered individuals confined to a few of the west-facing ridges at Rössing (Craven, 1986), fogs would appear to account for an insignificant component of the total precipitation at Rössing.

2.2.3 Evaporation

Evaporation rates are very high over most of the central Namib Desert and any moisture that does not soak into the soil very soon after falling will be lost. Daily "A" pan evaporation rates measured near Rössing range from 6 to 15 mm per day, whilst monthly evaporation rates reach a maximum in mid-summer (December) with a minimum in mid-winter (June). Gross annual potential evaporation at Rössing amounts to 3150 mm, whilst nett evaporation (after subtraction of rainfall and conversion to an open water surface) amounts to 2170 mm (Hydrology Division, 1988; Figure 2.2).

2.2.4 Temperature

Air temperatures at Rössing vary greatly on a day-to-day basis though seasonal variations are less marked. Mean diurnal temperatures range from 23.8 °C in late Autumn (May) to 15.4 °C in Spring (October), an annual range of 8.4 degrees. This is very similar to the 9 degree range reported for both Gobabeb and Swakopmund (Goudie, 1972). Minimum temperatures are recorded in the early morning and range from 2.0 °C in August to 12 °C in March (Earth Science Services, 1987; Figure 2.2). In contrast, the range of maximum diurnal temperatures shows very little month-to-month variation, ranging from 31.8 °C in July to 39 °C in January, due to the occurrence of hot Berg winds during the winter months. On very hot days, air temperatures measured in the Khan River gorge near Rössing may reach 44 °C, some 5 degrees higher than those measured at the mine (P.J. Ashton, unpublished data). Monthly temperature ranges vary from 28 degrees in summer to 32.9 degrees in winter (Earth Science Services, 1987; Figure 2.2).

Whenever air temperatures are high, soil and rock temperatures reach even higher levels, particularly if they are dark coloured. For example, Goudie (1972), Robinson (1976) and Craven (1986) recorded temperatures up to 60 °C, and even 70.5 °C on a few occasions, at the soil surface on the gravel plains of the central Namib Desert, where air temperatures are similar to those measured at Rössing.

2.2.5 Humidity

Atmospheric humidity levels at Rössing are very variable on both an hour- to-hour and day-to-day basis (Earth Science Services, 1987). The lowest values (5 to 8 %) are recorded during midday whilst the highest values (up to 84 %) are usually recorded during the early morning. Humidity levels rise rapidly immediately after one of the infrequent rainfalls and the afternoon sea breezes also contain appreciable humidity levels. However, these high humidity levels are usually of short duration and the diurnal average humidity level is usually below 15 %.

2.2.6 Insolation

As could be expected, insolation levels at Rössing are very high and cloudy or overcast periods have a very short duration (Earth Science Services, 1987). The presence of early morning fogs, which can extend to Rössing from the coast during the winter months, leads to a slight reduction in the effective daylength on approximately 50 days per year. However, these fog patches are relatively thin and have dissipated completely by mid-morning. Maximum insolation levels show a distinct cycle, varying from 1051 W m^{-2} in summer to 599 W m^{-2} in winter. The absence of appreciable cloud cover for sustained periods ensures that most days are bright. However, the mean daily insolation values recorded during summer are usually slightly lower than winter values due to the higher frequency of cloudy periods.

2.3 Geology

2.3.1 Regional Geological Setting

The Rössing uranium deposit lies within the Central Zone of the late Precambrian Damaran orogenic belt that occupies much of northern Namibia, lying between the Congo and Kalahari Cratons (Gevers, 1936; Ward, 1984; Mouillac *et al.*, 1986). The geology of the central part of the Damara Belt has attracted considerable attention (Wagner, 1921) and has been described in detail by several authors (Smith, 1965; Jacob *et al.*, 1986). In the Namib area, the zones of uranium mineralization are restricted to a specific structural zone approximately 50 km wide and extending north-east for a distance of over 100 km (Mouillac *et al.*, 1986). This zone, referred to as the Central Zone by Jacob *et al.* (1986) forms the core of the Damara Belt and played a particular role throughout the history of orogenic development. On a regional scale, the uraniferous bodies are spatially associated with migmatitic dome structures found only along the axial zone of the Damara Belt (Berning, 1986; Mouillac *et al.*, 1986).

2.3.2 Geological Origin of the Uraniferous Deposits

The genesis of the uraniferous deposits commenced in Precambrian times, of the order of 1000 million years ago, during the Damaran sedimentary cycle (Berning, 1986). The initial deposition took place in a shallow turbulent sea, and consisted of cross-bedded, coarse sediments of the Etusis Formation. This was followed by the deposition of siltstones, greywackes and marls that, upon later metamorphism, were converted to the rocks of the Khan Formation. Stable conditions prevailed and the fine-grained and homogenous sediments of the Khan Formation accumulated.

At a still later stage, quieter and deeper water conditions developed after the basins had been partially filled. In this deeper water, and under more stable conditions, the sediments of the Swakop Group, particularly the finer, more heterogeneous sediments of the Rössing Formation, were deposited. These are now represented by marbles and cordierite gneiss (Table 2.1).

Approximately 500 million years ago the Damaran orogeny movements took place. The mass of sediments began sinking to depths of about 5 kilometres and the resultant pressures and temperatures caused complex folding and metamorphism of the sediments (Berning, 1986). At about this time, and again in a later phase, the deeper lying older rocks melted to form a granitic magma which began migrating upwards. This formed the pegmatitic granite known as alaskite which contains the primary uranium. The alaskite was intruded into the upper Nosib and Swakop metasediments, such that the alaskite is now present in a range of intrusive bodies, which vary widely in texture, size and emplacement habit (Berning, 1986; Mouillac *et al.*, 1986).

Since then, sedimentary rocks and basalts from the Stormberg Series of the Karroo System were deposited and have been largely eroded away, leaving thin terrestrial superficial deposits. Also at about this time, numerous dolerite dykes intruded through tensional fissures in the Precambrian rocks to the surface (Smith, 1965). These north-east and east-northeast trending dykes are still prominent features of the landscape. During the last 65 million years only superficial deposits have changed the geological landscape (Smith, 1965). Large portions of the central Namib Desert are covered by Tertiary to Recent superficial sand, scree and duricrust deposits, such as gypscrete and calcrete (Jacob *et al.*, 1986).

TABLE 2.1: Lithostratigraphy of the Metasediments in the Vicinity of the Rössing Uranium Deposit. The Units enclosed by double lines (===), indicate the stratigraphic position of the Rössing uraniferous granitic pegmatites (late to post Damaran tecto-genesis).

Sequence	Group	Sub-group	Formation	Local Lithostratigraphic Units	Thickness (m)
Damara (late Pre-cambrian)	Swakop	Khomas	Kuiseb	Quartz-biotite schist	3 000
			Karibib	Marble and quartz-biotite schist	350
			Chuos	Tillite	300
		Ugab	Rössing	Feldspathic quartzite	50
				Upper biotite-cordierite gneiss	50
				Upper marble	60
				Conglomerate	5
				Lower biotite-cordierite gneiss	40
				Lower marble	40
	Nosib		Khan	Biotite-amphibole schist	15
				Upper pyroxene-hornblende gneiss	90
				Lower pyroxene-hornblende gneiss	110
			Etusis	Upper biotite gneiss	260
				Marker quartzite	5
				Lower biotite gneiss	180
				Feldspathic quartzite	200
Abbabis Complex (Precambrian)					

2.3.3 Local Geological Setting and Structure

The Rössing orebody is unique in that it is the largest known deposit of uranium occurring in granite. The main deposit, known as the SJ anomalies, is located on the south-westerly flank of a large domal structure of migmatized metasediments (Figure 2.3) that is clearly visible on ERTS photographs of western Namibia (Breed *et al.*, 1979). Tight vertical or slightly overturned folds trending north-east/south-west are the most striking feature of the regional structure. The orebody occurs along the northern limb of a complete synclinorium formed between the domal structure and Khan sediments to the south. Several transverse, vertical, oblique-slip faults occur around the domal

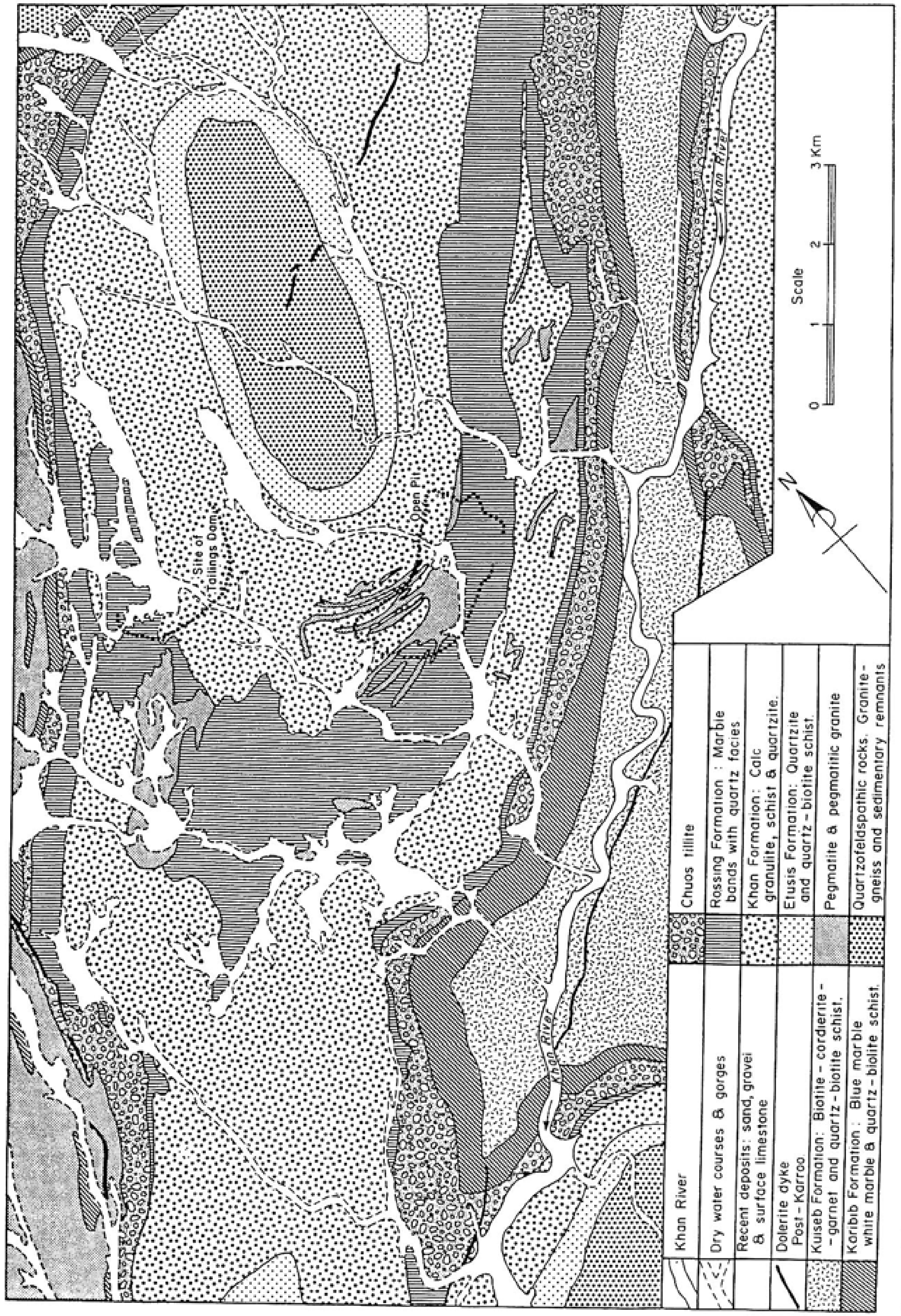


Figure 2.3: Detailed geological map of the area around the present day Rössing Uranium Mine. (Map redrawn from an original provided by the Geology Department, Rössing Uranium Mine).

structure, while both the alaskites and metasediments show strong jointing, trending in a north-northwesterly direction (Dames & Moore, 1982a; Berning, 1986). A spectacular post-Karroo intrusive dolerite dyke crosses the area from south-west to north-east (Figure 2.3).

The Rössing uranium deposit lies in a migmatitic zone in which uraniferous alaskitic granite/pegmatite and metamorphosed country rock show concordant, discordant and gradational relationships. Plan and vertical section views of the main Rössing orebody are shown in Figures 2.4 and 2.5, respectively. The country rock comprises deformed metasediments as well as metavolcanics, whereas the alaskitic rocks range from small quartzofeldspathic lenses to large intrusive bodies that differ widely in size, texture and emplacement habit (Berning *et al.*, 1976; Berning, 1986).

The uranium-bearing alaskites at Rössing are medium- to coarse-grained and vary in colour from grey to shades of pink and white. Much of this colour is due to the presence of pink microcline feldspar. Neutral to dark colours are due to biotite and some hematite, together with "smokey" quartz (Vernon, 1981). All of the primary uranium mineralization and the majority of the secondary uranium mineralization occurs within the alaskite. However, the alaskite is not uniformly uraniferous and much of it is unmineralized or of sub-economic grade (Vernon, 1981).

2.3.4 Uranium Mineralogy

Uraninite is the dominant radioactive mineral present and it occurs as grains ranging in size from a few microns to 0.3 mm. It is included in quartz, feldspar and biotite, but also occurs interstitially to these minerals or along cracks within them (Vernon, 1981; Berning, 1986). The uraninite displays a preferential association with biotite and zircon, with the latter mineral occurring as inclusions within individual uraninite grains or between clusters of grains. Alteration haloes around the uraninite grains are common. The arid climate has been an important factor in beneficiating primary ores with secondary minerals released by weathering, and in reducing leaching by rainfall (Mouillac *et al.*, 1986).

Betafite contains a minor proportion of the uranium in the ore. It occurs as inclusions in quartz and feldspar, often surrounded by radial cracks. Betafite has a high niobium and titanium content, together with some uranium and smaller amounts of tantalum and tungsten. Zircon, apatite and sphene are commonly associated with the radioactive minerals. Other associated, though less abundant, minerals include pyrite, chalcopyrite, bornite, molybdenite, arsenopyrite, hematite and ilmenite (Berning, 1986).

The primary uranium minerals uraninite and betafite give rise to secondary minerals that are usually bright yellow in colour. These occur either in situ, replacing the original uraninite grains from which they were formed, or along cracks as thin films and occasional discrete crystals. Of these secondary uranium minerals, beta-uranophane is by far the most abundant. This mineral is not always confined to the alaskite but may also be dispersed into the enveloping country rocks along cracks and fracture lines (Vernon, 1981).

Ore-grades at the Rössing Uranium Mine are very low, averaging about 0.035 % (Vernon, 1981). Uraninite comprises about 55 % of the uranium minerals present in the orebody, while betafite contributes less than 5 % and the secondary minerals account for about 40 %.

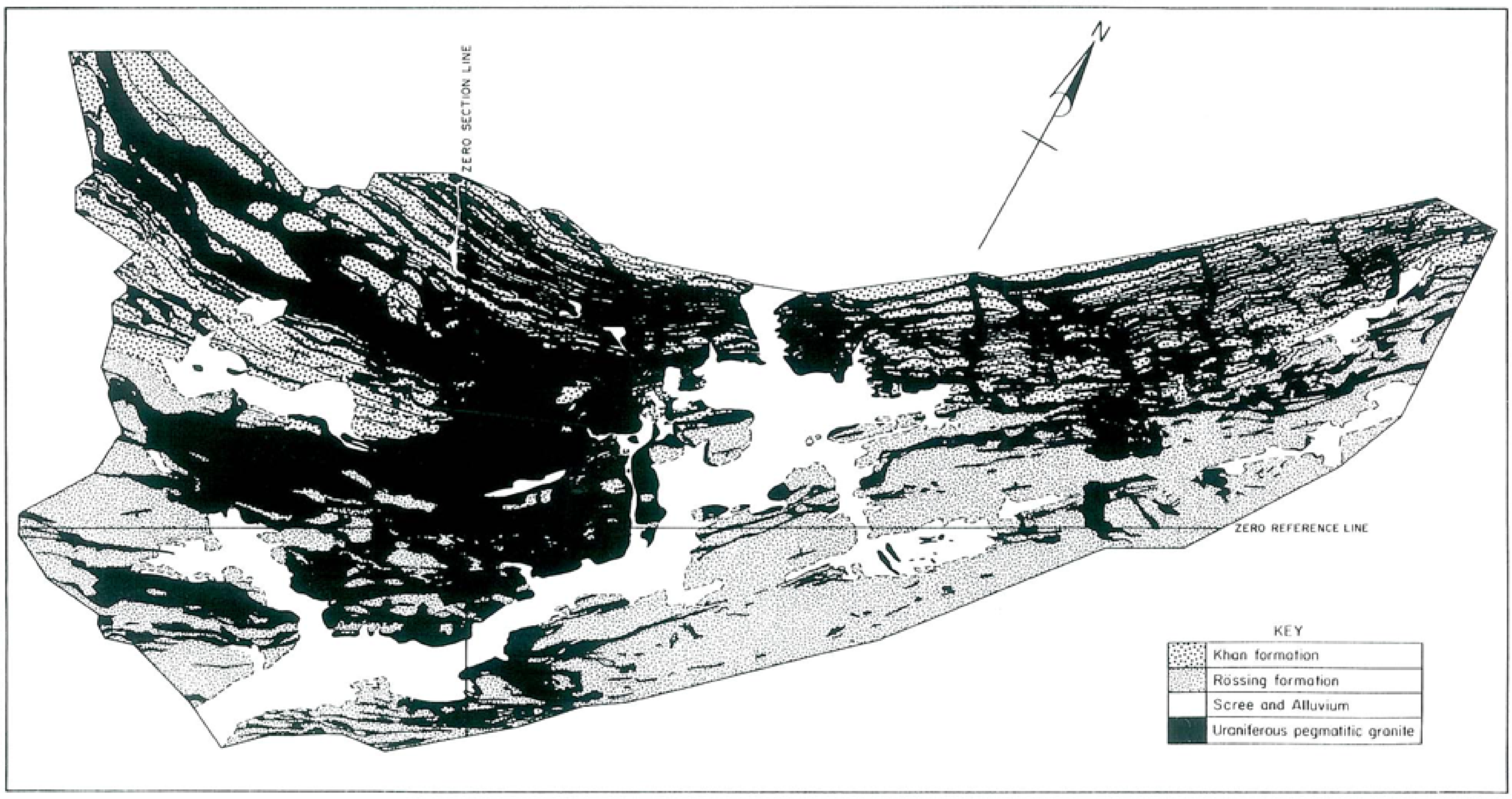


Figure 2.4: Generalized geological plan of the Rössing Uranium deposit. (Redrawn from an original provided by the Geology Department, Rössing Uranium Mine).

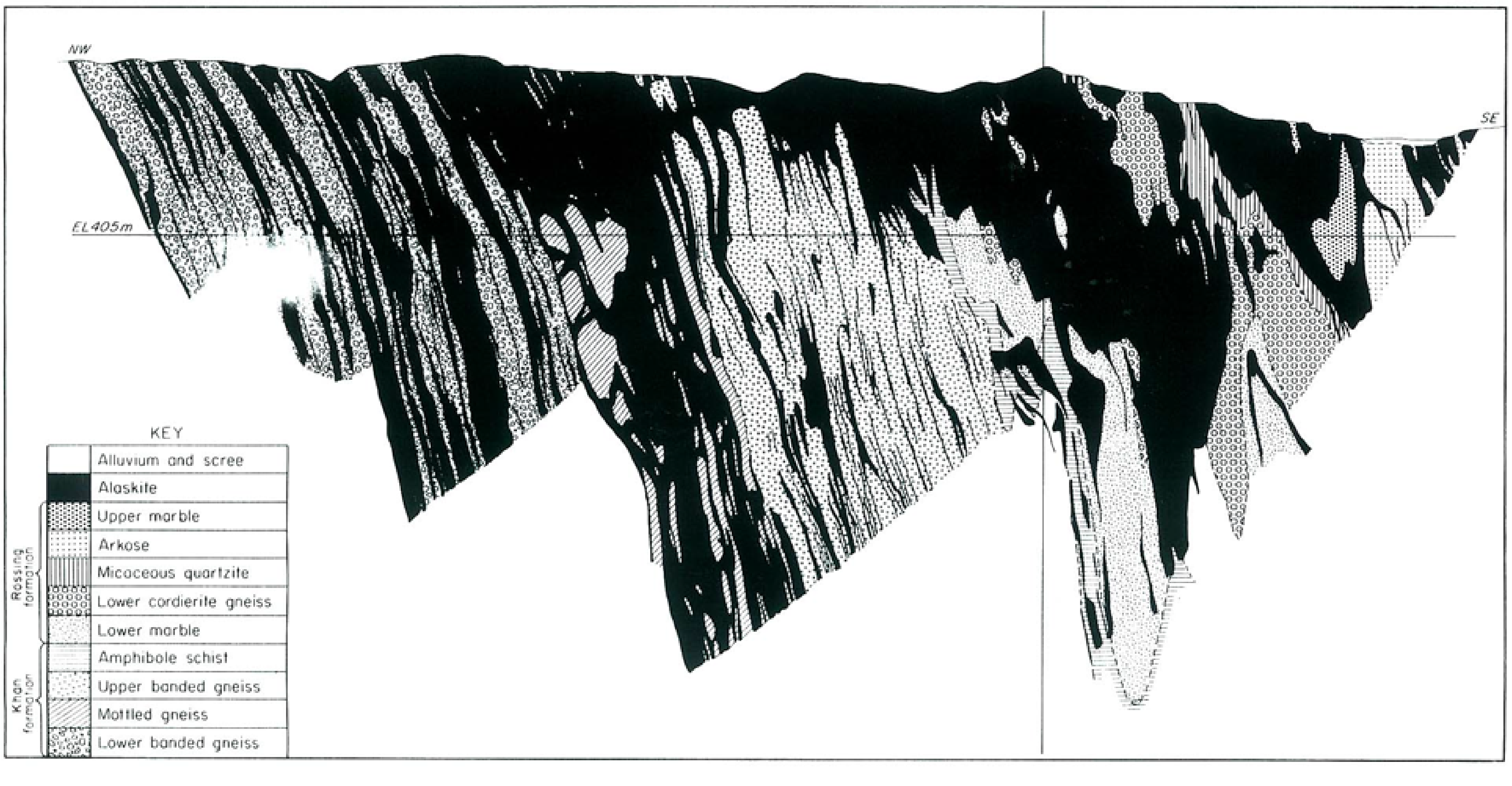


Figure 2.5: Vertical drill section zero through the Rössing Uranium deposit, showing geology.

2.4 Radioactivity

The presence of radioactive minerals in the Rössing area has been known since 1928 when autoradiographic tests were conducted by Captain Peter Louw and his wife. Subsequent investigations by the Anglo American Corporation between 1955 and 1958 located several uraniferous locales. Detailed geological exploration, plus airborne and ground scintillometer surveys, revealed the uranium deposit to be extensive, but low grade and erratic. Further surveys in the region revealed the presence of several other sites with elevated radioactivity levels.

The geological nature of the ore body at Rössing and other nearby deposits consists of uraniferous granite, irregularly emplaced into otherwise barren metasediments (Berning, 1986; Berning *et al.*, 1976; Corner *et al.*, 1986). This irregular distribution of uraniferous material gives rise to a highly irregular radioactivity pattern for the area. This situation is further complicated by the fact that two major radiochemical parameters affect the actual measurement of radiation. These are:

- secular disequilibrium, where the relative loss or gain of radioactive components in the ^{238}U decay chain leads to uncertainties in estimation of the quantity of uranium present; and,
- mineralogical characteristics, in particular variations in the U/Th and U/K ratios which affect estimates of the uranium grade present.

The degree of disequilibrium is generally not constant within a uranium deposit and is usually higher both where secondary minerals predominate and within the zone of fluctuation of, or above, the water table. While Rössing falls into this category, it is buffered by the arid climate prevailing in the Namib Desert (Corner *et al.*, 1986). An intermediate nuclide, ^{222}Rn, the noble gas daughter product of Ra_{226}, is particularly mobile in open environments such as fracture zones or weathered rock.

Background radiation levels in areas to the north and west of the uraniferous Rössing deposit are shown in Figure 2.6. The radiation values shown in Figure 2.6 were derived semi-quantitatively by correlating current ground level radiation readings with pre-mining aerial radiation surveys. Over-estimation of the values is therefore probable, especially in the higher lying regions. Whilst the background radiation levels recorded at Rössing are generally low and are within safe levels, they are higher than levels found within the United Kingdom, for example, where there are no uranium deposits. Nevertheless, to place the issue in perspective, there are also populated areas in other countries which have background radiation levels that are well above those measured near Rössing (A.W.J. Jooste, personal communication). The average natural radon exhalation rate from undisturbed rock formations near Rössing amounted to 0.02 Bq m^{-2} sec^{-1} (A. Abrahams, personal communication).

2.5 Soils

Saline soils are a feature of most deserts (Scholz, 1972) and the Namib Desert is no exception. Rocks are broken down first by physical and chemical weathering processes, after which chemical decomposition processes transform the stone fragments to progressively finer particles. The predominance of chemical weathering processes is accentuated by the dry climate and the occasional deposition of wind-blown salt of marine origin.

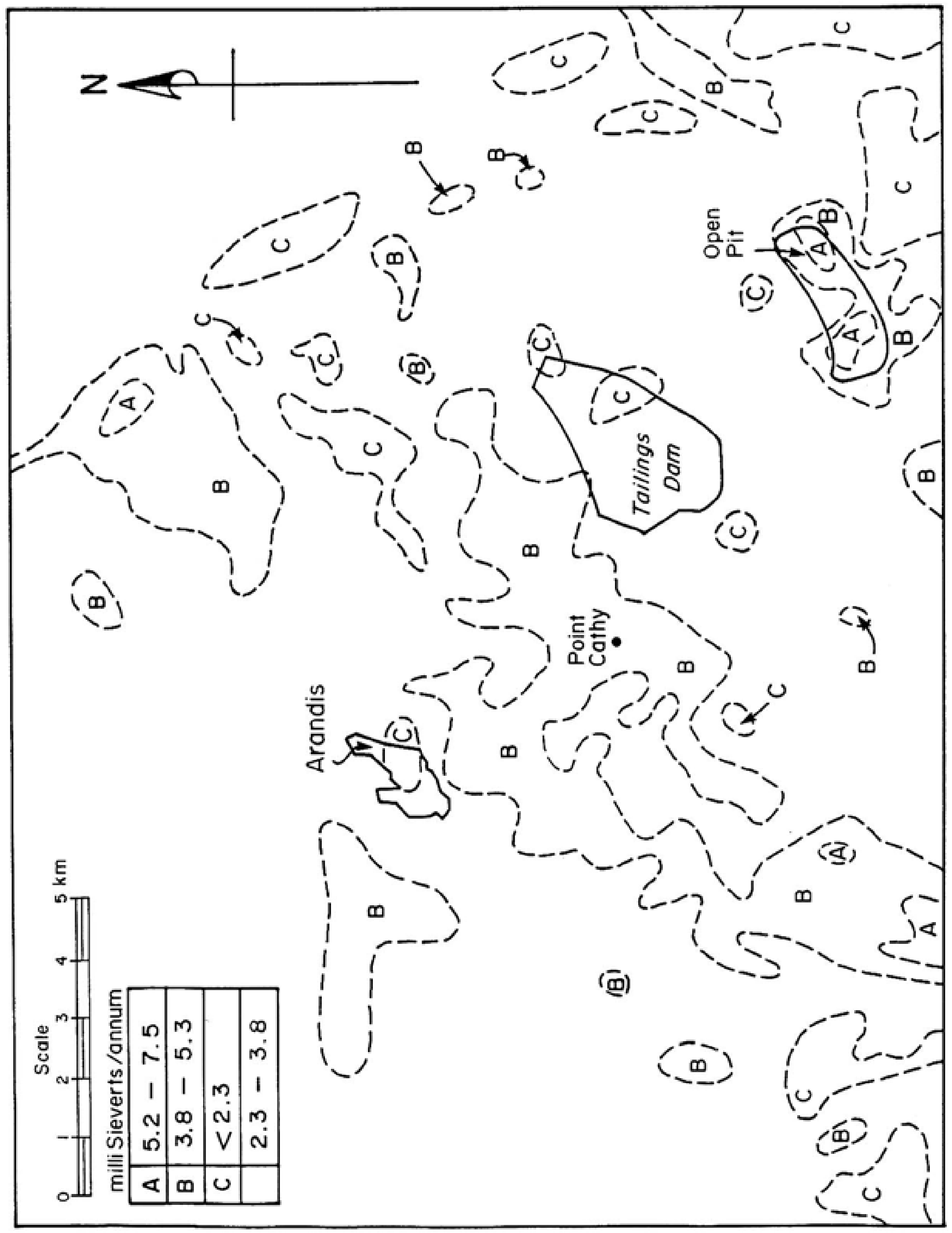
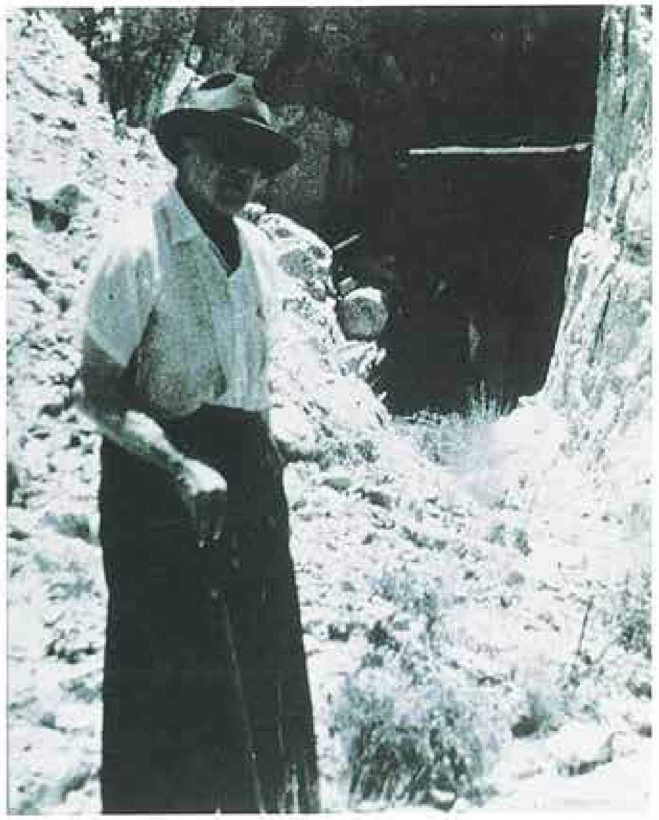


Figure 2.6: Contour map showing extent of background radiation in the area to the north and west of the Rössing Uranium Mine. All values are given in milliSieverts per annum. (Data supplied by A. Abrahams, Rössing Uranium Mine).

Plate 1



(A) The late Captain Peter Louw at the entrance to an adit excavated in 1956.

(B) Typical view across the bare gravel desert south of Arandis, showing shallow drainage lines leading to the upper part of Ostrich Gorge.

Plate 2

(A) Typical rock formation in lower Panner Gorge, showing pale marble bands of the Rössing Formation, interspersed with darker schists and quartzite of the Khan Formation. Dense growths of *Salvadora persica* occupy the base of the hillslope; alluvium floor of Panner Gorge is in foreground.

(B) View downstream along the dry bed of the Khan River, showing steep, bare hill slopes with isolated *Acacia erioloba* trees and clumps of saltbush (*Tamarix usneioides*) in the river bed

The soils in the vicinity of the Rössing Uranium Mine are generally very shallow (< 25 cm) and greyish or ochre in colour, with a large proportion of coarse fragments and occasional calcium carbonate concretions. In areas with surface calcrete or limestone deposits, "Schaumboden" or "foam soils" are frequently found. These are characterized by high soil pH values and the formation of a crusted surface layer. Hard surface crusts, often bound by and overlying a layer of blue-green algae (Cyanobacteria), are found in lower Panner Gorge. These surface crusts can reduce rainfall infiltration rates and accentuate runoff.

Aeolian sand deposits of varying depth are found in sheltered areas in the upper gorges and are particularly prominent on the leeward (eastern) slopes of Rössing Mountain. These sands are a mixture of dark to light brown grit, quartz and feldspar fragments, and biotite flakes.

Colluvium has been deposited on the shallower slopes of some of the hills, as well as at the base of steeper hills. The colluvium slope wash varies in thickness up to a maximum of about 1.5 m. The material consists of a mixture of grey-brown silty sand with an open, angular pebble layer and its consistency varies from medium-dense to dense (Robinson & Eivemark, 1987). The average permeability of the colluvium is about 10^{-2} cm sec^{-1}, but the deposits are discontinuous.

Alluvial silty sands and gravels form an almost horizontal fan in the valley bottoms, having been laid down during the infrequent flash floods. The material is laminated, consisting of layers of slightly coarse sand interspersed with layers of angular gravel and pebbles, in a matrix of grey-brown silty coarse sand (Plate 2). In the gorges, the alluvial deposits are estimated to vary in thickness up to about 8 m. The average permeability of the alluvium is likely to be about 10^{-1} cm sec^{-1}, (P. Marais, personal communication).

Alluvial deposits up to about 20 m in thickness are also found in the bed of the Khan River, with a composition very similar to those found in the gorges. However, successive layers of gravels, sands and silts are visible in flood-cut terraces, which vary in width from a few metres to several tens of metres. These stratification patterns indicate successive settling out of transported material with decreasing flood-water velocities. An important distinction of these Khan River bed deposits is the presence of conspicuous laminations of mid-brown or ochre, fine silty clay, reflecting the higher silt loads that are brought down by occasional surface floods (Hydrology Division, 1988; Ashton, 1988b).

2.6 Hydrology and Surface Water Quality

2.6.1 General Features of the Region

Virtually the whole of the central Namib Desert is drained by four river systems, namely the Omaruru, Khan, Swakop and Kuiseb rivers, that flow westwards to the Atlantic Ocean. Each of these rivers has its source in the high interior plateau of Namibia. Because of the rapid decrease in rainfall from east to west (Section 2.2.2.1), these rivers function mainly as runoff courses for the precipitation that falls in the interior (Smith, 1965). However, sub-surface water is invariably present, often at relatively shallow depths (Section 2.7).

The erratic and episodic nature of regional rainfall patterns combined with high rates of evaporation limit both the quantity of water carried by these rivers and the duration of flows (SWA DWA, 1987; Hydrology Division, 1988). All of the rivers draining the Namib Desert are classified as ephemeral or episodic rivers whose surface flows reach their river mouths only after exceptionally heavy rainfall events in the interior. Smaller tributaries draining the low-rainfall, westernmost parts of these rivers seldom carry surface flows for longer than a few hours at most.

The longitudinal profile of each of the major rivers shows a tendency towards convexity, rather than the concavity characteristic of rivers draining well-watered regions (Stengel, 1964; Goudie, 1972). This feature is caused by the sharp decrease in discharge that is associated with the east-west climatic gradient of the Namib (Goudie, 1972). Associated with this convexity in longitudinal profile is the presence of marked alluvial terraces which are a distinct feature of all Namib rivers. These reflect the process of alluvium deposition during flood events, followed by partial erosion of these deposits during subsequent floods. Where these terraces have been exposed for considerable periods of time, they may become capped with a layer of gypsum-calcrete and rolled pebbles, as noted in the lower reaches of the Kuiseb River (Goudie, 1972).

2.6.2 Surface Water Resources in the Rössing Area

Prior to the onset of mining activities, three sources of surface water were important in the Rössing area, namely the Khan River and the ephemeral and permanent springs. Water sources that formed after development started at Rössing (e.g. seepage pools) are addressed in Section 4 of this report.

2.6.2.1 *The Khan River*

The Khan river down to Rössing has a catchment of approximately 8200 km², of which only 6000 km² is considered to generate runoff. The altitude of the catchment varies from 1500 m above sea level north-west of Okahandja to some 460 m near Rössing. The average gradient of the river is 0.00549, which is considered steep (Hydrology Division, 1988). Approximately 25 km downstream of the Rössing Uranium Mine, the Khan River flows into the Swakop River which then flows westwards to the Atlantic Ocean at the town of Swakopmund (Figure 2.1).

The Namibian Department of Water Affairs has operated a number of gauging stations along the Khan River. However, the flow records are considered to be unreliable without correction, since the period of effective record starts during the 1960's or early 1970's, and at least one of these stations is located on an open unstable section where the river bed is subject to change during floods (Hydrology Division, 1988).

Based on a 62-year synthetic runoff record for the Khan River, the mean annual runoff expected in the Khan River at its junction with Dome Gorge amounts to some 3.41 Mm³. However, this mean value is greatly biased by a few exceptional flood events and is therefore of little value. In fact, annual runoff values were below average in 90 % of the years while no runoff at all was generated during 55 % of the 62 year record. The median value for annual runoff at the junction of the Khan River with Dome Gorge is zero (Hydrology Division, 1988). If extreme flood events are omitted from the analysis, the mean annual runoff amounts to 0.99 Mm³.

This analysis takes no account of any medium- to long-term cyclicity in rainfall patterns (Tyson, 1978; Lancaster *et al.*, 1984). Clearly, annual runoff values will tend to be above average during the so-called "wet" cycles and below average during "dry" cycles. In the Khan River below Dome Gorge, surface floods have been recorded on five occasions during a 22-year period (1966 - 1988); average flow rates have been estimated to vary from as little as 2 m^3 sec^{-1} to well over 100 m^3 sec^{-1} in the few years that floods have been observed (P. Marais, personal communication).
During localized, short-duration, high-intensity rainfalls, runoff is rapid and, in the absence of significant vegetation cover, acts as an effective transport mechanism for surface clay, silt and sand. Where surface-flow floods have been recorded in the Khan River, the silt content ranged from 0.2% to 22.8% (NIWR, 1966). Since an additional quantity of material would also have been transported