MINE VOID WATER RESOURCE ISSUES IN WESTERN AUSTRALIA

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MINE VOID WATER RESOURCE ISSUES IN WESTERN AUSTRALIA

by

S. L. Johnson and A. H. Wright

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Resource Science Division
Water and Rivers Commission
3 Plain Street
EAST PERTH
WESTERN AUSTRALIA 6004
Telephone (08) 9278 0300
Facsimile (08) 9278 0586

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Cover Photograph: Abandoned opencut mine at Mt Magnet gold operations (Case Study 10) containing a pit lake of brackish groundwater.

Acknowledgments

This report is based exclusively on the draft report titled 'Impact of mine voids on the groundwater resources in WA'. After discussions with stakeholders, it was decided that the draft report required condensing and editing before publication.

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Groundwater consultants, on behalf of mining companies, have completed hundreds of hydrogeological reports throughout the State dealing with groundwater investigations, monitoring and predictive modelling for mine closure. The authors would like to recognise the tremendous contribution and volume of information that the various groundwater consultants have generated.

Many people assisted in the successful completion of this study and all who contributed are thanked for their efforts. Special thanks to Kerryn Prosser for her efforts in figure compilation.

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Executive summary

This report provides an overview of the mine void issue, the creation of pit lakes and associated hydrogeological processes, an assessment of the potential impacts on groundwater resources, and water management considerations at mine closure. The report outlines the technical information required for the compilation of recommended guidelines, which will assist the mining industry in gaining environmental approvals related to proposed developments below the watertable. Eighteen case studies (detailed in Appendix 1) have also been completed to highlight differences between groundwater environments, regional setting and mine closure options.

The mine void issue

Mining is leaving a legacy of hundreds of mine voids throughout the State. There are numerous safety issues that must be addressed as part of mine closure and, until recently, there had been no assessment of the potential long-term environmental impacts of mining below the watertable. The mine void issue is vitally important to both the Government and mining industry, as neither wishes to be liable for rehabilitation or stabilisation of a mine void over a period of decades or possibly millennia. In Australia, mine void issues have previously focused on the coal mining industry, sand mining, and politically sensitive mines in the tropical areas of the Northern Territory.

Mine void-related impacts are a long-term concern for Western Australia, as there are currently about 1800 existing mine voids and more than 150 mines operating below the watertable. The size of mine voids varies from borrow pits (about 100 m in diameter) to the enormous pits in the Goldfields and Pilbara. The larger mines require substantial groundwater abstraction (dewatering) from sumps or in-pit/perimeter bores to facilitate dry-floor mining practices. On cessation of dewatering, the waterlevel recovers to create a 'pit lake' within the mine void, thus initiating geochemical and hydrological processes that evolve with time. The infilling of the void with water may take centuries, with chemical evolution via evaporation continuing much longer.

There is potential for many pit lakes in Western Australia to become point sources of hypersaline water and impact on the surrounding groundwater resources. The low annual rainfall and high evaporation experienced over much of the State produces a rainfall deficit, which contributes to the development of hypersaline water bodies. There are also potential problems with the generation of acidic conditions in pit lakes, particularly for the coal mining industry in the higher rainfall, southwest region and a few isolated metalliferous mines.

The salinisation and acidification of pit lakes has the ability to affect local and regional groundwater resources, as well as the broader natural environment. The extent of impact on the surrounding groundwater environment is largely dependent on the local hydrogeology, as to whether the mine void will act as a (1) groundwater sink or (2) groundwater throughflow cell. In the groundwater sink regime, evaporation exceeds the rate of groundwater inflow into the void and is typical of most hard-rock mines throughout Western Australia. Mine voids where groundwater inflow exceeds evaporation act as a 'groundwater throughflow' type, forming potential environmental hazards with saline plumes moving out of the void and affecting other groundwater resources.

Post-mining options with mine voids

The primary concern at mine closure has always been to ensure that any mine void is geologically stable and safe, although recently, both industry and regulators have started to focus on the environmental, visual and social impacts associated with abandoned mine voids. There are three mine void closure strategies that are commonly applied at mine closure: (1) open void, (2) waste storage, and (3) water storage.

Most mine voids are abandoned as ‘open voids’ as it is the easiest and most practical option, particularly where there is a possibility of further mining, and for most large pits in the Pilbara and Goldfields. The open-void strategy may also have long-term social benefits, with the development of innovative water-treatment approaches for pit lake water and the utilisation of treated water for commercially viable projects such as tourism, fish farming, tree farming and horticulture.

From an environmental viewpoint, and in keeping with community expectations, the backfilling of final voids with waste may be considered the most desirable outcome. However, this is only possible where the volume of ore is small compared with the volume of the material extracted, and/or the long-term environmental benefits outweigh the capital cost. Several of the Pilbara iron ore mines require backfilling as the voids are hydrogeologically connected to significant groundwater resources.

The increasingly stringent environmental constraints on the discharge of excess water, primarily from dewatering, into riverine or salt-lake environments has forced mining companies to consider water storage in nearby abandoned mine voids. Also, the natural flooding of mine voids from intense rainfall events and diversion of surface runoff demonstrates the viability of final voids as potential surface-water reservoirs on an opportunistic basis. Water storage also has the advantage that should further mining ever be considered, the mine void only requires dewatering.

Mine voids and the mine approval process

Previously, in the mine approval process, there has been little attention paid to the issue of mine voids and associated environmental impacts. Mine closure plans were initially not integrated into feasibility, approval and run-of-mine (ROM) planning and companies did not consider closure issues until a few years prior to mine cessation. In recent years, there has been increasing demand from government regulators for new mine proposals to consider final rehabilitation strategies and mine closure during the mine approval process. Major mining companies have also started to recognise the merit in early mine closure planning, as part of sustainable development principles.

There are increasing requirements for the proponent to define how the mine void will function, and to demonstrate the extent of any impact on adjacent fresh to brackish groundwater resources, the environment and/or cultural sites. Several EPA environmental assessments, particularly in the Pilbara, have required proponents to provide greater detail with regard to mine void closure and predictions of water-quality evolution.

The way forward with mine voids and pit lakes

During active operations, minesite water management is well understood and regulated through of a number of government acts and regulations. The management of water quality following mine closure is less familiar, and presents a wide range of challenges depending on the physical and social environments surrounding the final void. Currently, there are few detailed regulatory guidelines that address the performance of final pit lakes, and other government agencies require solutions to meet the broad goals of ecological sustainability.

Existing publications on mine closure provide only limited discussion on environmental considerations related to mine voids. In conjunction with other government agencies and the mining industry, the Water and Rivers Commission is keen to participate in developing guidelines to assist the mining industry with addressing the issue of mine voids and pit lakes in the mining approval process. The guidelines will also provide detail on regulatory requirements, particularly the provision of groundwater information, predictive modelling and monitoring.

The core objective of the guidelines and final-void management for mining companies and Government should be to:

- render the site acceptable and safe over the long-term;
- minimise environmental and health risks in the vicinity of the site;
- maximise to the practicable extent any potential future usage of the site; and
- develop a 'walkaway' solution.

1 Introduction

1.1 Background

Western Australia is a major global exporter of minerals, which places significant economic and environmental responsibility on the State's mining industry. In the past, there was little attention either to environmental management during operations, or to final rehabilitation. There were few regulations governing environmental impacts; hence, the mining industry tended to walk away with little consideration for the long-term environmental issues. In recent times, the mining industry has begun to accept that good environmental management and rehabilitation are an essential part of mining if the industry is to work towards sustainable development.

Mining operations face a variety of water-resource issues ranging from insufficient water availability for processing to excessive mine dewatering. These issues also change as a mine operation proceeds through its development, commonly starting with a water deficiency and moving into surplus as deeper pits require more dewatering. Operating mines have to contend with three main issues: water supply, wastewater disposal, and contamination of local water resources. In contrast, post-closure issues are related to aquifer recovery or re-establishment of groundwater equilibrium, isolation of waste products and — the focus of this report — the development of pit lakes in mine voids and associated long-term impacts (Fig. 1).

Final voids are an aspect of mining that has received limited attention. A final mine void is defined as that remaining when an opencut mine has ceased to be mined and is not planned to be mined or used as access for underground mining in the near future (Mallet and Mark, 1995). Mining may cease for a number of reasons: the ore is exhausted, a lease boundary is encountered, changes in overburden/ore ratios, and price fluctuations impacting on the economic viability.

Opencut mining is common throughout Western Australia with many mine voids extending below the watertable. Once dewatering ceases, the waterlevel recovers and the mine void fills with groundwater, becoming a 'window' to the watertable. Hydrochemical evolution of the resultant pit lake may take centuries, making it difficult to determine the long-term impact of the final mine void on the surrounding groundwater environment. These complexities present a significant challenge to the authorities responsible for managing the State's water resources, who regulate based on modelling predictions. Also, the size of mine voids means that any remedial action addressing water quality in the pit lake can be expensive and unrealistic.

The issue of pit lakes and mine voids at closure has received considerable attention in North America. In Australia, mine void issues have previously focused on the coal mining industry, sand mining and politically sensitive mines in the tropical areas of the Northern Territory. Mine void-related impacts are a long-term concern for Western Australia, as there are currently about 1800 existing mine voids and more than 150 mines operating below the watertable (Fig. 2). The impact of mine voids on groundwater salinity in the arid Western Australian environment has been reviewed by Commander et al. (1994), Hall (1998, 2000) and Wright (1999, 2000a,b).

The significance of the issue of mine voids and resultant pit lakes throughout Western Australia has led to the establishment of the Centre for Sustainable Mine Lakes (CSML). The core functions of the CSML are the provision of research and educational programs to predict the evolution of water conditions in mining lakes over time, devise solutions to poor water quality conditions, and identify opportunities to use mine lake water for community benefit or commercial enterprises.

The Pilbara Iron Ore Environmental Committee (PIEC), a Western Australian Government inter-agency committee responsible for the coordination of policy responses to environmental issues associated with the Pilbara iron ore industry, prepared an information paper on 'Mining below the watertable in the Pilbara' (DRD, 1999). The paper focused on mine voids in the Pilbara, highlighting those

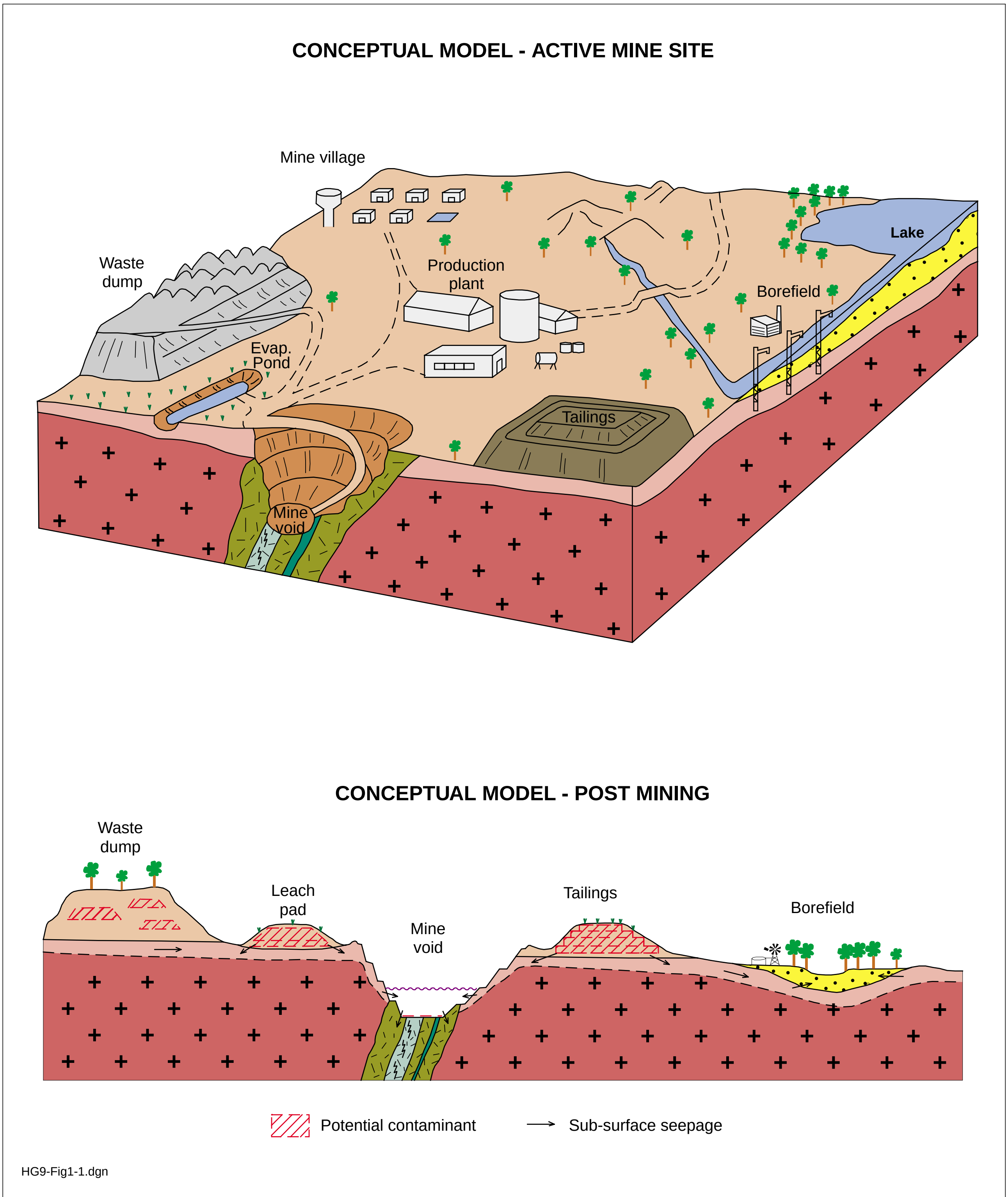

Figure 1. Mine voids — an integral part of both mining operations and rehabilitation

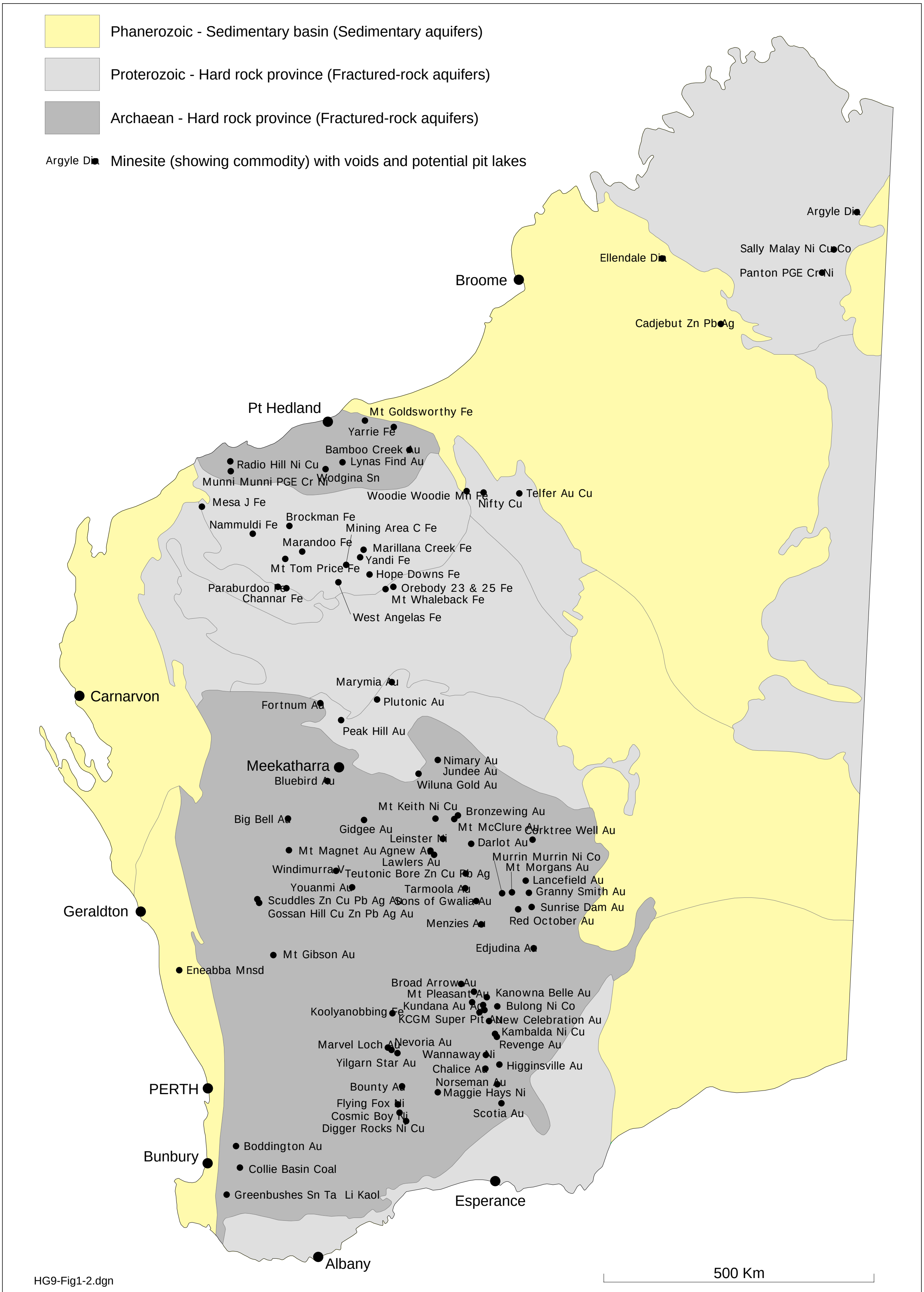

Figure 2. Distribution of significant mine voids in Western Australia

environmental impacts and issues associated with mining below the watertable that require attention in the environmental impact assessment process.

DRD (1999) made the following recommendations:

- mining below the watertable may be acceptable provided that any potential environmental impacts can be satisfactorily managed; and
- develop guidelines which differentiate the type and potential significance of the environmental impacts associated with mining below the watertable, and outline the technical investigations required for environmental impact assessment.

1.2 Scope and purpose

In light of the recommendations by DRD (1999), this project aims to evaluate the potential impacts on groundwater resources throughout Western Australia of those mine voids extending below the watertable. The information will enable the Water and Rivers Commission, as the State’s water-management agency, to formulate groundwater protection strategies and provide technical advice to both government and industry on the mine void issue.

The project is focused primarily on metalliferous mines in the arid interior of the State, in particular the Murchison–Northern Goldfields and Pilbara Regions, where numerous mine voids exist near significant fresh to brackish groundwater resources. The mining of coal, bauxite and mineral sands in the higher rainfall southwest region is not thoroughly reviewed, as these sectors have been previously assessed by other regulatory agencies. The key components of this project were to:

- identify opencut mines that extend below the watertable;
- determine the hydrogeological processes and potential issues of pit lakes (concentrating on the resultant impacts on the groundwater environment before and after closure);
- differentiate and classify mine sites into regional categories;
- undertake case studies at selected mines from each regional category;
- obtain input from the mining industry; and
- highlight mine closure issues and options to assist in guideline development.

The large number of mining voids throughout the State made it impossible to review all mining operations; hence, it was decided to select representative case studies. Eighteen case studies (Appendix 1, Table A1) highlight differences between groundwater environments, regional setting and mine closure options were completed between 1997 and 1999. Delays in publication has meant that information in many of the case studies may have been superseded; however, the suggested approaches for mine closure are still considered appropriate.

2 The mine void issue

2.1 Overview

Improved earthmoving techniques and more efficient processing techniques of low-grade ore bodies has increased the number of large-scale opencut mining operations. The size of mine voids varies from that of borrow pits (about 100 m in diameter) to the enormous pits in the Goldfields and Pilbara. Mount Whaleback in the Central Pilbara, for example, will have final-void dimensions of 5.5 km by 2.2 km and a depth of 500 m. Mine voids are invariably not backfilled where there is potential for additional mining in the future.

Opencut mining has resulted in massive mine voids that extend below the watertable. These mines often require substantial groundwater abstraction (dewatering) from sumps or in-pit/perimeter dewatering bores to facilitate dry-floor mining practices. On cessation of dewatering, the waterlevel recovers, creating a ‘pit lake’ within the mine void initiating geochemical and hydrological processes that evolve with time. The filling of the void with water may potentially take centuries, with chemical evolution via evaporation continuing much longer.

2.2 Hydrochemical evolution of pit lakes

It is often difficult to predict void-water evolution and determine the potential impact that a final void lake may have on the surrounding groundwater environment. Wright (1999) indicated that understanding water quality evolution in pit lakes is complex, as the hydrological and chemical inputs are qualitatively different from those of natural lakes.

The final water quality in the pit lake is dependent on a host of factors including the oxygen status of the lake, pH, hydrogeological flow system, composition of wall rock, concentration through evaporation (evapo-concentration), biological activity and hydrothermal inputs (Fig. 3). The circulation pattern within pit lakes is important because of the central role of oxygen in the chemical reactions affecting water quality, particularly water containing iron and arsenic. During mining, the rocks in the pit wall and floor are exposed to the atmosphere with reduced surfaces becoming oxidised and generating soluble metal-bearing salts. Flushing of the rocks with water during lake development can release constituents dissolved from the rocks into the lake water; these then become biologically available.

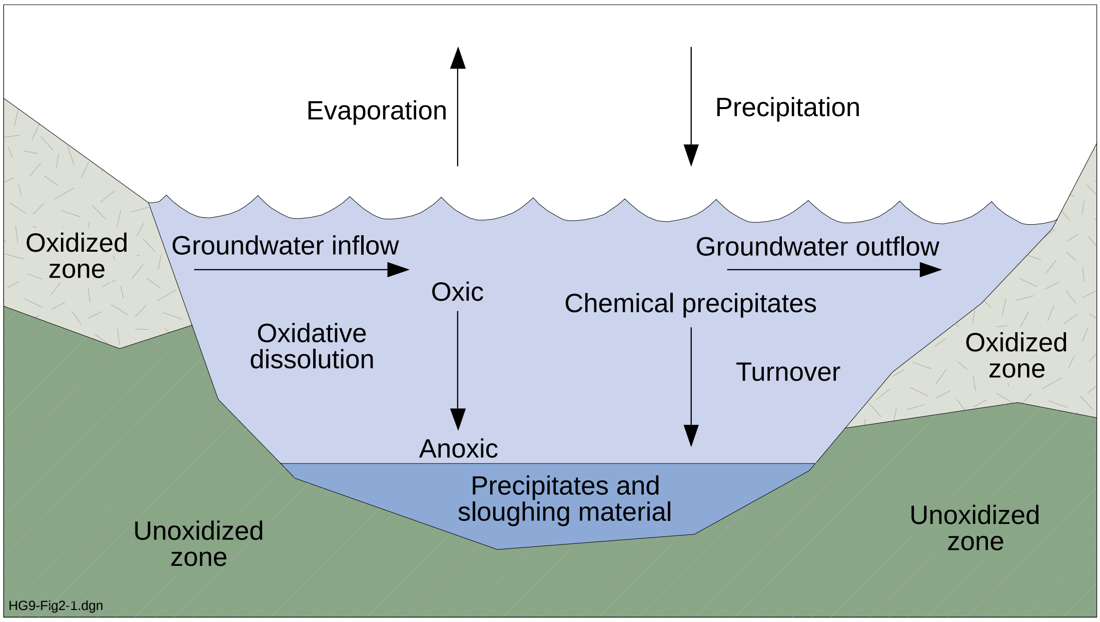

Figure 3. Chemical and physical processes in pit lakes (after Miller et al., 1996)

In a semi-arid climate, the concentration of all constituents in a pit lake increases significantly due to evapo-concentration. In situations where net evaporation greatly exceeds precipitation, this can result in dramatic increases in total dissolved solids content to produce saline to brine water bodies, particularly where surface inflow to the pit is largely restricted to direct precipitation. The generation of relatively dense, saline water at depth and periodic addition of fresh rainwater to the surface layers can result in a stratified water body.

The water quality of pit lakes that develop in sulphide-rich rocks deteriorates with increasing acidity, dependent on the amount of lime-rich rock available to neutralise any acid-generating material. However, mine voids in oxidised rock that contain appreciable carbonate often have better quality and neutral pit lake water.

The prediction of final water quality and quantity in mine voids is a relatively new challenge in mine-site rehabilitation. Existing modelling techniques, such as stochastic water-balance modelling, are capable of providing accurate predictions of waterlevels in the final pit lake. The length of time needed for the lake to reach final waterlevel is dependent on several factors, including the area and depth of the pit, the rate of groundwater infiltration, direction of groundwater flow, rate of evaporation and the amount of rainfall.

There are difficulties in long-term predictions of water quality. The prediction of water-quality evolution in mine voids requires an understanding of the hydrogeological, limnological and biological/ biochemical processes that control solute fate and transport quality. Jones (1997) observed that present models do not adequately account for all of these processes. As most mine pit lakes in the State are relatively young, there are insufficient data available to support the testing and validation of available computer models.

Barr and Turner (2000) demonstrated that prediction of long-term chemical composition of pit lakes is achievable by coupled modelling, using a mass balance model WSIBal (Barr et al., 2000) and the chemical equilibrium model PHRQPITZ (Plummer et al., 1993). The long-term prediction of water quality in pit lakes is currently being refined by the Centre of Water Research at the University of Western Australia, as part of the CSML.

2.2.1 Salinisation

A major long-term concern is the potential for pit lakes in Western Australia to become point sources of hypersaline water with a detrimental impact on the surrounding groundwater resources. The low annual rainfall and high evaporation experienced over much of the State produces a rainfall deficit, which contributes to the development of hypersaline water bodies.

Hall (1998) indicated that it is difficult to assess the statewide impact of the salinity issue owing to the lack of empirical hydrochemical and post-mine closure data. Final mine voids that form ‘groundwater sinks’ will become progressively more saline (Fig. 4). A long-term concern is the down-gradient movement of saline plumes from ‘throughflow’ mine voids, which can extend large distances and potentially impact on other groundwater resources. The limited monitoring data from the Mount Goldsworthy pit (Case Study 3) demonstrates that the salinity of the pit lake has increased from 1400 mg/L to 5500 mg/L TDS over a 14 year period (Table 1).

2.2.2 Acidification

The generation of acidic waters, a major issue elsewhere in Australia, is only a significant issue for the coal mining industry in the higher rainfall southwest region and for a few, isolated metalliferous mines. Highly acidic water is present in many abandoned mine voids in the Collie Basin, the State’s premier coal mining area (Case Study 18). The opencut strip-mining method is the main problem, with the waste rock and spoil, which is deposited in the void immediately adjacent to the active strip, coming into direct contact with water and resulting in the potential leaching of solutes.

In contrast, the potential for acid-water generation in most metalliferous mines is relatively limited, with little sulphide-rich ore mined in Western Australia. Most sulphide-rich ore comes from underground operations, whereas opencut pits lie in the oxidised,

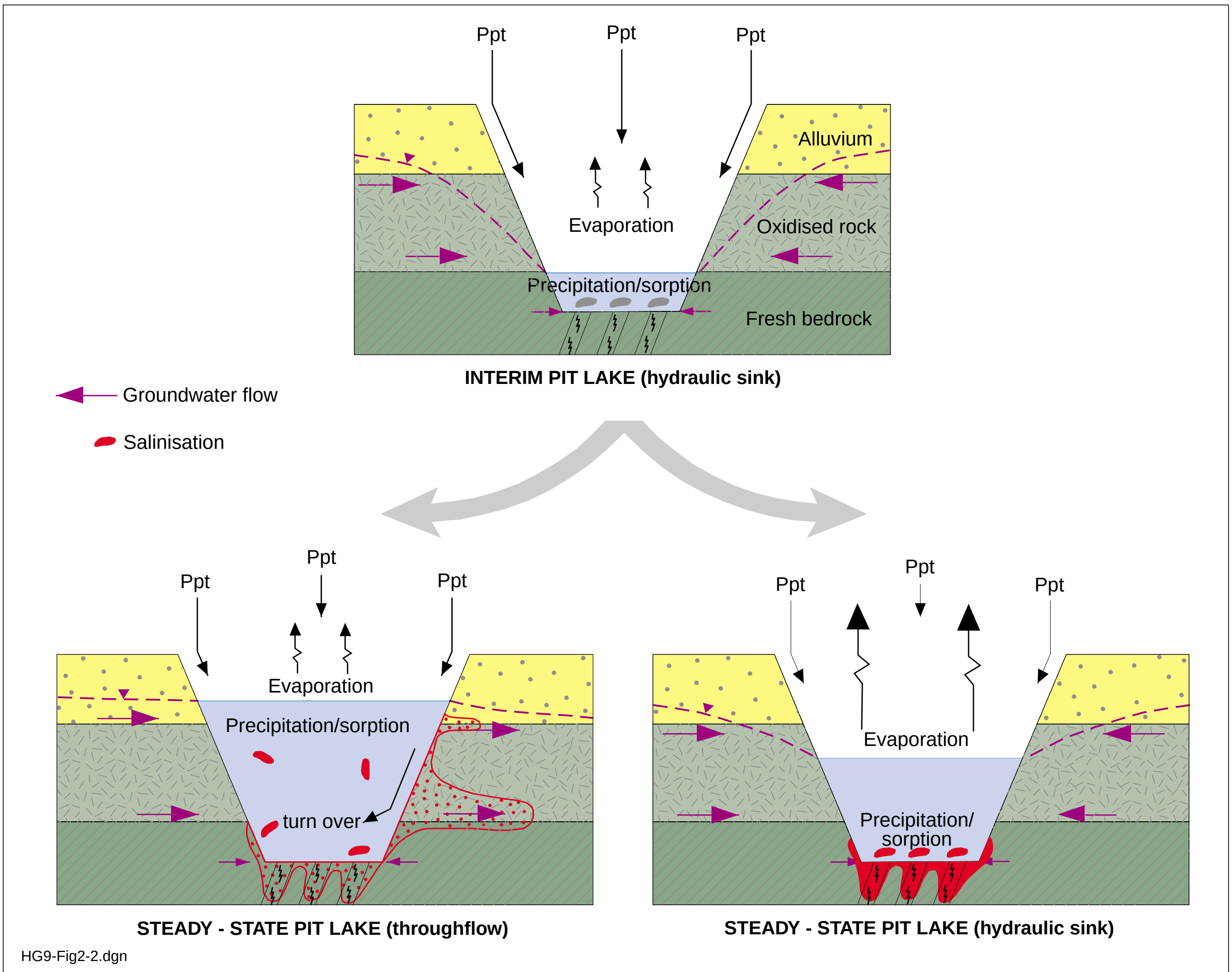

Figure 4. Hydrogeological processes contributing to the salinisation of pit lakes

Table 1. Salinisation of pit lakes at selected mine sites

Mine site (Region)	*Pit lake salinity (mg/L TDS) At closure*	*Recent*	*Years since closure*
Mt Goldsworthy Pit (Pilbara)	1 400	5 500	14
Quasar Pit (Murchison)	2 000	10 000	5
Keringal Pit (NE Goldfields)	15 000	79 000	3
North Orchin Pit (S Goldfields)	220 000	330 000	3

weathering zone. However, as mines progressively deepen, the potential for exposing large volumes of primary or sulphidic ore increases (Williams, 1995). Table 2 gives some appreciation of the acid-water generating potential for selected mines in the State.

Nickel deposits have variable carbonate alteration associated with nickel mineralisation and the potential for producing acidic water will vary widely from mine to mine. The proposed Harmony nickel mine (Case Study 13) near Leinster is a good example of a mining company having identified and managed potential acidification issues. In contrast, the close relationship between base metal deposits and sulphide mineralisation suggests that the oxidation of sulphidic material present in abandoned pit walls will produce acidic water.

Table 2. Geo-environmental characteristics of sulphide deposits (after Williams, 1995)

Deposit characteristics	*Environmental signature*	*Deposits*
Pyrite-rich massive sulphides	Very low pH, high metals	Iron-ore deposits, Scuddles
Sulphide-rich ore dominated with pyrite and bornite and wall-rock altered to silica, alunite, kaolinite	Low pH, high metals	Big Bell, Mulline, Bamboo Creek
Pyrite and base metal-rich polymetallic veins and disseminations in wall-rock with low acid buffering ability	Moderate-low pH, moderate to moderately high metals	Telfer, Paddys Flat, Mt Clement Sandstone, Golden Crown, Fraser, Horseshoe
Pyrite-rich, base metal poor veins and disseminations in wall-rock with low acid buffering ability	Low pH, relatively low metals	Golden Pole, Watertank Hill, Hill 60, Bounty, Reedy, Copperhead S, Nevoria, Bellevue, Grants Patch
Pyrite and base metal-rich polymetallic veins that are carbonate rich or occur in wall-rock altered to contain carbonate	Near neutral pH, moderate metals	Teutonic Bore, Kalgoorlie, Copperhead N, Granny Smith, Paddys Flat, Three Mile Hill
Pyrite and base metal-rich polymetallic replacements and veins in carbonate-rich sediments	Near to above neutral pH, moderate metals	Cadjebut
Polymetallic veins with moderate to low pyrite and base metal content that are carbonate rich or occur in carbonate-rich wall-rock	Near to above neutral pH, low metals	Gidgee, Nevoria, New Celebration, Harbour Lights, Paddington, Norseman, Wiluna, Leinster, Mt Keith, Blue Bird
Pyrite-poor polymetallic replacements in carbonate-rich sediments	Above neutral pH, very low metals	Cadjebut
Pyrite-poor gold–tellurium veins and breccias with carbonate gangue	Above neutral pH, very low metals	Kalgoorlie

The greenstone-hosted gold mines in Western Australia have limited potential for the development of acidic waters. The deep weathering profile and extensive carbonate alteration associated with the gold mineralisation have the capacity to neutralise any acid water generated by the weathering of sulphides in the orebody. Although the presence of carbonate may limit the likelihood of acid-water generation, there is still potential for the release of other metals or metal compounds depending on the specific geochemistry and environmental conditions for each deposit (Williams, 1995). The case study for Revenge gold mine (Case Study 16) discusses the issue of acidification and is relevant to most gold mines.

Several of the Pilbara iron ore mines encounter the Mount McRae Shale, a highly reactive black pyritic shale, which has the potential for acid-generation upon exposure to air, water and bacteria over a period of time (Johnson and Wright, 2001). Spontaneous pyrite oxidation and subsequent generation of H_2SO_4 is a significant problem during mining operations. There are also significant mine closure issues where the final mine void still contains pyritic shale either in the pit floor or the walls. Any water passing over these surfaces may become more acidic and result in acid mine drainage. It is therefore important that any mine closure strategy should address the covering of these surfaces with sterile backfill material or water.

2.3 Types of mine voids

Mine voids are rarely hydrogeologically isolated from the surrounding area; hence, there is potential for contamination of local groundwater resources. The extent of impact on the surrounding groundwater environment is largely dependent on the local hydrogeology. Commander et al. (1994) defined three broad hydrogeological environments for mine voids (Fig. 5).

Groundwater sink: Evaporation exceeding the rate of groundwater inflow; hence, the void acts as a groundwater sink. Waterlevels recover slowly to a level lower than that of the pre-mining watertable. Continued evaporation with no outflow leads to progressive salinity increase with the formation of brine, and either to salt crystallisation in the pit or reflux brine discharge driven by its density against the apparent hydraulic gradient. Most hard-rock mines in the State will form groundwater sinks.

Groundwater throughflow: Groundwater inflow exceeds evaporation with the void acting as a throughflow cell. The post-mining waterlevel will recover relatively slowly (decades) and probably stabilise at a level lower than pre-mining. The salinity increases slowly in the pit lake with the development of a brackish to saline plume. Movement of the plume from the pit results in increased groundwater salinity down-gradient of the void. The salt concentration and resultant impact on the surrounding aquifer depends largely on the rate of throughflow. This type is primarily associated with voids in high-permeability ore bodies surrounded by lower permeability rocks.

Groundwater recharge: Inflow to the pit greatly exceeds evaporation from the pit lake surface and waterlevels may recover rapidly (years) to pre-mining levels. This is most likely to occur in areas of high rainfall, or where surface water is diverted into the void once mining has ceased. The void acts as a recharge area for the local aquifer and may overflow during periods of excessive rainfall. The monsoonal zone in Northern Australia, for example, commonly experiences tropical rain depressions that result in deluges of rain during the wet season. The pit lake water may increase slightly in salinity during the dry season, but will have minimal impact on the surrounding aquifer as the diluted 'plume' moves along the groundwater flow path.

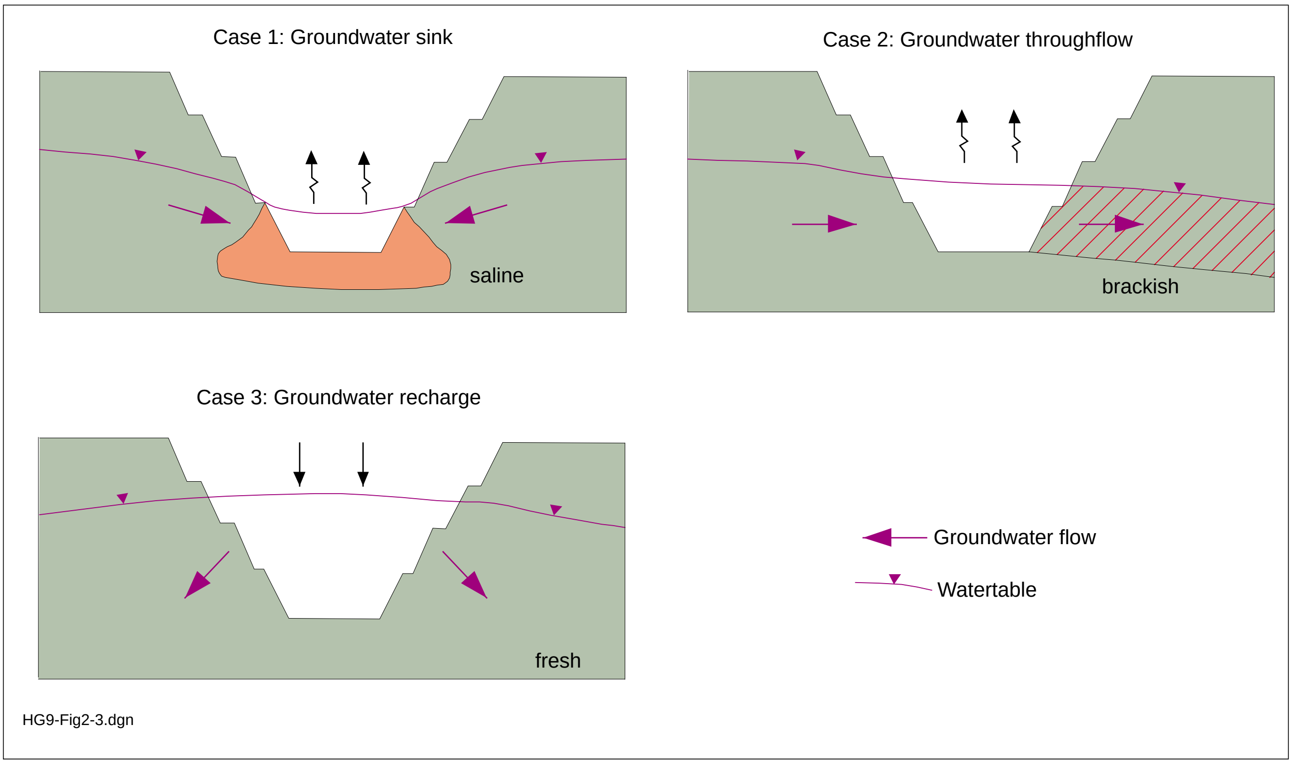

Figure 5. Hydrogeological environments for mine voids (after Commander et al., 1994)

2.4 Environmental consequence of mine voids

The creation of pit lakes and potential problems of salinisation and acidification may adversely affect local and regional groundwater resources, as well as the broader natural environment. The magnitude of the impact may range from insignificant in low-permeability rocks and saline groundwater systems, through to considerable in high-permeability rocks and low-salinity groundwater environments. Mining below the watertable may have an impact on ecosystems and the natural environment by altering groundwater quality or levels. In particular, environmental systems associated with surface expressions of groundwater, shallow groundwater aquifers or subterranean groundwater ecosystems are often especially sensitive to change.

2.4.1 Reducing the beneficial use of water resources

The concept of 'beneficial use' is fundamental to establishing a context for evaluating environmental implications of mine voids and resultant pit lakes. Beneficial use is defined as "*an environmental value or use of the environment or any element or segment of the environment which is conducive to public health, welfare, safety, or aesthetic enjoyment and which requires protection from pollution sources*" (ANZECC, 1998).

The intrinsic (or resident) water quality represents the base for defining the beneficial use of a water resource. Beneficial use can be considered as the highest value use of a water resource. In most cases, where a water resource is of potable quality, the beneficial use is for town water supply and human consumption. Similarly, where resources are of stock-water quality (up to 10 000 mg/L), then this is its beneficial use. In water resources where salinity is greater than stock-water quality, the only beneficial use is for mining purposes. In general, therefore, the largest range of beneficial uses is associated with fresh to potable water resources.

Any predicted impact on the water resource is assessed in terms of balancing potential reduction in beneficial use options against the overall economic and social benefits of a project, and the present beneficial use in supporting the project. It is therefore important that the proponent and other stakeholders, in consultation with Government, identify the potential beneficial use of the groundwater resource prior to development so that appropriate management objectives can be developed during project planning.

2.4.2 Extent of environmental impacts

Most environmental impacts associated with operating mines are concentrated near the mine, although mine dewatering can affect groundwater levels over large distances. Longer term impacts on regional groundwater quality are also a major concern, particularly as saline plumes from 'throughflow' mine voids may extend large distances down-gradient and affect other groundwater resources. The lateral extent of a saline plume is dependent on the presence and hydraulic connection of permeable aquifers, such as palaeochannels, specific weathering profiles, or structural features. It is possible for a saline plume to extend for tens of kilometres from the mine void, a consideration in evaluating potential impacts on nearby groundwater resources.

2.4.3 The time factor

As mentioned in Section 2.2, the water quality and final pit-lake level may take centuries to reach equilibrium. In cases where the resultant saline plume is able to move from the mine void, the rate of movement will be in the order of metres to tens of metres per year. As such, water supply borefields and towns at significant distances from an abandoned pit may not be affected for several millennia.

Qualitative predictions of saline plume movement can be made but their reliability is expected to decrease as the time frame increases. Both estimated and measured parameters may be used, with appropriate conceptual and numerical models. Long time frames make validation of the predicted impacts hazardous, if not impossible. It is therefore difficult to dispute, by direct measurement, any claims concerning the presence or absence of future adverse impacts.

There are two possible approaches to addressing long-term effects:

- manage the impact by appropriate closure design, regardless of the time it would take the impact to develop; or
- set a time, which may be 100 years, 1000 years or longer, beyond which it is considered unrealistic for the proponent to manage an environmental impact.

2.4.4 Cumulative impacts

Additional research is required to assess the cumulative impact of numerous mine voids in a relatively small area. This is particularly relevant where the surficial aquifers are important sources of potable and stock-water supplies, such as in the Pilbara and Murchison–Northern Goldfields regions. Many mining operations create a multitude of pits or mine voids, which individually may not pose a significant long-term problem. However, collectively the mine voids may act as a diffuse pollution source.

2.4.5 Health and safety issues

Water in the final void may give rise to additional hazards, including:

- potential for harbouring water-borne diseases;
- risk of drowning (which is managed by excluding unauthorised visitors); and
- risks to fauna well-being or human health if void water becomes non-potable and is subsequently consumed.

A crucial hazard is the potential for spreading water-borne disease from bodies of open water, such as pit lakes. This is particularly significant in northern parts of Australia, where Ross River virus, Barmah Forest virus and Australian encephalitis are endemic. The availability of quiescent surface water bodies at abandoned mines may provide a permanent breeding habitat for mosquitoes, some of which could be vectors for these human diseases.

Native mammals, particularly kangaroos and wallabies, are natural hosts of Ross River virus and Barmah Forest virus, whereas waterbirds are hosts of the Australian encephalitis virus. These animals tend to congregate around artificial or natural water bodies, thereby facilitating the transmission of disease to nearby humans. The risk of spreading these diseases may be increased because many of the voids may be visited on a regular basis by mine company personnel and others for authorised purposes. Moreover, some mosquito species breed in saline water, so the long-term salinisation expected in some pits may not decrease the disease risk from this source.

2.4.6 Environmental disturbance

In a regional context, mining has a localised impact on the natural environment. Government agencies, in conjunction with the mining companies, endeavour to minimise and control the extent of this impact. The following are some of the more-obvious environmental impacts associated with mining below the watertable:

- physical disturbance, such as clearing of native vegetation, interference with land uses or alteration to natural drainage, at the mine site itself;
- temporary creation of new or enhanced environments during the discharge of water into arid environments by mine-dewatering processes and the resultant decline of these environments when mining is completed; and
- temporary lowering of the surrounding watertable during mine dewatering may adversely affect water dependent and aquatic flora and fauna (including subterranean fauna).

3 Regional characterisation of mine voids

The Australian Centre for Minesite Rehabilitation Research developed a classification for Australian mining void types based primarily on climate (Mallet and Mark, 1995). Final mine voids were classified at a national level into eight major types (Fig. 6) with three present in Western Australia. Turner and Jones (1998) further refined the classification of voids into three major categories and several sub-categories on the basis of mining type into metalliferous (base metals, gold and iron ore), coal and others (bauxite, mineral sands and construction materials). The major distinction between types is the occurrence of reactive sulphides and heavy metals, interaction between mine waste and water in the pit, the depth of the void, and whether progressive backfilling and rehabilitation is undertaken during mining.

After a review of mining throughout the State, it was decided to redefine mine void groupings within nine regional categories (Fig. 7), based on geology, climate, groundwater quality, type of ore and regional setting. Groundwater salinity and beneficial use of the groundwater resources were also factored into determining categories. It is important to note that the regional categorisation is subjective and boundaries are generalised. Several of the regions have no opencut mining below the watertable, and, are not described in detail. Table 3 summarises the characteristics of each regional category.

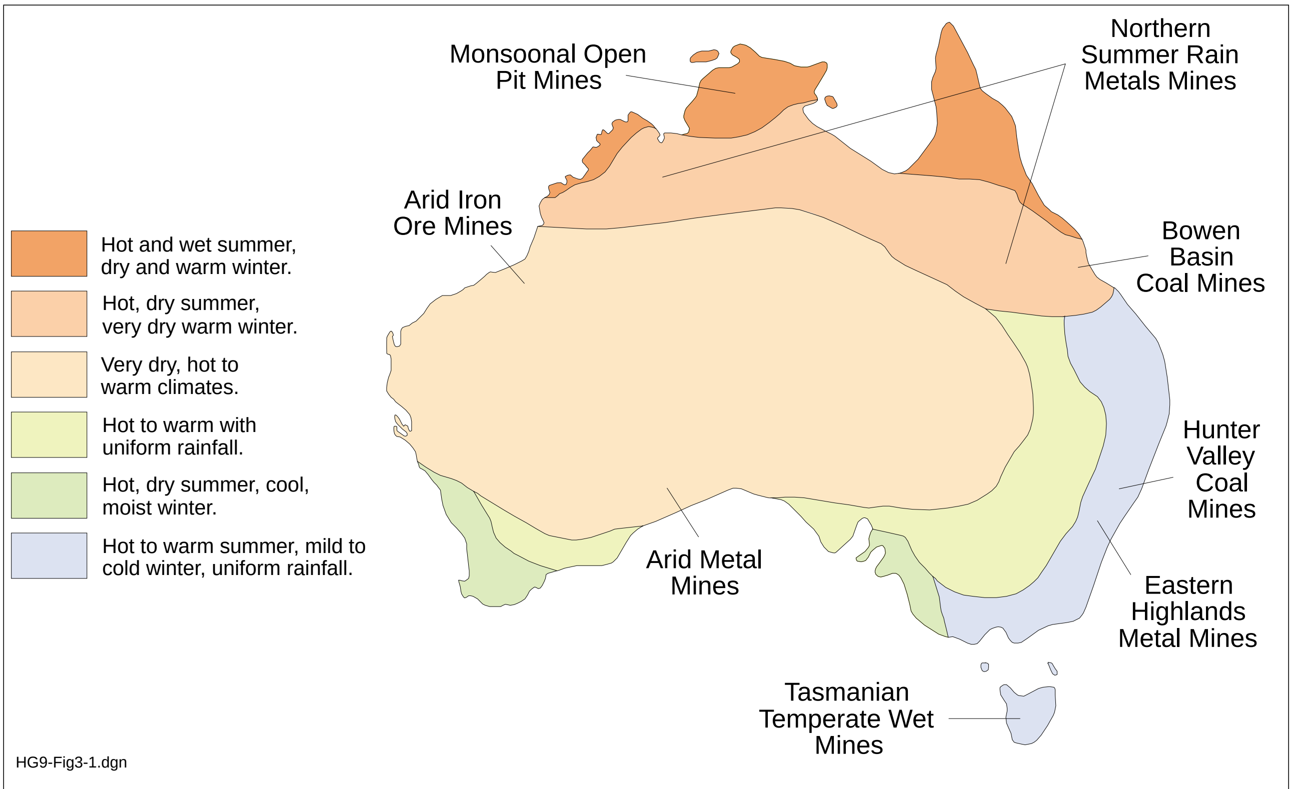

Figure 6. Final mine void classification throughout Australia (*after* Mallet and Mark, 1995)

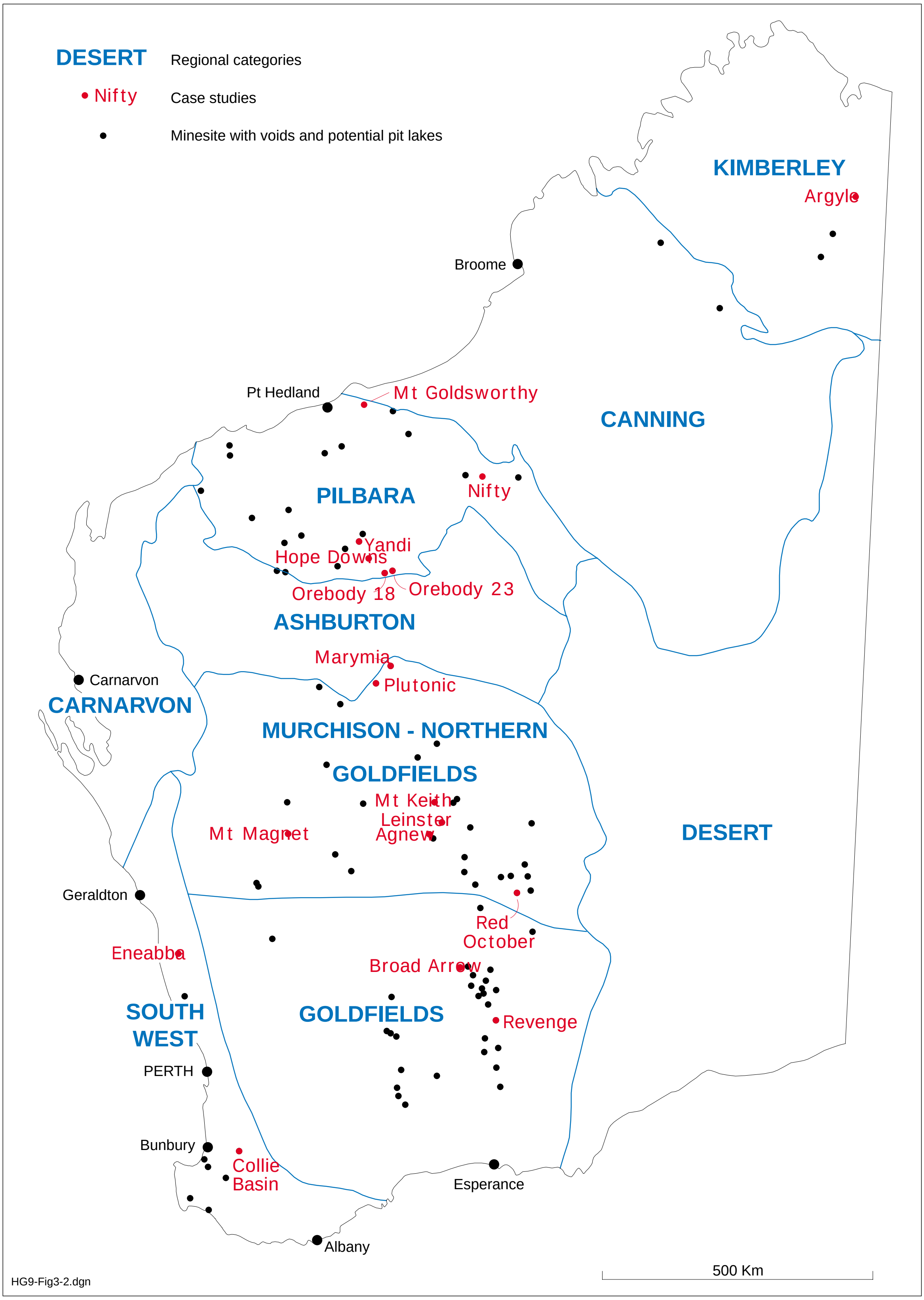

Figure 7. Regional classification of mine void groupings and selected case studies in Western Australia

Table 3. Key characteristics of each regional category for mine voids

Mine void region	*Climate*	*Geology*	*Groundwater salinity*	*Beneficial use rating*	*Prominence of mining*
Kimberley	Tropical (summer rain)	Fractured-rock	Fresh – marginal	High	Low
Canning	Arid (summer rain)	Sedimentary basin	Fresh – saline	Moderate	Low
Pilbara	Semi-arid (summer rain)	Fractured-rock	Fresh – brackish	High	High
Carnarvon	Semi-arid (winter rain)	Sedimentary basin	Marginal – saline	Moderate	Low
Ashburton	Semi-arid (winter rain)	Fractured-rock	Marginal – saline	Moderate	Low
Murchison–Northern Goldfields	Semi-arid (summer rain)	Fractured-rock	Marginal – saline	Moderate	High
Goldfields	Arid (non-seasonal rain)	Fractured-rock	Saline – hypersaline	Low	High
Desert	Arid (non-seasonal rain)	Sedimentary basin	Brackish – saline	Moderate	Low
South West	Temperate (winter rain)	Sedimentary basin	Fresh – brackish	High	Moderate

3.1 Kimberley

The Kimberley Region lies within the dry-hot tropical climatic zone. Annual rainfall varies from about 350 mm in the south to over 1400 mm along the northwest coast. Most rainfall occurs from November to March associated with monsoonal depressions, tropical cyclones and thunderstorms. The change in seasonal and annual quantity of rainfall is highly variable. Evaporation rates are high, up to 4000 mm/yr.

There is extensive surface-water drainage, with most rivers and creeks flowing only in the wet summer months. Peak flows are considered very high and occasionally result in extensive flooding. Groundwater exists throughout the region and serves as an important water supply for towns, Aboriginal communities and the pastoral industry. Fresh to marginal groundwater (500–1500 mg/L TDS) occurs in fractured-rock aquifers and localised valley-fill aquifers.

The regional geology is dominated by the King Leopold and Halls Creek Orogens, which extend along the southeast and southwest boundaries. Mining is restricted largely to those geological provinces with various small-scale gold and base metal deposits. The most significant opencut mine is Argyle Diamond Mine (Case Study 1), which is located on the northern end of the Halls Creek Orogen.

Final pit lakes in the Kimberley region are likely to form either ‘groundwater sink’ or ‘groundwater throughflow’ types, depending on the nature of surrounding lithologies and presence of aquifer systems. In the long term, the high evaporation rates will increase salinity of pit lake water as evaporation still vastly exceeds rainfall, although it is possible that significant rainfall events during the ‘wet-season’ may dilute any evaporation effects.

From a hydrogeological perspective, allowing the final voids to fill with water is an attractive mine closure option. The water storage option, whether for irrigation or recreational (tourism) purposes, may have great merit in the Kimberley region and provide economic benefits to the local community (for example aquaculture and tourism).

3.2 Canning

The Canning Region experiences an annual rainfall varying from 200 mm in the south to 550 mm in the north resulting largely from tropical summer cyclones. A large portion of the region is occupied by the Great Sandy Desert with evaporation rates of up to 4500 mm/yr.

The region has no major surface-water resources, with internal drainage features flooding only rom infrequent cyclonic rainfall. There are significant groundwater resources stored within the Canning Basin, which comprises multi-layered, extensive sandstone aquifers. Most groundwater occurs at depth throughout the area. Even though the Canning Basin has large groundwater storage, it receives only limited recharge. Groundwater salinity typically ranges between 1000 and 7000 mg/L TDS and salinity increases with depth and distance from recharge areas.

Mining is restricted largely to the Devonian–Early Carboniferous sediments of the Lennard Shelf, with base metal mining at Cadjebut and diamond mining at Ellendale, which is located along the northern boundary with the Kimberley Region. The remainder of the region has no mining activity; there is little likelihood of opencut mining, and most mineral prospectivity related to petroleum reserves. No case studies have been undertaken for the Canning Region.

3.3 Pilbara

The Pilbara Region has a semi-arid to arid climate with annual rainfall ranging from 200 mm to 350 mm in the central Hamersley Ranges. Rainfall events are infrequent, irregular and intense. The most intense rainfall occurs in the summer and is related to tropical cyclones during January and March, with a frequency of about seven cyclones every decade. Annual evaporation rates are high at about 4000 mm/yr.

The Hamersley and Chichester Ranges are prominent surface-water divides. Streamflow is highly variable and erratic and takes place over short periods. The Pilbara has numerous rockholes, springs, river pools and watercourses with many sites of high conservation, recreation or heritage value, which require protection and careful management.

The Pilbara Craton, Hamersley Basin and Paterson Orogen are the major geological provinces. Iron ore is mined throughout the Hamersley Basin, as well as along the northern rim of the Pilbara Craton. There is a multitude of smaller gold and base metal mines within the Pilbara Craton, and two large-scale mining operations (Telfer Gold Mine and Nifty Copper Mine – Case Study 2) in the Paterson Orogen on the edge of the Great Sandy Desert. Mining is the major economic activity in the region, although large tracts of land are under pastoral lease.

The scarcity and unreliability of surface water resources has necessitated widespread groundwater resource development for water supplies to towns, industry and agriculture (Johnson and Wright, 2001). Groundwater is also essential for the maintenance of the environmental ecosystems associated with springs and permanent pools in the drainage systems. Groundwater occurs throughout the region in fractured rock (igneous and sedimentary), valley-fill and chemically deposited rock (calcrete and pisolitic limonite) aquifers. The groundwater is generally fresh to brackish with potable supplies in localised areas.

Six case studies (Nos 2–7) have been completed and are considered representative of the various hydrogeological environments throughout the Pilbara. In all cases, the regional groundwater resources are fresh and there is potential for pit lakes to become point sources of hypersaline water. The case studies highlight that although there are various mine closure options for the Pilbara, hydrogeological connection of mine voids with important wetlands or groundwater resources is a major consideration.

At Mount Goldsworthy (Case Study 3), the mine void is hydrogeologically isolated from any significant groundwater resource; hence, there should be no significant contamination of the local groundwater resources from the resultant saline plume. In contrast, the other case studies exhibit varying degrees of throughflow into adjacent aquifers of regional significance, and companies, therefore, have been required to develop closure strategies for mining approval. The Hope Downs operation (Case Study 6) is the worse-case scenario for mine closure because the adjacent aquifer is sensitive to any groundwater abstraction (dewatering) and is fully allocated to providing environmental water requirements.

3.4 Carnarvon

The Carnarvon Region occupies the semi-arid summer and winter rainfall climatic zones. Annual rainfall ranges from 250 mm in the north to 400 mm in the south, is unreliable, and varies significantly between years. Winter rainfall is associated with intense, southwest frontal systems, whereas infrequent, summer rainfall is derived largely from thunderstorm activity. The area experiences hot summers and mild winters with evaporation rates of about 3000 mm/yr.

Surface drainage consists of well-defined rivers that flow westward to the sea or discharge into the coastal Lake MacLeod. The Gascoyne River, the major drainage feature, supports significant agricultural activity along its lower reaches.

Regional groundwater resources exist primarily within the Carnarvon Basin. Unlike other sedimentary basins in Western Australia, the Carnarvon Basin comprises predominantly shale of low aquifer potential with few sandstone aquifers. The Birdrong Sandstone is an important confined aquifer, which is characterised by artesian groundwater conditions in western areas. Groundwater quality is fresh in eastern recharge areas becoming saline near the coast.

Salt is the main mineral commodity of the region and is produced via solar evaporation or harvesting brines from salt lakes, such as Lake MacLeod. At present, there are no large-scale opencut mines in the Carnarvon Region. It is unlikely that opencut mining would be developed in the Carnarvon Basin. Although there has been coal exploration at Wandagee, most prospectivity is related largely to petroleum deposits. It is anticipated that any mine void would act as a ‘throughflow’ type and that backfilling would be the preferred closure strategy.

3.5 Ashburton

The Ashburton Region has a climatic regime similar to that of the Carnarvon Region. Annual rainfall, although highly variable, is about 200 mm/yr. Evaporation is high, in the order of 2500 mm/yr. The region lies between the Ashburton and Gascoyne Rivers, which flow intermittently. The physiography is characterised by broad alluviated plains, which are separated by a series of strongly dissected ranges.

The main regional aquifers include valley-fill (alluvium and colluvium), calcrete and fractured metasedimentary rocks. The depth to groundwater is typically shallow, less than 10 m from surface. Groundwater quality ranges from fresh beneath catchment divides to saline in the lower drainages. Stock watering and domestic purposes are the most common uses of groundwater.

Since the 1890s, there has been small-scale mining of gold, base metals and gemstones. At present, there is no major mining in the region; however, there is significant potential for mineral discoveries. In the event of opencut mining, it is most probable that the mine voids would act as ‘groundwater sinks’ owing to the high evaporation rates, or ‘throughflow’ types, depending on the presence of fractured-rock aquifers. The selection of the preferred closure strategy is dependent of the proximity of the mine void to local groundwater resources, although most mine voids would be left to reach equilibrium and form a pit lake.

3.6 Murchison – Northern Goldfields

The Murchison – Northern Goldfields Region is arid to semi-arid. Rainfall ranges between 200 and 250 mm/yr and is highly variable with long periods of drought, although the region often experiences flooding as a result of cyclonic activity. Annual evaporation rates are high, varying from 2800 mm in the southwest to 3800 mm in the northeast.

Surface drainage is ephemeral with any streamflow towards the coast in the west (Murchison) or eastward into inland salt lakes (Northern Goldfields). Three broad, sub-parallel southeast-trending palaeodrainages are present in the Northern Goldfields (Johnson et al., 1999); these have very low hydraulic gradients and contain large playa lakes. The playa lakes become inundated during intense rainfall events resulting in connection between lakes, overflowing and discharge towards the Eucla Basin.

Groundwater occurs in surficial aquifers comprising alluvium, calcrete and palaeochannel sand, as well as locally in fresh and weathered fractured-rock aquifers. Groundwater salinity is variable, ranging from fresh to hypersaline with the lowest salinity along groundwater divides. Fresh to brackish groundwater is more common in the north, where recharge from rainfall is more effective (Johnson et al., 1999). The mining industry is the primary groundwater user requiring large quantities of fresh to hypersaline water for mineral processing, dust suppression and dewatering. Other groundwater users include towns (fresh water) and pastoral properties (fresh to brackish water).

Seven case studies (Nos 8–14) have been completed for the Murchison–Northern Goldfields Region, illustrating specific or different hydrogeological aspects relating to the final mine voids. Most mine voids are located along structural lineaments within the fractured-rock environment that contain brackish to saline groundwater. The creation of hypersaline pit lakes has the potential to impact on local groundwater resources, except where mine voids are located near salt lakes. The Plutonic gold mine (Case Study 8) is a good example of a mine void in fractured-rock aquifers that contain fresh to brackish groundwater, whereas the Red October mine (Case Study 14) is representative of a mine void in a salt-lake environment.

A potential water resource concern in the Murchison–Northern Goldfields is the cumulative impact of numerous mine voids. Many of the gold operations have created a multitude of pits or mine voids which individually may not pose a significant long-term problem; however, the mine voids may act collectively as a diffuse pollution source. There are concerns about long-term salinisation of groundwater resources impacting on the surficial aquifers, which are often important sources of potable and stock-water supplies.

3.7 Goldfields

The Goldfields Region has a semi-arid climate with a highly variable annual rainfall ranging from 100 mm to 500 mm. Winter rainfall is associated with cold, southwesterly fronts, while summer rainfall results from thunderstorm and cyclonic activity. High evaporation rates of 3000 mm/yr produce a rainfall deficit in most years.

The region is characterised by undulating sand plains, granite outcrop and north-trending greenstone ridges. Surface drainage consist of short ephemeral creeks which flow only after heavy rains. The drainages terminate in saline playa lakes, as well as ephemeral fresh water lakes or clay pans near Kalgoorlie. Salt lakes of various sizes are contained within ancient palaeodrainages (former deep drainage lines filled with sediment) that are internally draining.

The discovery of gold in the late 1800s resulted in the development of Australia's premier goldfields. In the 1980s, new mineral processing technologies led to increased demand for water and extensive utilisation of the local groundwater resources. Groundwater, which occurs primarily in the palaeochannels (Commander et al., 1992) and localised fractured-rock aquifers, is used mainly by the mining industry, who abstract large quantities of saline to hypersaline water for mineral processing, dust suppression and dewatering activities.

All mines in the Goldfields lie within a saline groundwater environment, where the resident groundwater salinity can reach 300 000 mg/L TDS. As such, the creation of hypersaline pit lakes will have negligible impact on the existing hypersaline conditions (Case Studies 15 and 16).

3.8 Desert

As the name implies, the Desert Region is dominated by the Gibson Desert, Great Victoria Desert and the Nullarbor Plain. The climate is arid with an annual rainfall of less than 250 mm and evaporation rates up to 4500 mm/yr. The region has no surface water resources, although numerous internally-draining features occasionally flood during cyclonic rainfall. Brackish to saline groundwater resources are stored within the Eucla and Officer Basins, which contain multi-layered, extensive limestone and sandstone aquifers respectively. There is no current or planned mining in the region.

3.9 Southwest

The Southwest Region encompasses the coastal strip from Geraldton in the north to Albany in the south, and extends inland to include the Collie Basin. Annual rainfall, most of which occurs over the winter months, varies from 400 to 1400 mm/yr. Evaporation is about 1800 mm/yr. There are significant surface-water resources, as streamflow is often perennial. The combination of geology and reliable rainfall has resulted in the Perth Basin containing the State's largest fresh groundwater resource. Groundwater resources are utilised for town water supplies, industry and irrigated agriculture. The aquifers also sustain numerous wetlands on the coastal plain.

Mining is varied, comprising mineral sands, bauxite, coal (Collie), gold (Boddington), minor base metals (Greenbushes) and construction materials. Most mining, excluding the coal operations, involves shallow opencut operations. There has been a great deal of research on the environmental impact from mining activity in this area, particularly in respect to mineral sands and coal mining. It was therefore decided not to initiate further investigations, although two case studies were undertaken to emphasis specific management issues. Case Study 17 addresses void closure strategies for mineral sand mining in the northern Perth Basin, and Case Study 18 outlines creek diversion into deep coal mine voids in the Collie Basin.

4 Post-mining options with mine voids

The primary concern at mine closure has been ensuring that any mine void is geologically stable and safe to the public under Department of Minerals and Energy guidelines (DME, 1996). However, both industry and regulators have recently started to focus on the environmental, visual and social impacts associated with abandoned mine voids. Adequate mine void management strategies are required for officially closed voids, as well as mining operations under ‘care and maintenance’. There are three mine void closure strategies that can be applied:

- open void;
- waste storage; and
- water storage.

Mallet and Mark (1995) developed a useful decision pathway to identify the steps and technical data necessary in selecting the most suitable option with climate, site geology and social setting being the primary factors. The final decision requires careful cost-benefit analysis, considering engineering costs, liability risks, public image (cost or benefit), economic benefits, environmental benefits and regulatory acceptance. At a number of mine sites throughout the State this selection process has been followed, although a major shortcoming is a lack of consideration for impact on water resources.

4.1 Open void

Most mine voids are abandoned as ‘open voids’ as it is the easiest and most practical option, particularly where there is a possibility of further mining. Many of the older mine voids, such as Mount Goldsworthy (Case Study 3), were closed or abandoned prior to the introduction of the modern, stricter, environmental requirements. It should be noted that the majority of these mines, if closed today, would probably still have been left as open voids and allowed to naturally fill with water.

Open void is the only practical option for the very large pits, such as Mount Whaleback and Tom Price in the Pilbara and the Super Pit at Kalgoorlie, which are not directly linked to significant regional water resources and are too large to backfill. Even mines that are directly connected to local aquifers, such as Nifty copper, Telfer gold and Argyle diamond, are too large to readily backfill and are left as open voids. Fortuitously, these mines are also remote and isolated from other groundwater users.

Most non-operating pits are left as open voids, as there may be potential for future deeper mining or no imperative to incur the substantial backfilling costs. Although, there are important issues that require careful consideration associated with mine closure in salt lake environments, including pit wall stability (slumping, water and wind erosion) and safety aspects (Dames and Moore, 1999), it may be preferable to allow the pits to fill with water and become part of the lake system

The open void strategy may also have potential long-term benefits to the community. Various initiatives exist to encourage the development of innovative water-treatment approaches for pit lake water and the utilisation of treated water for commercially viable approaches for tourism, fish farming, tree farming and horticulture enterprises, including those of Placer Dome Pty Ltd (Miles, 2002) and the Centre of Excellence in Sustainable Mine Lakes.

4.2 Mining waste storage

From an environmental standpoint, and in keeping with community expectations, the backfilling of final voids with waste may be considered the most desirable outcome. This is possible only where the volume of ore is relatively small compared with the volume of the material extracted, and/or the long-term environmental benefits outweigh the capital cost. Several of the Pilbara iron ore mines are good examples of where backfilling is required, as the voids are hydrogeologically connected to significant groundwater resources, and the cost of backfilling is outweighed by complying with environmental constraints at mine closure, such as Hope Downs (Case Study 6) and Yandi (Case Study 7) mines.

4.2.1 Waste-rock storage

The practice of backfilling is widely used by the broader mining industry because of cost savings, both in disposal and rehabilitation. Major mining companies in the State, as part of best mining practice, encourage the backfilling of mine voids in preference to the creation of on-surface waste dumps. Prior to backfilling, it is important to ensure that the mine void is sterile with no prospects for future mining. Backfilling with waste-rock is finding greater acceptance in the gold mining industry, particularly where abandoned voids are in close proximity to ongoing mining operations, such as at Mount Magnet (Case Study 10) and Broad Arrow (Case Study 15).

4.2.2 Tailings storage

In-pit storage is a useful alternative for handling sulphidic tailings and slurry waste material. Jones (1999) noted that underwater disposal is the most practical technology for the containment of sulphidic material, which has potential for acid mine drainage. Any final mine void considered for tailings storage should be geologically stable with the walls comprising competent rock. The void must be filled to the original land surface, with any sulphidic material stored below the final recovery waterlevel to ensure that it is maintained in a completely saturated condition. The material above the final watertable should consist of inert waste rock. In the case of subaqueous tailings storage, the tailings surface must be covered by at least 5 m of water at all times (DME, 1996).

Potential problems involved with in-pit tailings storage include:

- reduction of the material strength in the void wall;
- integrity and strength of the tailings material;
- possible contamination of groundwater; and
- rehabilitation difficulties as a result of the influx of hypersaline groundwater.

Successful in-pit tailings storage requires substantial dewatering during the tailings deposition process. Rehabilitation requires a stable tailings surface of sufficient bearing capacity for equipment to traverse the surface of the tailings storage facility (TSF), as well as resistance to wind erosion. Groundwater monitoring bores must be installed around the TSF and it is critical to regularly monitor waterlevel and quality. Over time, the tailings water may leach into the local groundwater, resulting in potential contamination of the groundwater resource. There are numerous examples of successfully engineered in-pit tailings disposal within the gold mining industry, such as Marymia (Case Study 9) and Plutonic (Case Study 8).

Eneabba West Mine (Case Study 17) illustrates where the backfilling of a mine void with tailings material has altered the local groundwater flow pattern and waterlevels, as the tailings have a lower hydraulic conductivity than the surrounding lithologies. Groundwater modelling indicates that five artificial lakes and strategically-placed phreatophytic vegetation will be required to prevent any significant increases of waterlevel and development of saline areas.

4.3 Water storage

4.3.1 Storage of dewatering discharge

The increasingly stringent environmental constraints on the discharge of excess water, primarily from dewatering, into riverine or salt lake environments has forced mining companies to consider water storage in nearby abandoned mine voids. Water storage also has the advantage that, should further mining ever be considered, the mine void will require only dewatering.

The storage of dewatering discharge is not suitable where hypersaline water is stored in mine voids within a less saline groundwater environment. It is necessary for the proponent to demonstrate that the proposed storage void is not hydrogeologically linked to any significant groundwater resource, and that any potential groundwater contamination will be localised. This is the case at the Wallaby Project near Lake Carey, where hypersaline groundwater in excess of 250 000 mg/L was temporarily stored in abandoned mine voids (Granny and Goanna pits) with a resident groundwater salinity between 15 000 and 40 000 mg/L. Recent groundwater monitoring has shown that, owing to the low permeability of the fractured-rock aquifers, the area of impact to groundwater resources was limited to the vicinity of the mine void.

Problems may arise with storing dewatering discharge in mine voids that intersect permeable features (palaeochannels, regional faulting etc.) resulting in significant leakage. This is the case at New Hampton’s Nobel Pit near Kalgoorlie, where the mine void intersects a palaeochannel resulting in stored discharge water artificially recharging the underlying palaeochannel aquifer. Here, the situation may be highly advantageous to down-gradient groundwater users; however, it would be unacceptable where there is significant deterioration in the groundwater quality.

4.3.2 Diversion and capture of surface water

The natural flooding of mine voids from intense rainfall events demonstrates the viability, on an opportunistic basis, of final voids as potential surface-water reservoirs. The capture of surface water runoff enables mining operations to reduce groundwater abstraction with potential savings in pumping and treatment costs.

In the Goldfields, many mine voids are often used as surface-water reservoirs to supplement process water. The Back and Beyond pit at Mount Morgans gold mine contains 100 ML of impounded water (Johnson et al., 1999). The potential for voids to be filled from either streamflow capture or intense rainfall events was demonstrated during Cyclone Bobby in 1995, when the Bannockburn pit in the Northern Goldfields was completely flooded. However, storm events of this magnitude are only expected to occur every twenty years and cannot provide a reliable, long-term water supply.

The capture of surface runoff and creek diversion is common practice in the Murchison – Northern Goldfield region. A good example is Windich pit at Granny Smith mine (Dames and Moore, 1994), which is capable of filling with diverted creek runoff and holding three year’s supply of process water. The creek diversion captures peak surface runoff, which only represents less than one percent of total flow into Lake Carey. As a result, the mining company has achieved considerable cost savings with minimal impact on the regional hydrology.

Mine closure strategies at Lone Pine mine void (Case Study 10) and Harmony mine void (Case Study 13) have indicated that the diversion of local creek systems may help to dilute concentrations in void lakes that may become progressively saline. Mining operations at Mount Magnet are utilising streamflow capture for supplementing process-water supply and to reduce the potential cumulative impacts of numerous potentially hypersaline pit lakes (Gerrard, 2002).

Streamflow capture is also considered a management tool in controlling increased salinity and acidification within pit lakes. As part of the mine closure schedule, the WO5B mine void in the Collie Basin (Case Study 18) will receive streamflow capture to prevent acidic and saline void water interacting with local water resources. Seepage can be expected from the void lake into the nearby underground collieries and the poorer quality water may migrate into surrounding aquifers. The diversion of the south branch of the Collie River into the final void will accelerate rates of lake filling, permit seasonal topping-up and overflowing of the lake, and also facilitate recharge into depleted deeper aquifers.

5 Mine voids and the mine approval process

5.1 Current regulatory framework

In Western Australia, mines are subjected to stringent environmental requirements and conditions as part of government legislation. The most important legislation in regard to mining and its possible impact on water resources is the *Mining Act 1978*, the *Rights in Water and Irrigation Act 1914*, and *Environmental Protection Act 1986*.

5.1.1 Mining Act 1978

The Mining Act regulated by the Department of Industry and Resources (DoIR) provides controls to mitigate or prevent adverse environmental effects of mining operations. Terms and conditions are set on the granting of a mining lease that provide for environmental protection and rehabilitation of disturbed areas. Under Section 84 of the Act, the Minister may amend lease conditions at any time "for the purpose of preventing or reducing, or making good, injury to the surface of the land".

In practice, prior to the commencement of mining (or at any time thereafter), the Minister for Mines may require submission of an environmental report. The environmental report assists in the determination of appropriate conditions for managing environmental effects, as well as including the setting of a performance bond to guarantee compliance with the environmental conditions of the lease. Section 95(2) of the Act provides that, in the event of a mining lease being surrendered, the lessee remains liable for meeting the conditions of the lease.

5.1.2 Rights in Water and Irrigation Act 1914

The Water and Rivers Commission carries out water-resource conservation, protection and management functions which are vested under the *Rights in Water and Irrigation Act 1914*. The Act provides for the licensing of groundwater exploration and abstraction with conditions to be placed upon the quantity of groundwater abstracted. The scope of the Act does not provide a mechanism for addressing the post-closure impacts of abandoned pits on groundwater resources.

5.1.3 Environmental Protection Act 1986

The Environmental Protection Act is regulated by the Department of Environmental Protection with the objectives of protecting the environment, as well as controlling, preventing and abating pollution. The scheme of the Act provides three distinct, although inter-related, strategies for attaining these objectives.

- Part III of the Act permits the development of statutory Environmental Protection Policies (EPP), which provide a regulatory framework for managing specific areas of environmental concern;
- Part IV of the Act sets out the environmental impact assessment (EIA) process applying to development proposals having significant potential environmental effects. The process enables the Minister for the Environment to set conditions for development projects to safeguard the environment; and
- Part V of the Act provides for prevention of pollution, as well as approving and managing premises having significant pollution potential. Regulations made under the Act deem mines that dewater in excess of 50 000 tonnes per year to be prescribed premises, and these must be licensed under Part V.

5.2 Current approval process

The licence to mine and the general environmental control by Government are achieved under the Mining Act. A Notice of Intent (NOI) is required for all new mine projects, while some mining proposals are subjected to formal EIA by the Environmental Protection Authority (EPA) requiring comprehensive documentation as either Consultative Environmental Review (CER), Public Environmental Review (PER) or Environmental Review and Management Plan (ERMP).

The proponent in all cases is required to provide a detailed description of the project and the existing environment. In recent years, a large number of substantial proposals that involve mining below the watertable and creation of pit lakes have been subjected to the formal EIA process. The process often takes about six to nine months to complete and typically requires:

- identifying environmental factors, potential adverse impacts and public consultation (scoping);
- collecting data (air, land and water) on the existing environment for those environmental factors identified as likely to be impacted;
- referring the mining proposal to the EPA for setting the level of assessment based on an initial assessment of data and impacts;
- collecting additional data (if necessary), prediction of impacts, formulation of environmental management commitments and preparation of environmental review document;
- submitting the environmental review document to the EPA to assess suitability of review document for public release;
- a review of the proposal by government departments and the public;
- the proponent responding to submissions and, if necessary, amending the commitments made in the environmental review;
- the EPA preparing a report containing advice to the Minister for the Environment;
- releasing the EPA's report which is open to appeal for a fortnight;
- the Minister for the Environment deciding whether to accept or not accept EPA advice and to subsequently issue approval with conditions which are binding on the proponent;
- auditing performance against conditions by DEP or delegated agencies; and
- monitoring by the proponent during operation and post-mining until the lease is relinquished.

The EPA conditions imposed on mining operations are considered flexible and often allow scope for additional hydrological or technical studies to be completed. The EPA may alter conditions where initial predictions or studies may prove to be incorrect through measuring and monitoring of impacts during the early stages of the project. The emphasis is on developing a commitment to environmental management and responsibility, rather than the imposition of strict limits or controls.

5.3 Mine closure considerations

Previously, in the mining approval process, there has been little attention paid to the issue of mine voids and potential environmental impacts. Mine closure plans were initially not integrated into feasibility, approval and run-of-mine (ROM) planning and companies did not consider closure issues until a few years before mine cessation. In recent years, there has been increasing demand from government regulators for new mine proposals to consider final rehabilitation strategies and mine closure during the mine approval process. Major mining companies have also started to recognise the merit in early mine closure planning as part of sustainable development principles.

In the Goldfields, the mine void issue is typically addressed in mining approval documentation (NOIs, etc.) with statements such as ‘the pit will be allowed to fill with hypersaline groundwater to the natural hydrostatic level, until its final end use is determined’. This approach assumes that the mine void will act as a ‘groundwater sink’ and the absence of permeable features which may permit leachate movement from the pit. There are increasing requirements for the proponent to demonstrate the functioning of the mine void, and extent of impacts, where there are adjacent fresh to brackish groundwater resources and/or potential to impact on the environment or cultural sites.

Several EPA environmental assessments, particularly in the Pilbara, have required proponents to provide greater detail with regard to mine void closure, particularly predictions of water-quality evolution. This is the case for the proposed Hope Downs iron ore mine (Case Study 6), which constitutes one of the most difficult mine void closure scenarios in the

State. The proponent was required to assess various final void management scenarios to ensure there was no potential impact on a nearby wetland of significant cultural and ecological importance. In consultation with the Government, the proponent agreed that the preferred void strategy is to backfill the mine void and artificially maintain water flow to the wetland over 20 years. Another important consideration is that the Government needs to be satisfied that the proponent has adequate funds for the cost of rehabilitation, which is in excess of $200 million.

6 The way forward with mine voids and pit lakes

6.1 Final void management

During active operations, minesite water management is well understood and regulated through of a number of government acts and regulations (Johnson, 2003). The management of water quality following mine closure is less familiar, presenting a wide range of challenges depending on the physical and social environments surrounding the final void. Currently, there are few detailed regulatory guidelines that address the performance of final pit lakes, and other government agencies require solutions to meet the broad goals of ecological sustainability.

Management options must outline solutions that require no ongoing intervention, as neither mining companies nor the Government wish to take on a liability over a period of hundreds or perhaps thousands of years. The early introduction of closure plans in the mine planning process often allows companies to evaluate and address the long-term issues, in particular the potential impact of the final mine void on the environment.

The aims of final void management should be:

- Rendering the site acceptable and safe over the long term;
- Minimising environmental and health risks in the vicinity of the site;
- Maximising to the practicable extent any potential future usage of the site; and
- Developing a ‘walkaway’ solution.

Technology will continue to advance and other solutions may eventuate before many of the current and planned mines close; however, it is necessary that closure plans are based on existing technology. The mine closure process should include an assessment of most practical technology options, as well as a risk analysis of post-closure liability. The need to obtain advance agreement on weighting factors for the risk analysis is critical, since the most acceptable option may change. The weighting factors must be site specific and dependent on the final usage of the void and its surrounds, impacts on water quality, extent of integration required with the existing topography, and the geomorphic and geochemical stability of on-surface tailings storage facilities and waste rock dumps.

The proponent, in consultation with the Government and other stakeholders, must define the potential beneficial use of the local and regional groundwater resources prior to development so that appropriate management objectives can be considered during project planning. In considering any mining proposal, it is critical to assess potential impacts on the water resource in terms of balancing any reduction in future beneficial use against the overall economic and social benefits.

Another consideration in final void management is post-mine closure usage of the pit lakes and the associated long-term benefits to the local community. The Centre of Excellence in Sustainable Mine Lakes is working toward developing innovative water-treatment approaches for pit lake water and research into the use of treated water for commercially viable approaches for tourism, fish farming, tree farming and horticulture enterprises. Placer Dome Pty Ltd at Granny Smith mine near Laverton have been actively developing aquaculture techniques to make use of discarded openpits, utilising them for either commercial or recreational aquaculture activities. Species including trout, silver perch, black bream, barramundi, yabbies and marron are currently being studied in order to determine their suitability to local climatic factors (Miles, 2002).

6.2 Considerations in guideline development

Existing publications on mine closure (ANZMEC/MCA, 2000; Chamber of Minerals and Energy, 1999) provide only limited discussion on environmental considerations related to mine voids. In consultation with other government agencies and the mining industry, the Water and Rivers Commission is working toward developing guidelines to assist the mining industry with addressing mine voids and pit lakes in the mining approval process. The guidelines will also provide detail on regulatory requirements, particularly the provision of groundwater information, predictive modelling and monitoring.

DRD (1999) made a number of suggestions about guideline development for proposals that involve mining below the watertable. These suggestions express the views of the different government agencies and have been incorporated in the following discussion. The major recommendation from DRD (1999) is that the guidelines should assist proponents to adequately address the mine void and pit lake issue during the three phases of mining:

- prior to construction (during the feasibility and approvals stage);
- during operation of the mine; and
- after mining has been completed.

It is critical that the guidelines cover the period until the mining company is permitted to relinquish the lease, after which the company would be deemed to have no further responsibilities with respect to their previous operations. The guidelines should highlight the suite of environmental impacts and effects on water resources associated with those mining projects that extend below the watertable, in particular the potential for long-term change in the level or quality of the pit lake as well as the surrounding regional groundwater resources.

The guidelines should ensure that sufficient data are collected and adequate interpretations are undertaken for reliable prediction of the quality and waterlevel in the final void, and to determine any consequential impacts on water resources and associated ecosystems. These impacts would have to be identified and accepted through the approval process with Government providing conditional approval, assuming that the long-term impacts can be acceptably managed. If post-mining monitoring confirms these predicted impacts, relinquishment of the lease subject to appropriate regulatory requirements will be considered.

The guidelines will address water allocation and disposal issues associated with mine voids. At present, there is some confusion about the correct protocol relating the utilisation or abstraction from pit lakes and the disposal of excess dewatering discharge into mine voids. In addition, the guidelines will also outline the different roles and responsibilities of each government agency to improve efficiency and effectiveness of the approval process.

6.3 Groundwater information requirements

An accurate assessment of the potential impact of mining below the watertable requires collection and interpretation of the best available groundwater information (Johnson, 2003). Most mining companies engage reputable hydrogeological consultants, who are aware of Government's requirements, to undertake the collection and interpretation of this information.

There are different groundwater information requirements during the life of any mine project, ranging from licensing groundwater exploration and water-supply development in the earlier stages to assessing the long-term impacts of pit lakes on groundwater resources. Post-closure information requirements are greatly different from development and operational requirements. It is therefore important that mining companies maintain high-quality records on groundwater abstraction and monitoring, as these will be critical for understanding the local groundwater environment and potential post-closure impacts.

6.3.1 Before mining

In future, new mining projects which involve mining below the watertable will undergo a more intensive initial assessment. The project appraisal will require an accurate assessment of the impact of mining and the final mine void on the groundwater environment. It will be crucial to identify local and regional water resources and determine the respective beneficial usage of these resources. Project proposals are currently required to provide the following groundwater information:

1. Identification and description of local and regional aquifers.
2. Understanding of interconnection between groundwater, surface water and the environment.
3. Determination of waterlevels and groundwater flow systems.
4. Determination of the regional groundwater quality.
5. Groundwater supply requirements and identification of possible sources.
   a) Impacts of proposed abstraction.
   b) Sustainability of proposed abstraction.
6. Identification of nearby and downstream groundwater users.
7. Identification of groundwater dependent ecosystems.
   a) Impacts of proposed abstraction.
   b) Outline remedial actions (if required).
8. Identification of sites of heritage or sacred importance.
9. Assessment of the mine position in the groundwater flow system.
   a) Means of discharge of dewatering wastewater — quality and quantity.
   b) Placement and leakage of residue areas (waste dumps and tailings).
   c) Position of mine voids and evaporation ponds.
   d) Potential for land-surface subsidence.
10. Identification of possible impacts of the mining activity on the groundwater system.
11. Assessment of impacts over different time intervals.
12. Proposed groundwater management practices and mitigatory measures.

In project proposals involving mining below the watertable, proponents are required to develop a conceptual model, if necessary with additional predictive modelling, to determine long-term changes in the level and quality of the final void. The completion of these initial steps in the project approval process will help identify, and make all parties aware of, any issues for mine closure. In determining what closure strategy to adopt, the mining company must:

- provide some prediction of pit lake water quality over time;
- determine the presence of any significant groundwater resources and the beneficial use of the aquifer;
- identify the hydrogeological linkage between the void and adjacent aquifers;
- determine the potential impact of the selected void-management strategy on the groundwater system (highlighting the worst-case scenario); and
- develop and implement a monitoring programme to confirm the predicted trends, so that regulators are able to sign off on the closure plan.

6.3.2 Commencement of mining

In the early stages of mining, proponents should focus on confirming the predicted impacts of the mining or the identification of predictive errors. Early identification of errors will allow for refinement of the conceptual model (and computer model, if relevant) and determination of additional data requirements for development of the closure plan. The mine closure plan should be developed and initiated as early as possible following mine commencement.

The closure plan should be considered a ‘living’ document that is reviewed on an annual or biennial basis. As computer modelling is only a predictive tool, any results will require confirmation by field measurements and monitoring. The development of a conceptual model prior to project commencement will enable the mining company to conduct monitoring during the mine life and achieve validation of modelling predictions before mine closure. This may result in significant cost savings associated with final rehabilitation.

6.3.3 Cessation of mining

It is important that the final mine closure plan has adequate compliance monitoring, particularly in areas with fresh to brackish groundwater resources. The compliance-monitoring programme requires the setting of “trigger” levels in pit lake, both for waterlevel and water quality, that should any impacts different than those predicted will initiate an agreed management and/or mitigation response. A time frame should be set for the mining company to confirm predicted impacts of the mine final void on the groundwater system, and that any anticipated environmental impacts are developing within the predicted pattern.

7 Conclusions

Mining is leaving a legacy of hundreds of mine voids throughout the State. There are numerous safety issues that must be addressed as part of mine closure and, until recently, there had been no assessment of the potential long-term environmental impacts of mining below the watertable. The mine void issue is vitally important to both the Government and mining industry, as neither wishes to be liable for rehabilitation or stabilisation of a mine void over a period of decades, centuries, or possibly even millennia.

Mine voids may be problematic in certain areas and hydrogeological environments, but these can be overcome through a number of innovative approaches. If correctly approached, mine voids provide the mining industry with a number of management strategies that both eliminate the environmental issue and have definite financial benefits. It is therefore important that the mining industry is innovative in dealing with mine void closure.

The determination of the final usage of a mine void before mining commences can be difficult, as the economically recoverable resource is often not completely delineated. There are advantages for the early introduction of closure plans in the mine planning process, as this allows companies to identify future mine closure issues, develop alternate closure strategies, and reduce rehabilitation costs following mining.

Mining companies, in conjunction with Government, should aim with final void management to:

- render the site acceptable and safe over the long term;
- minimise environmental and health risks in the vicinity of the site;
- maximise to the practicable extent any potential future usage of the site; and
- develop a ‘walkaway’ solution.

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Appendix 1 Case studies

The large number of mining voids throughout the State made it impossible to review all mining operations; hence, it was decided to select representative case studies. Eighteen case studies (Table A1) were completed between 1997 and 1999 to highlight differences between groundwater environments, regional setting and mine closure options. Figure A1 shows the location of each case study throughout Western Australia.

The case studies are site-specific and have been written to be independent of each other. The structure of each case study is similar, with an introduction discussing site location, mining details, climate and physiographic setting; description of geology and hydrogeology in the mine void; an assessment of potential impacts of the mine void on groundwater resources; and a conclusion discussing preferred closure options. Although delays in the publication of the report has meant that information in many of the case studies may have been superseded, the suggested approaches for mine closure are still considered appropriate.

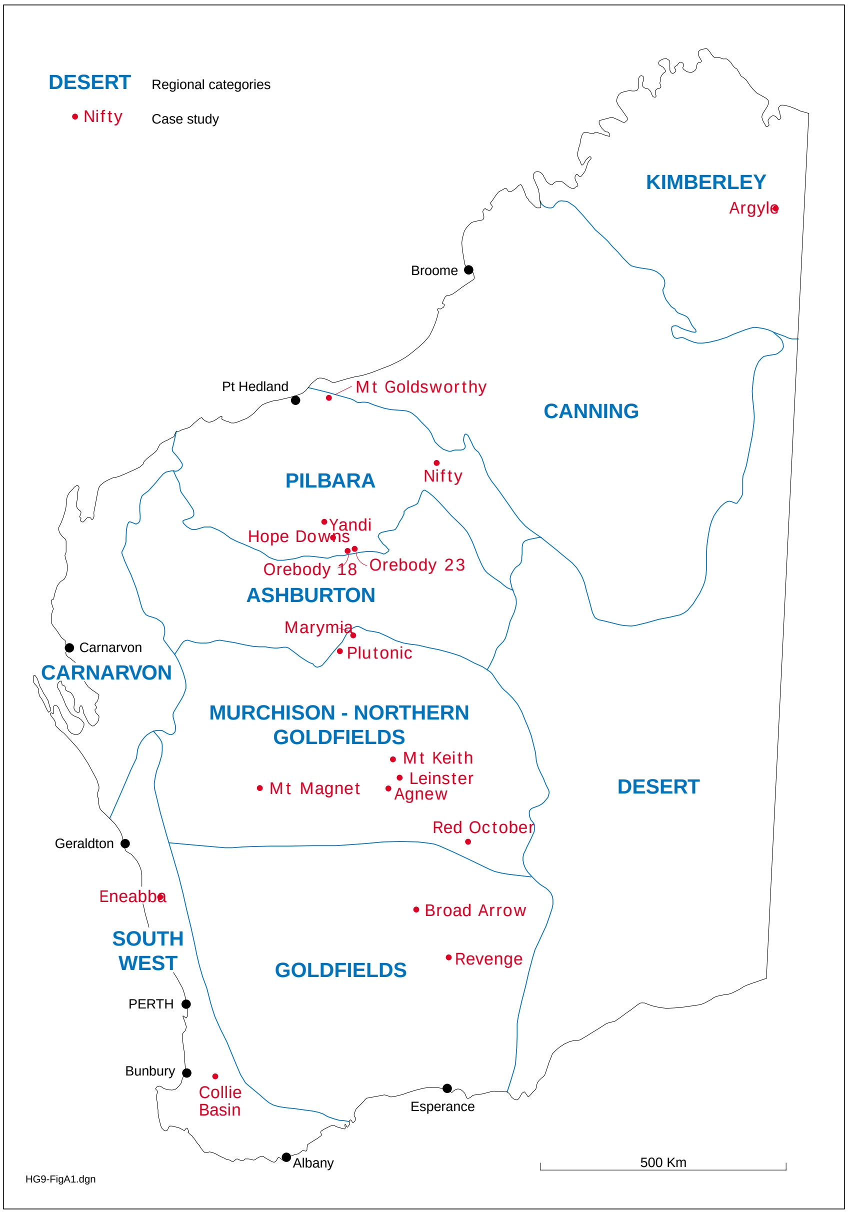

Figure A1. Location of case studies in Western Australia

Table A1. The key hydrogeological and mine closure issues for each case study

Mine void	*Case study No.*	*Commodity*	*Region*	*Key hydrogeological and mine closure issues*	*Potential for*		*Closure option*			
					Salinity	*Acidity*	*Void*	*Water*	*Waste*	*Tailings*
Argyle - AK1	1	Diamond	Kimberley	Seasonally recharged local aquifer – net outflow	X		X			
Nifty Copper	2	Copper	Pilbara	Isolated local aquifer – groundwater sink	X	X	X			
Mt Goldsworthy	3	Iron ore	Pilbara	Isolated local aquifer – mine closed for 17 years	X		X	X		
Orebody 23	4	Iron ore	Pilbara	Linked to alluvial borefield – partial throughflow	X	X		X		
Orebody 18	5	Iron ore	Pilbara	Isolated local aquifer – groundwater sink	X		X			
Hope Downs	6	Iron ore	Pilbara	Linked to ecological / cultural site – throughflow	X	X			X	
Yandi [BHP & HI]	7	Iron ore	Pilbara	Mining of regional aquifer – throughflow	X		X		X	
Plutonic - Salmon	8	Gold	Murchison – N. Goldfields	Groundwater sink - potential for creek diversion	X		X	X		
Plutonic – Perch	8	Gold	Murchison – N. Goldfields	Isolated local aquifer – groundwater sink	X		X		X	X
Marymia	9	Gold	Murchison – N. Goldfields	Used for tailings storage	X	X	X	X	X	X
Mt Magnet – Spearmont	10	Gold	Murchison – N. Goldfields	Groundwater sink – potential for stormwater capture	X		X	X		
Mt Magnet – Boogardie Pits	10	Gold	Murchison – N. Goldfields	Throughflow cells in weathered fractured rock aquifers	X		X	X	X	
Mt Keith	11	Nickel	Murchison – N. Goldfields	Groundwater sink located on linear geological system	X		X			
Agnew - Emu	12	Gold	Murchison – N. Goldfields	Cumulative impact within linear geological system	X	X	X		X	
Leinster Nickel - Harmony	13	Nickel	Murchison – N. Goldfields	Located within creek system	X	X	X	X	X	
Red October	14	Gold	Murchison – N. Goldfields	Located within salt lake – groundwater sink	X		X			
Broad Arrow	15	Gold	Goldfields	Used for water and waste rock storage	X	X	X	X	X	
St Ives – Revenge	16	Gold	Goldfields	Located on salt lake – groundwater sink	X	X	X		X	
Eneabba West	17	Mineral sands	Southwest	Linked to coastal lake system – partial throughflow	X		X		X	X
Collie – WO5	18	Coal	Southwest	Potential diversion of river system	X	X	X	X		

1 Argyle diamond mine

Introduction

The Argyle diamond mine, located in the eastern Kimberley, has been operational since the early 1980s. The AK1 lamproite orebody is currently mined by opencut methods (conventional opencut benching techniques) with waste transported to adjacent waste rock dumps. Opencut mining is scheduled to cease in 2007, although underground operations are being considered. The mine void will have final dimensions of 2 km by 1 km and total depth of 450 m. It is anticipated that on cessation of dewatering, the waterlevel will recover to partially fill the void.

The AK1 mine lies within the Blatchford Escarpment at the eastern end of the Matsu Range, which rises more than 300 m above the surrounding plains and low undulating hills (Fig. A2). The area experiences a sub-tropical monsoonal climate with an unreliable wet season (average rainfall of 570 mm/yr) extending from November to April, and a distinct dry season with maximum temperatures of 34° to 42°C. The annual rainfall deficit is in the order of 2400 mm/yr.

Geology and hydrogeology

Regional geology is dominated by Proterozoic rocks within the fault-bounded Halls Creek Mobile Zone (Table A2). The orebody, a lamproite pipe, is intruded into slightly metamorphosed sedimentary strata that are northward-dipping at about 30° (Fig. A2). The rocks have little or no primary, intergranular hydraulic conductivity; groundwater flow is associated with fractures and shear zones. The fractured-rock environment is structurally complex with interbedded aquifers and aquitards hydraulically connected by major faults and discontinuities.

The AK1 mine intersects a variety of fractured-rock aquifers. The lower portion of the mine pit is dominated by aquitards, whereas the upper portion in the west and east ridges comprises major quartzitic aquifers. During the wet season, rapid groundwater flow occurs along joint planes and contact zones resulting in seepage from the pit wall. Major inflows are associated with faults that extend through the quartzitic aquifers of the Matsu Range into the mine. Continuous dewatering is required to maintain dry-floor mining conditions.

Table A2: Geology and hydrogeology at Argyle

Age	*Geological unit*	*Lithology*	*Aquifer type*
Recent–Tertiary	Terrace gravel	gravel, sand and silt	ephemeral aquifer
“	Lamproite pipe (orebody)	lamprophyre intrusion	aquitard
Upper Devonian	Ragged Range Member	conglomerate and siltstone	aquitard
Lower Cambrian	Antrim Plateau Volcanics	basalts, sandstone and chert	aquitard
Neoproterozoic	Ranford Formation	sandstone, siltstone, shale and claystone	aquitard
Mesoproterozoic	Glenhill Formation	shale, siltstone and fine sandstone	aquitard
“	Lissadell Formation	sandstone, shale and siltstone	fractured-rock aquifer
“	Golden Gate Formation	siltstone, shale, mudstone and tuff	aquitard
“	Hensman Sandstone	massive quartz sandstone	fractured-rock aquifer
Palaeoproterozoic	Revolver Creek Formation	basalt, sandstones, siltstone and shale	aquitard

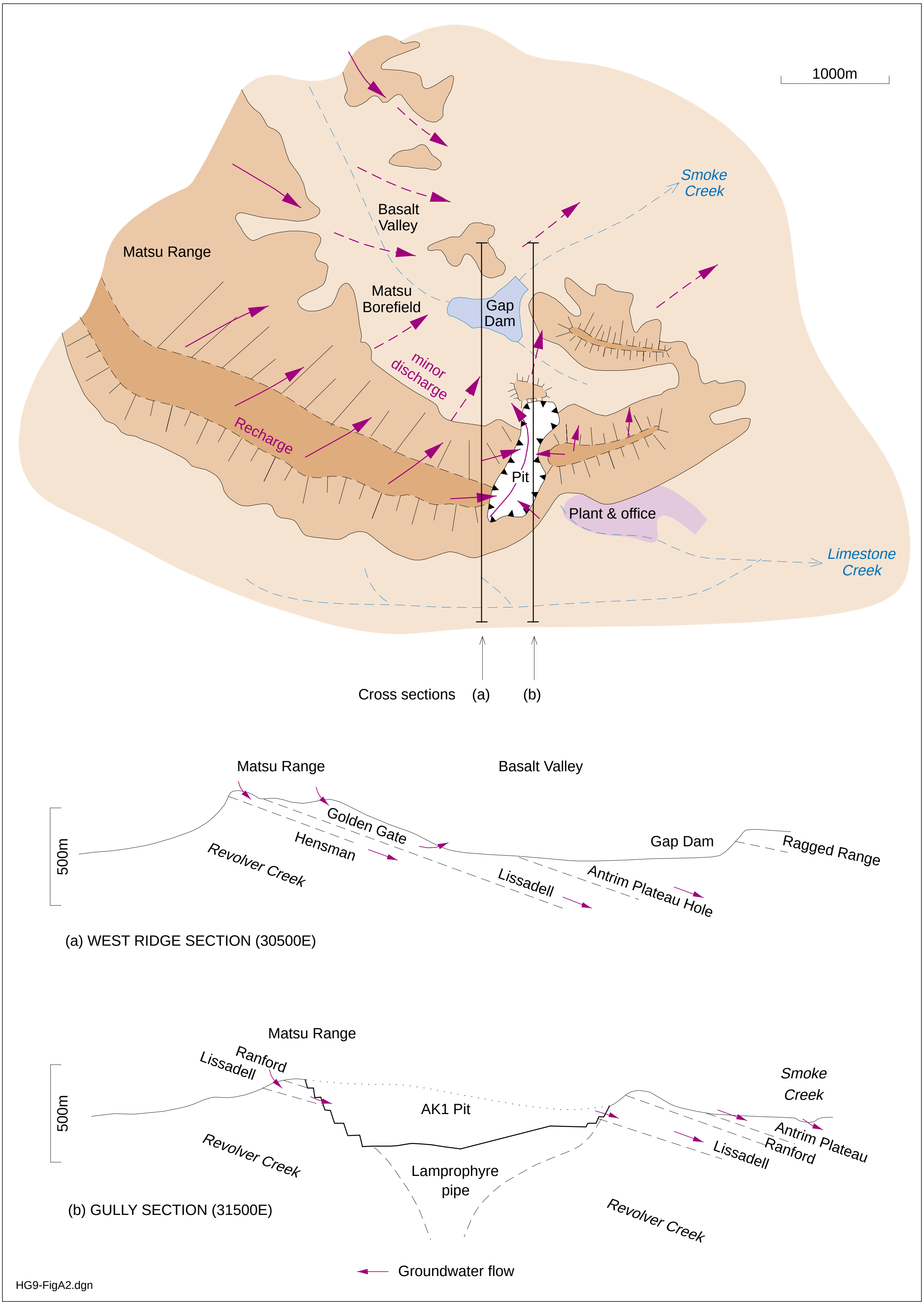

Figure A2. Regional setting and geology at Argyle diamond mine (AK1)

The aquifer system in the vicinity of the mine is complex, due mainly to the secondary nature of the hydraulic conductivity. The quartzite units of the Hensman Sandstone and Lissadell Formation constitute the major aquifers, although the Revolver Creek Formation contains quartzite units which are only minor aquifers. The fault zones and lineaments are the main conduits for groundwater flow (Fig. A3), whereas the siltstone and shale units are regarded as aquitards.

The watertable is about 20 m below ground level with significant waterlevel fluctuations of up to 6 m responding to rainfall recharge. The Matsu Range is an important recharge area, where direct rainfall and localised runoff infiltrates the fractured quartzite. A number of springs are associated with the Lissadell Formation through the surface expression of a fault or lineament. Seepages are common from the pit wall following significant rainfall events.

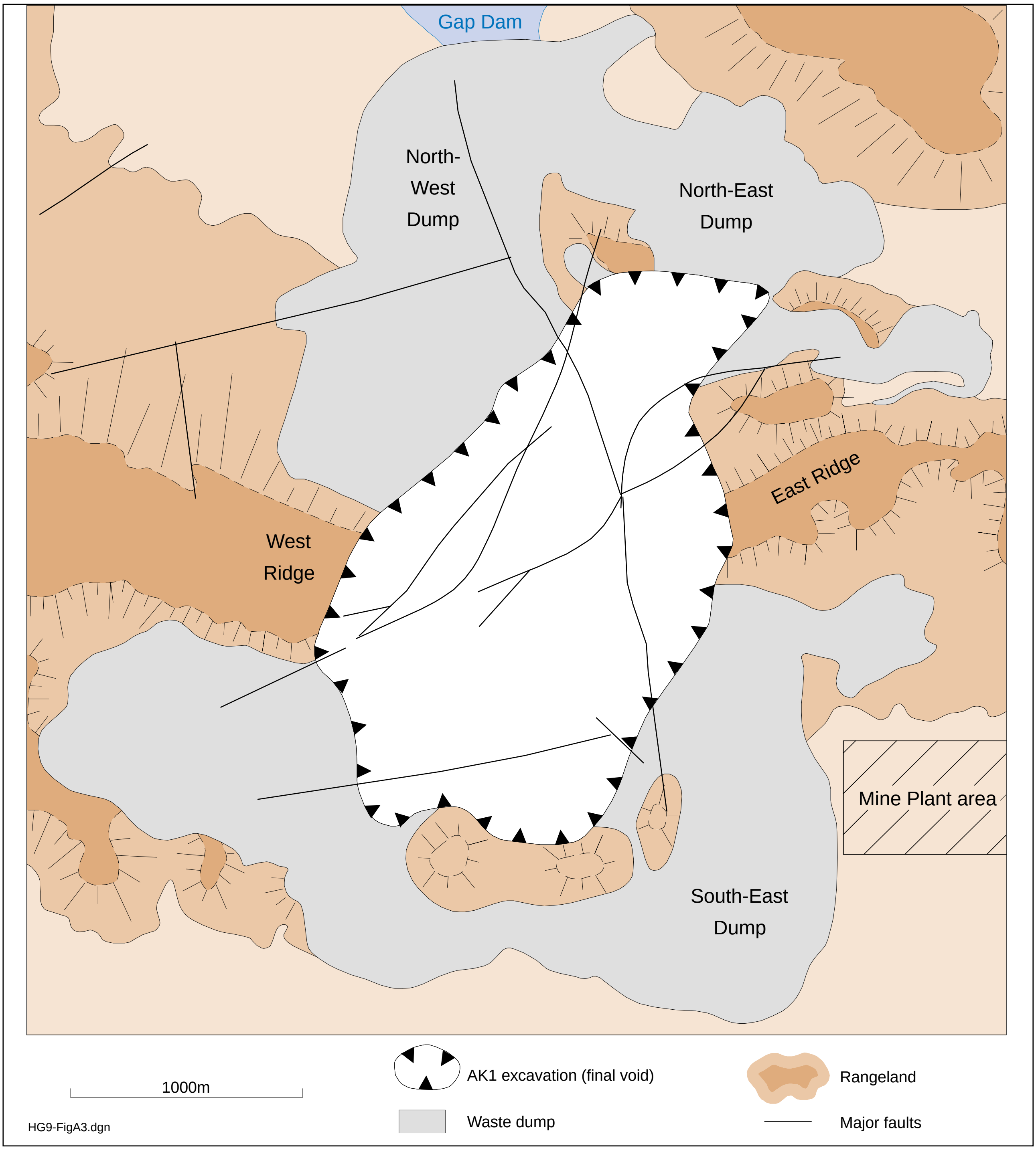

Figure A3. Location of major structural features at Argyle AK1 mine

Potential impact of mine void

It is anticipated that the final mine void will form a ‘groundwater sink’. Evaporation should exceed groundwater flow into the pit and the level of the pit lake should remain below the pre-mining waterlevel. Owing to the close proximity to the recharge zone and quartzitic nature of the aquifer, the groundwater is fresh (less than 100 mg/L TDS) with a pH range of 5–7. During the wet season, significant rainfall and runoff may dilute the pit-lake water; thus, preventing salt accumulation and brine formation. In the event of brine formation, there will be only localised migration of a hypersaline plume from the pit because of the impermeable nature of the aquitards.

Conclusions

It is considered that the most appropriate mine closure option for AK1 is to allow the final void to slowly fill with water to form a pit lake. There is also merit for the water-storage option, whether for irrigation or recreational (tourism) purposes. The main considerations are the geotechnical stability of the abandoned mine void, engineering costs, liability risks, economic benefits, public image and regulatory acceptance.

2 Nifty copper operation

Introduction

The Nifty copper mine is located in the Great Sandy Desert of the eastern Pilbara. Mineralisation is preferentially developed within a carbonate host rock with the copper extracted using a heap-leaching process. Mining commenced in 1992 with current mine void dimensions of 1000 m by 500 m and a depth of 75 m, which will be extended in an easterly direction resulting in final void dimensions of 1700 m by 550 m and a depth of 155 m. There is also potential for underground mining to extract primary sulphide mineralisation to 500 m below surface.

The climate is arid with an average rainfall of 150 mm/yr and evaporation in excess of 3000 mm/yr. Rainfall is seasonally unreliable, related to tropical activity, and ranges from no rain in dry years to 1000 mm/yr during wet years. Maximum daily temperatures range between 25˚ and 40˚C, although temperatures will exceed 50˚C in summer.

The mine is located within an undulating dune terrain. Parallel easterly trending sand dunes up to 20 m high extend for tens of kilometres, with inter-dunal swales varying in width from 100 m to 3 km. Owing to the lack of surface water, groundwater resources provide all construction, operational and domestic water supply requirements. Mining is the only economic activity in the area, with other nearby mine operations including Woodie Woodie manganese mine (35 km to the west) and Telfer gold mine (70 km to the east).

Geology and hydrogeology

The Nifty deposit lies within the Broadhurst Formation of the Yeneena Group. The Broadhurst Formation, deposited in the Palaeoproterozoic Paterson Basin, consists of carbonaceous, pyritic, micaceous shale and siltstone with minor interbeds of arenite and dolomite. The main orebody is hosted in the Nifty Carbonate Member (Fig. A4) which has been folded into the south-easterly plunging Nifty Syncline. The massive carbonate beds become thinner and shalier towards the east. The hangingwall is deeply oxidised to 80 m with major fracturing to a depth of 220 m. A Proterozoic dolerite dyke intrudes the sequence to the east of the current pit.

Mineralisation is hosted within the carbonate and shale units on the northern limb of the syncline (Fig. A4). There are two oxidised copper orebodies in the upper portion of deposit; (1) a sub-vertical stratabound deposit within the Nifty Carbonate Member; and (2) a supergene-enriched zone that is located outside the Nifty Carbonate Member between the pre-mining watertable and the base of oxidation. The primary mineralisation occurs throughout the Nifty Carbonate Member below the base of oxidation, with the thickest ore sections in the Lower Massive Carbonate.

The carbonate-hosted orebody is the major aquifer in the mining area. Groundwater occurrence and movement is related to secondary permeability developed as a result of structural deformation and chemical dissolution of the carbonate. The secondary permeability is best developed in the oxidation zone to a depth of about 100 m. The groundwater is brackish, ranging between 2000 and 4000 mg/L TDS.

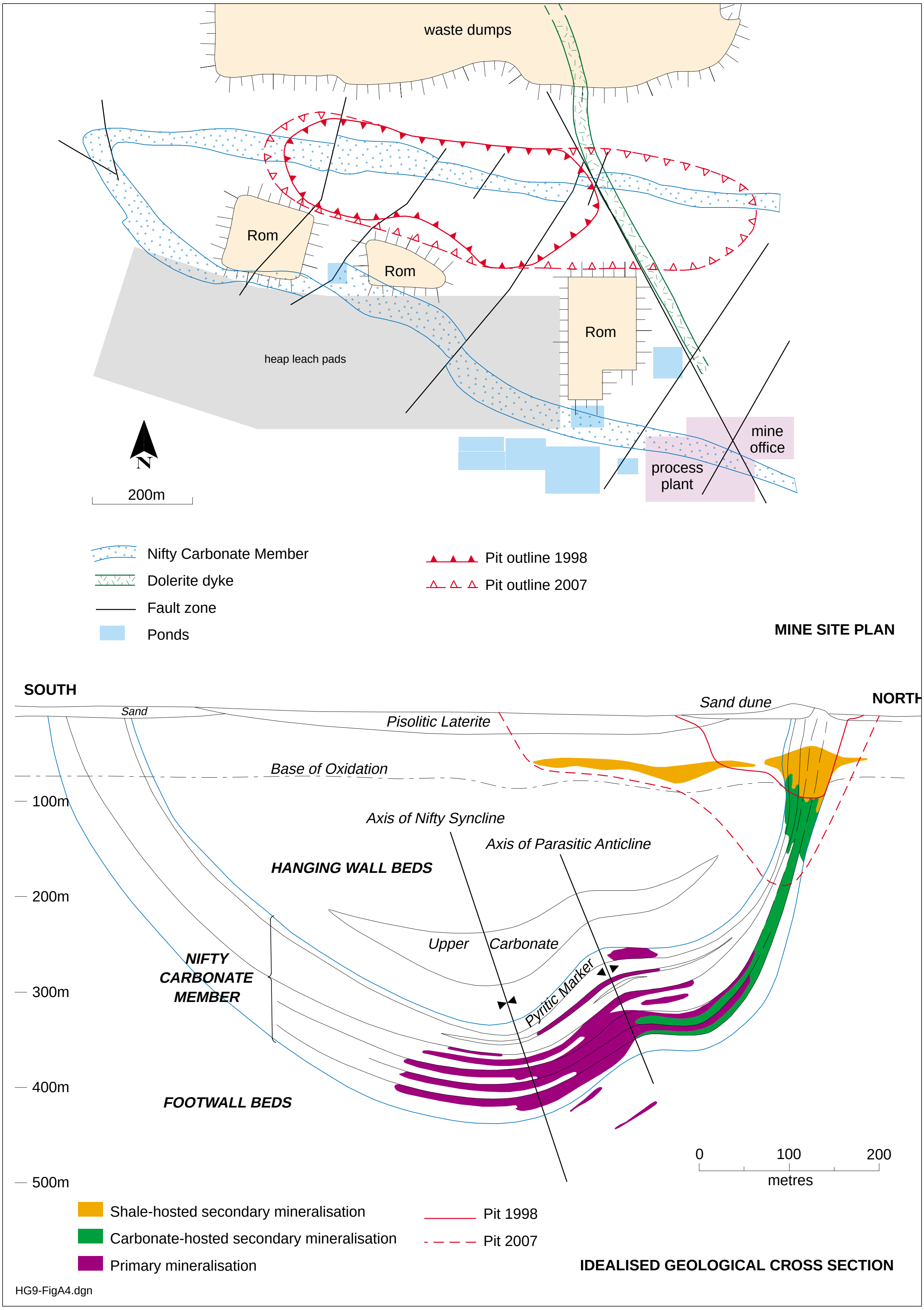

Figure A4. Site plan and geology at Nifty copper mine

The carbonate aquifer is semi-confined between shaly aquitards. There are siltstone horizons within the shale of moderate permeability that are often associated with localised groundwater seepage. The dolerite dyke, east of the current pit, acts as a barrier restricting east–west groundwater flow through the carbonate aquifer.

The Nifty Palaeochannel, a shallow alluvial aquifer, broadly follows the axis of the Nifty Syncline. The alluvial sequence, deposited within incised channels in the bedrock, is exposed in the eastern wall of the mine pit. The palaeochannel depth, which varies from 80 to 120 m, becomes progressively deeper towards the east. The Nifty Palaeochannel aquifer has relatively low permeability and appears not to be in hydraulic connection with the East Nifty Palaeochannel, located 8 km east of the mine.

Mine dewatering (2.5 ML/day) is achieved through a combination of perimeter production bores, in-pit sumps and horizontal seepage holes. Dewatering has created a localised flow pattern (Fig. A5) controlled by the geometry of the Nifty Carbonate aquifer and structure of the Nifty Syncline. The negligible change in waterlevels south-southeast of the pit indicate substantial leakage from the Nifty Palaeochannel and surrounding pelitic units.

Potential impact of mining void

On cessation of dewatering, it is anticipated that the mine void will progressively fill with water. Evaporation will exceed groundwater flow into the pit and the level of the pit lake should remain below the pre-mining waterlevel. The pit will therefore act as a ‘groundwater sink’, which will locally modify the pre-mining hydraulic gradient.

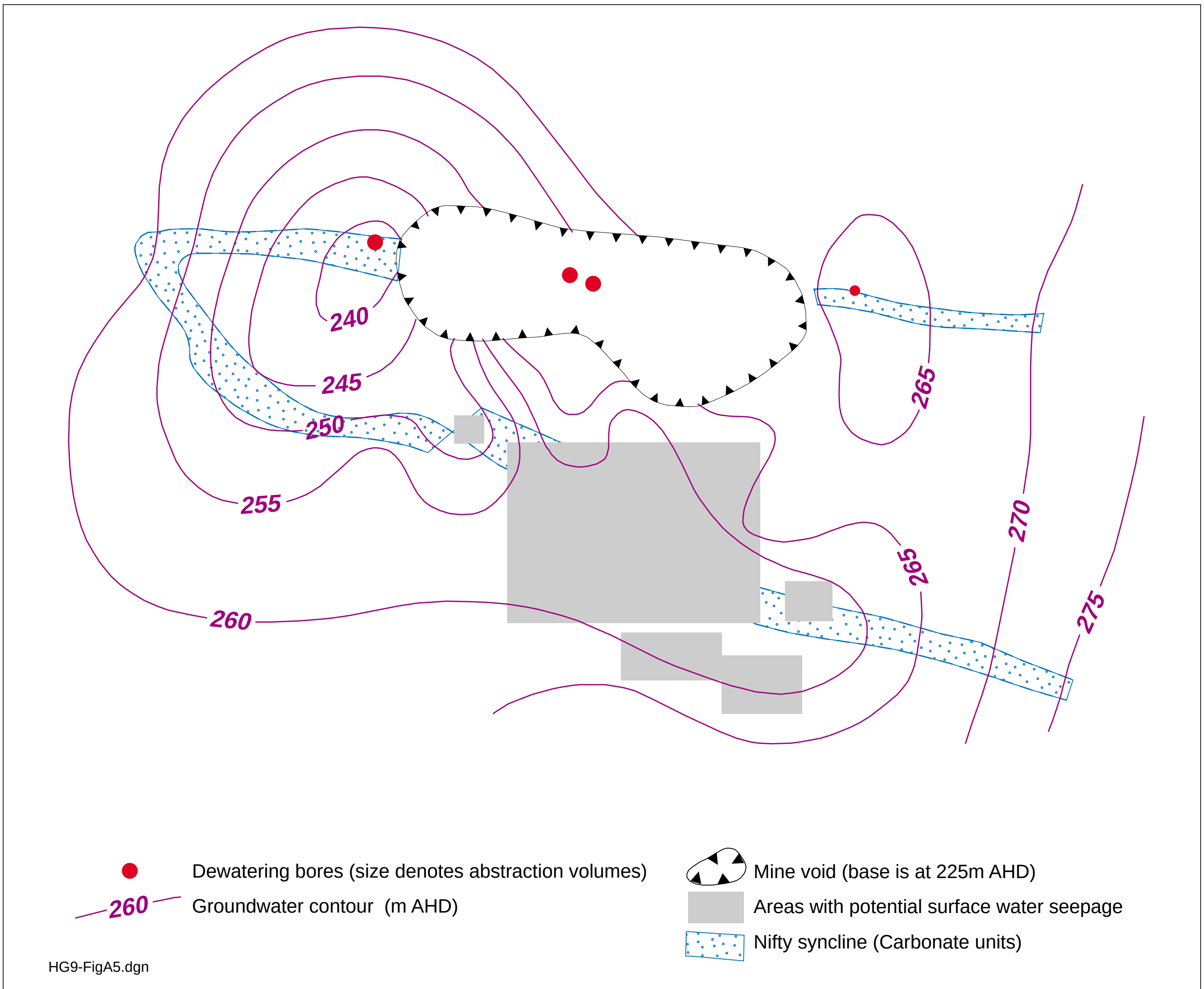

Figure A5. Groundwater contours (December 1997) at Nifty

The most important closure issue at Nifty copper mine is the potential for groundwater contamination below the heap-leach pads and ponds to migrate into the pit lake. Over time, the pit lake will increase in groundwater salinity associated with increased concentration of sodium, chloride and sulphate levels. Modelling has suggested that mixing and dilution will produce a final pit lake salinity of 3500 mg/L TDS and that the major driver of long-term increase in pit water salinity will be evaporation rather than leakage from beneath the heap leach.

Conclusions

The final mine void will be too large for backfilling to be considered as a viable option. The most practical option is to allow the pit to slowly fill with water to form a ‘groundwater sink’, which will ensure any seepage from beneath the heap leach will be drawn into and isolated within the pit. As the local groundwater is brackish, beneficial use is restricted to limited irrigation, stock-watering and mining. The mine void may be suitable as a water-storage facility for future mining operations. Modelling has indicated that the final pit lake will not impact on the East Nifty Palaeochannel aquifer, which is the only significant groundwater resource in the area.

3 Mount Goldsworthy mine

Introduction

Most of the data and information used in this case study on the abandoned Mount Goldsworthy operation are taken from Waterhouse and Davidge (1999).

The Mount Goldsworthy mine was the first major iron ore mine in the Pilbara. It operated for 20 years prior to closing in 1982. The now abandoned town of Goldsworthy had a maximum population of 1000 people. The mine is located within the Ellarine Range, which divides the alluvial plains extending south to the De Grey River and north to the Indian Ocean (Fig. A6). The De Grey River is a major seasonal drainage system with important alluvial aquifers that supply potable water to Port Hedland. The smaller Pardoo Creek, which flows to the west of the mine and across the northern plain, has no interconnected aquifers. The old Goldsworthy borefield was hydraulically linked with the De Grey system.

The area falls within the semi-desert (tropical) meteorological climatic zone, which experiences high evaporation (3000 mm/yr) relative to rainfall (150 mm/yr). Rainfall is concentrated in the summer months from January to March and derived from isolated storms or large cyclonic disturbances.

Opencut mining resulted in a final void with dimensions 1200 x 500 x 200 m (depth). The mine void extended 177 m below the pre-mining watertable. On closure, the void was allowed to fill slowly with water to the point where waterlevels have now recovered by almost 60% (Fig. A7).

The entire mine area was rehabilitated by BHP and there is little evidence of the town site, mine infrastructure and borefield. The waste dumps have been reshaped, ripped and seeded. The pit was surrounded by a safety bund and fenced off to ensure that the public and livestock do not have access to the final void.

Geology and hydrogeology

The mine is located in an elongate range of Archaean rocks including shale, volcanic rocks and banded iron-formations. The rocks have been subjected to tectonic deformation, which resulted in extensive fracturing and faulting. The orebody was a vuggy hematite that was more permeable than the host rocks. Pyritic shale was entirely removed during mining. The Archaean basement was considered an unprospective aquifer owing to the presence of “dissolved toxic and aggressive salts” in the water. The direction of groundwater flow largely reflects the predominant fault direction. Saline groundwater occurs within shallow alluvial aquifers along the Pardoo Creek and on the northwestern plain.

The mine water supply borefield was located 6 km south of the mine between Pardoo Creek and the De Grey River. The bores were located in the shallow alluvial aquifer of the De Grey River, which is seasonally recharged from surface flows.

Few historic hydrogeological data are available for the mine area as mining pre-dated the current environmental reporting requirements for Western

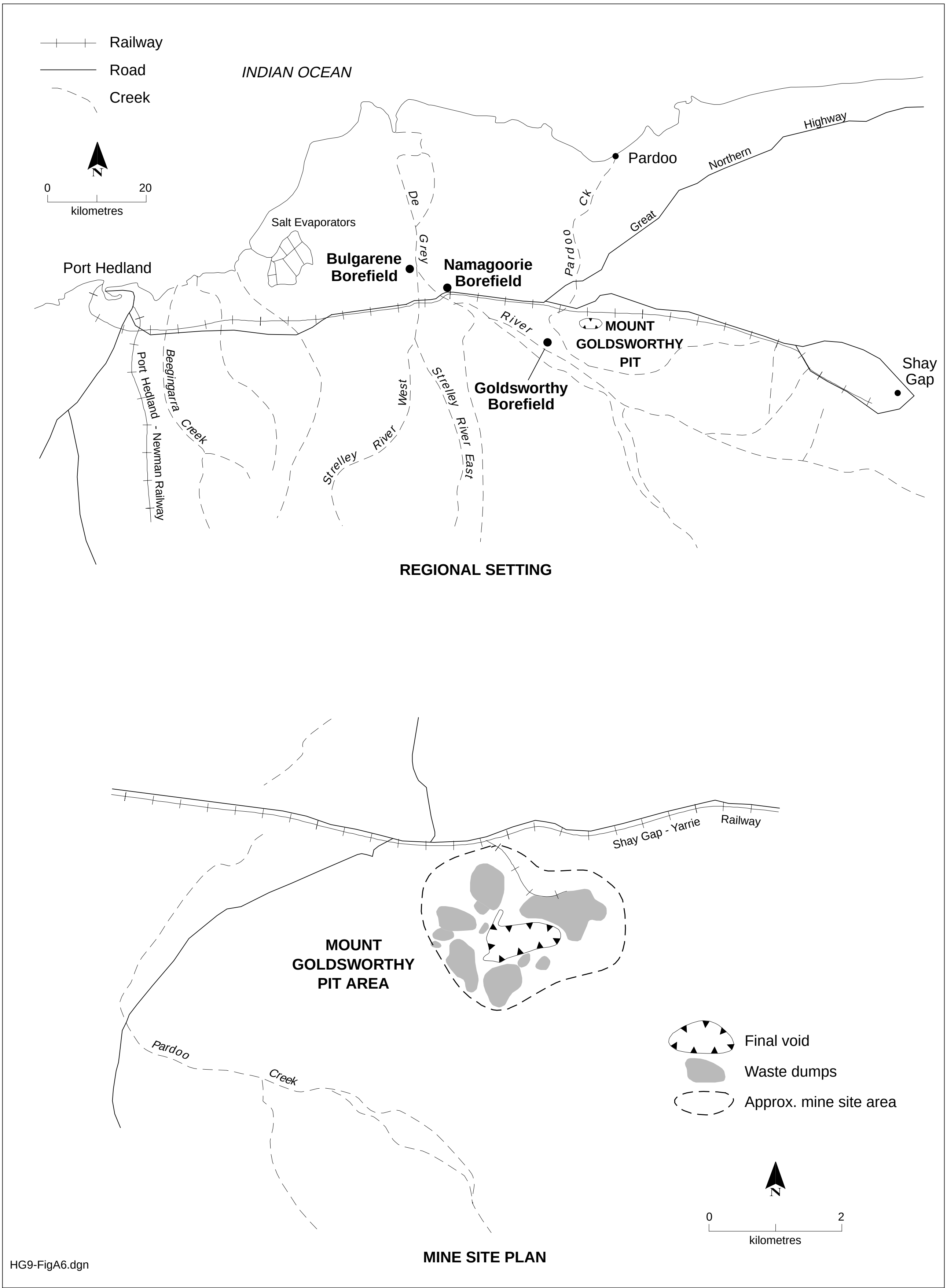

Figure A6 Location of final mine void at Mount Goldsworthy mine (*after* Waterhouse and Davidge, 1999)

Table A3. Water quality in the mine void lake (1992/96)

Parameter	*Year*	*West wall seepage*	*Depth below surface (m)*			
			0	*15*	*35*	*90*
pH	1992	8.0	7.6	7.5	7.4	7.3
	1996	8.2	8.0	8.0	7.3	7.4
Salinity (mg/L TDS)	1992	4 400	4 900	4 800	4 800	4 900
	1996	4 900	N/a	5 600	5 600	5 600

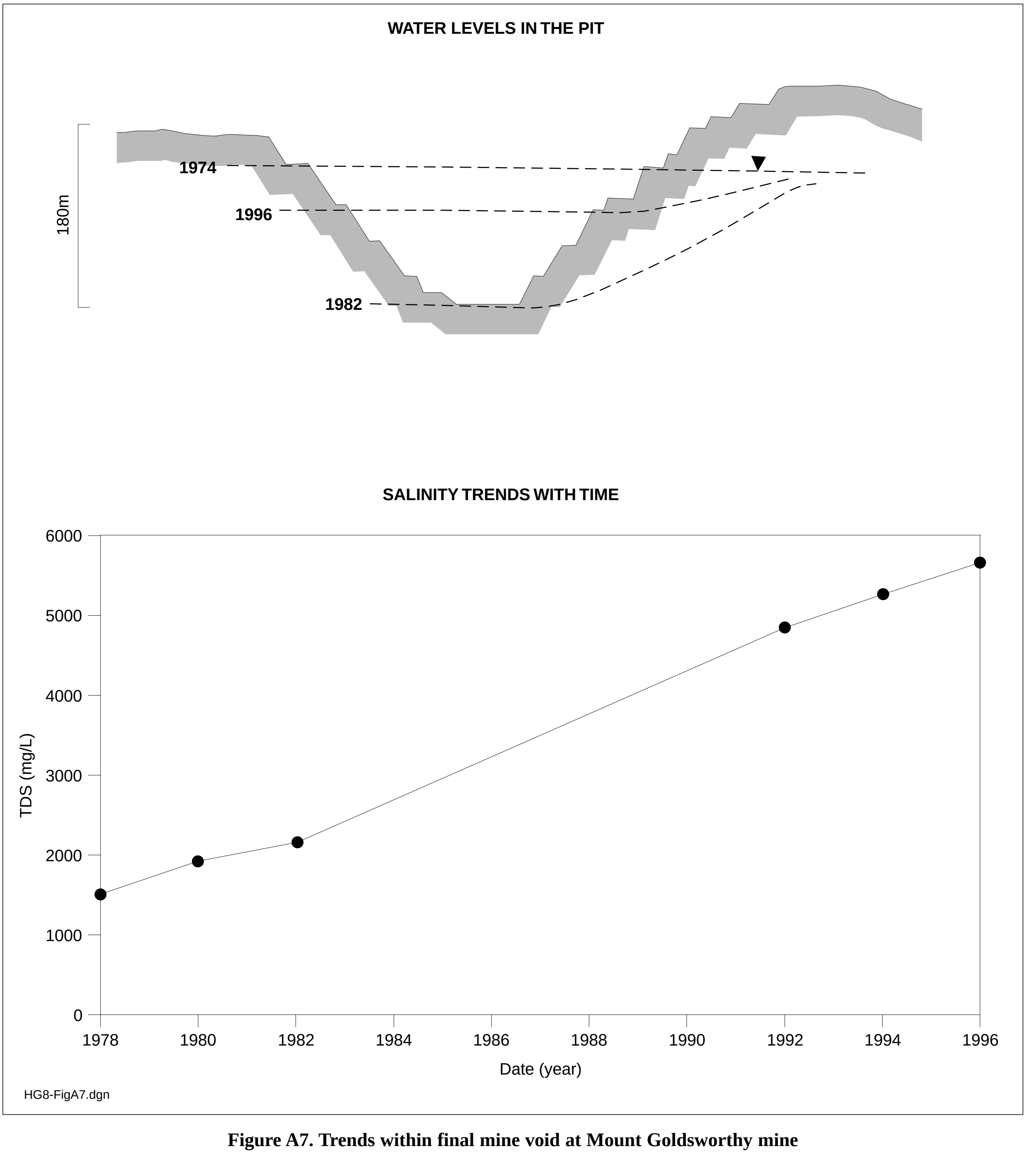

Figure A7. Trends within final mine void at Mount Goldsworthy mine (*after* Waterhouse and Davidge, 1999)

Australia. BHP has, however, recently initiated monitoring to comply with their corporate environmental responsibility.

Potential impact of mining void

On the completion of mining, the pit was abandoned and has slowly filled with water. Waterlevels, recorded since 1992, are about 50 m below the pre-mining watertable (Fig. A7). The water is rising at a rate of 2.1 m/yr with no direct evidence of structurally controlled groundwater inflow. The rate of inflow will decrease with time as the waterlevel rises and the flow gradient towards the void decreases.

Initial pit-lake salinity following mine closure was apparently between 1400 to 2000 mg/L. Since 1992, the salinity has been increasing at a rate of 200 mg/L/yr, although chemistry is not changing significantly (Fig. A7). There is a temperature gradient in the water body and a constant temperature of 22˚C at a depth of 20 m. The pH is neutral (Table A3) and nutrient levels are low, which will minimise biological colonisation of the water body. The water body is well mixed with respect to the major ions, but salt will probably eventually crystallise on the pit floor.

Conclusions

After mining ceased in 1992, the Mount Goldsworthy mine void started to naturally fill with water. The void is about two-thirds full, with water becoming more saline. In the long-term (centuries), it is conceivable that a density-driven plume of saline groundwater could emerge from the pit along a structurally controlled permeable feature. The rate of plume movement would be limited by the rate of accession of cyclic salt to the void lake. At present, there is no risk to any regional water resources as the alluvial aquifers of the De Grey River are about 10 km to the west.

The Mount Goldsworthy mine void can be abandoned relatively safely to naturally re-establish equilibrium. Monitoring of the final void, which is relatively large and experiences typical Pilbara climatic conditions, is providing a valuable insight into what can be expected with the many other iron ore mines in the region. Mount Goldsworthy is an ideal site for research into hydrochemical changes that occur within fractured-rock mine void lakes. The only disadvantage is the lack of readily available historical mine and hydrogeological data.

References

WATERHOUSE, J. A., and DAVIDGE, S., 1999, The evolution of the water body in the final void of the Mount Goldsworthy Mine: *in* Water 99 Joint Congress – Brisbane, Australia, 6-8 July 1999, pp. 895-900.

4 Orebody 18

Introduction

Most of the data and information used in this case study relating to the Orebody 18 operation is taken from BHP (1996). Orebody 18 is a proposed iron ore mining operation located 32 km east of Newman in the East Pilbara. Mining will remove 116 Mt of iron ore over a 12–15 year period. Opencut mining will result in a final mine void that will be 4 km long, 500 m wide and 120 m deep. Dewatering will be required in the later stages of mine development to access ore reserves that extend to 43 m below the watertable.

On completion of mining, it is anticipated that the resulting pit lake will form a final surface area of 8 ha. The mine void will act as a groundwater sink with the salinity of the lake water to increase over time. Although, there are small areas of black pyritic shale in the area, these units will not be intersected in the pit and there is no potential for acid production.

Orebody 18 is located on the southeastern limits of the Ophthalmia Range (Fig. A8). The mine will be established on the slopes overlooking the alluvial plain between the Shovelanna and Jimblebar Creeks. The orebody is situated at the head of a catchment, with surface drainage to both the east and west. Streams generally flow after high-intensity rainfall events.

The area, which is in the subtropical summer rainfall zone, experiences hot summers with periodic heavy rains and mild winters with occasional rainfalls. Annual rainfall is 300 mm and evaporation in the order of 3800 mm/yr.

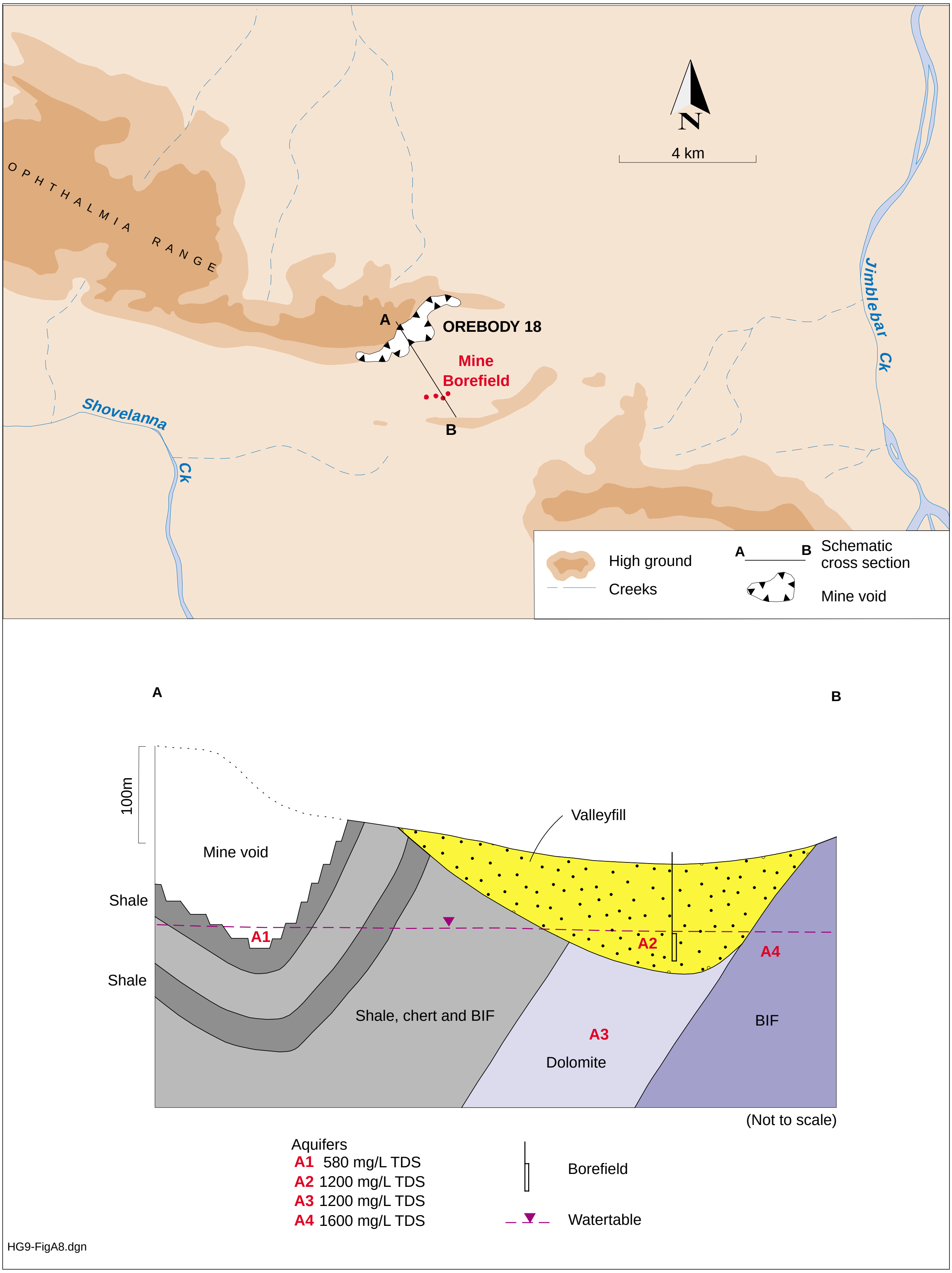

Figure A8. Location and geology at Orebody 18 (*after* BHP, 1996)

Geology and hydrogeology

Orebody 18 lies within the Brockman Iron Formation, which comprises banded iron-formation (BIF), chert, and minor shale bands. The orebody within the Shovelanna Syncline is bound by Mount McRae and Mount Sylvia Shale to the southeast, and steeply dipping shales and BIFs of the Weeli Wolli Formation in the northwest (Fig. A8). Valley-fill deposits, consisting of partially to entirely consolidated ferruginised silt, sand and gravel, overlie the Wittenoom Formation and Marra Mamba Iron Formation. Subsurface flow beneath the creek bed is not likely to be sustained after surface flow events, as regional waterlevels are at 50 m below surface.

The local groundwater system consists of four aquifers.

- Orebody 18 aquifer – the orebody itself (mineralised Dales Gorge BIF)
- Dolomite aquifer – formed along the eroded upper Wittenoom dolomite
- Shallow alluvial aquifer – formed by scree and alluvial clay deposits that contain minor calcrete developed below the watertable
- Marra Mamba aquifer – formed by the mineralised and fractured Marra Mamba BIF.

Shale intervals within the Mount McRae and Mount Sylvia Shales have low hydraulic conductivity and form an aquitard (hydraulic barrier) between the orebody and other local aquifers (Fig. A8). Differences in water quality and waterlevels suggest that the orebody aquifer has very limited connection with the other aquifers. The mine water supply borefield is located in the valley-fill to the south of the mine and will abstract groundwater from the Marra Mamba aquifer.

Potential impact of mining void

Because of the narrow widths and high pit wall configuration, there is no indication that the final mine void will be backfilled. The mine void will slowly fill with water on cessation of dewatering and the resultant pit lake should only be small. High evaporation rates and small groundwater inflow to the final void (groundwater sink) will result in a pit lake that will become progressively saline, but the extent of this salinisation has not been modelled. There is potential for the development of hypersaline water, although the mine void should be hydrogeologically confined to the void and isolated from all neighbouring aquifers.

Conclusions

The final mine void at Orebody 18 will form a ‘groundwater sink’ that is hydrogeologically isolated from any other aquifer. Although the pit lake will become hypersaline over time, it will not have a significant impact on surrounding groundwater resources.

References

BHP, 1996, Orebody 18, Consultative Environmental Review (unpublished).

5 Orebody 23

Introduction

Most of the data and information used in this case study relating to the Orebody 23 operation are from BHP (1997). Orebody 23 is located 13 km northeast of Newman in the East Pilbara. Opencut mining began in 1992 with 3.4 Mt of detritals and Brockman ore recovered from above the watertable. In 1997, proposals were submitted for the mining of an additional 12 Mt of ore below the watertable. The mining will necessitate the removal of 102 Mt of overburden and waste rock over a period of four years, producing a 130 x 95 x 140 m (deep) mine void. Dewatering will be required for the duration of the project, although the final void can be expected to fill with groundwater on cessation of mining.

Orebody 23 is on the southern side of the Ophthalmia Range, at the junction of Homestead Creek and the Fortescue River in Ethel Gorge (Fig. A9). The mine is about 2 km downstream of Ophthalmia Dam on the Fortescue River. The climate is subtropical–summer rainfall, comprising hot summers with periodic heavy rain and mild winters with occasional rainfall. Annual rainfall is 300 mm and the evaporation is about 3800 mm/yr. All creeks are seasonal and flow only after major rainfall. Ophthalmia Dam impounds

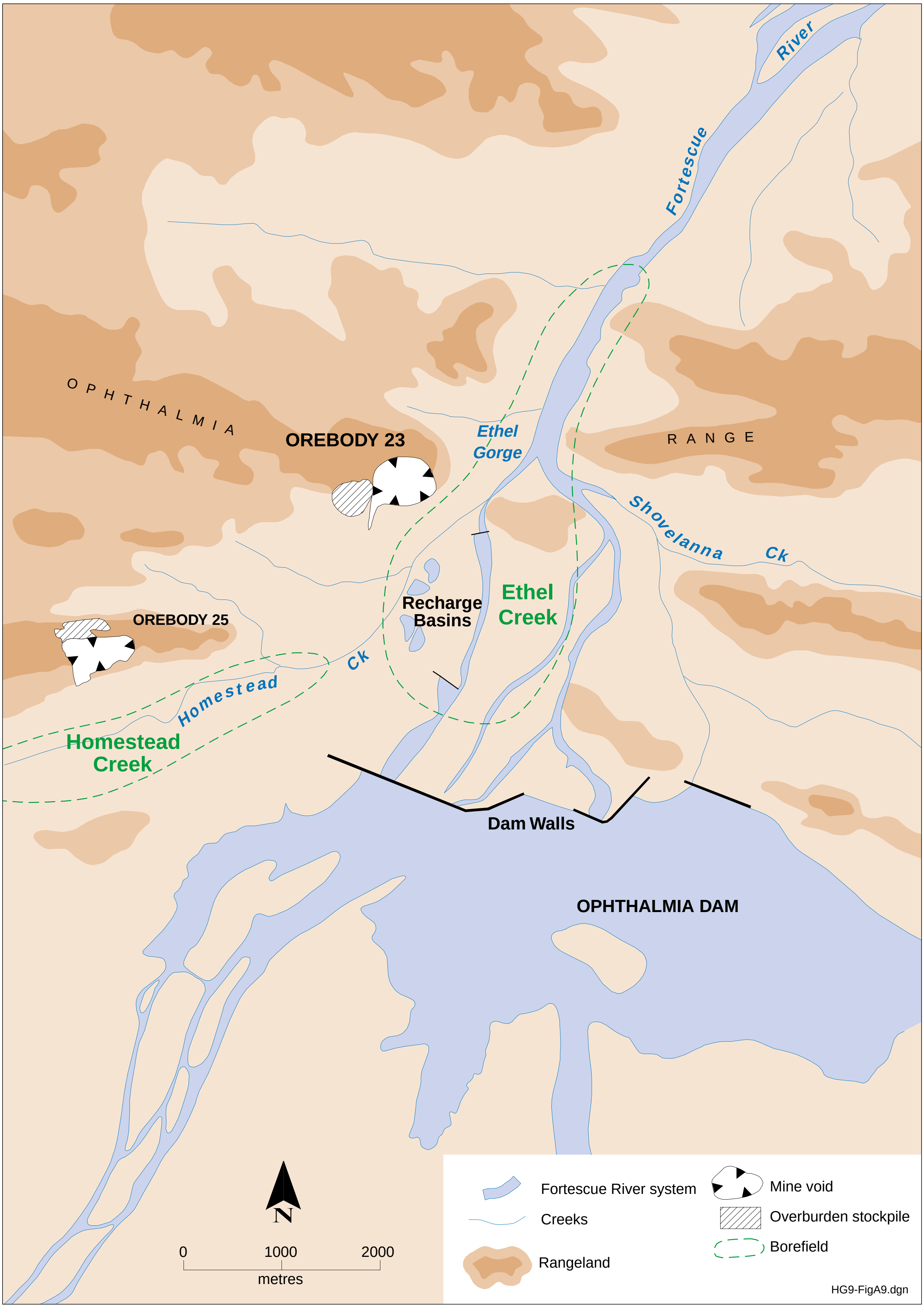

Figure A9. Location of the Orebody 23 mine site

the Fortescue River upstream of Ethel Gorge. Surface flow in the Fortescue River near Orebody 23 results from releases, leakage or overflow from the dam and runoff generated downstream of the dam. The local vegetation consists of a few large shrubs and a rich array of small shrubs. The creek lines contain significant stands of River Red Gum and Coolibah woodlands.

Geology and hydrogeology

The mineralisation at Orebody 23 lies within the Brockman Iron Formation (Fig. A10) and is flanked to the south by the Mount McRae and Mount Sylvia Shales, and to the north by the Whaleback Shale and Joffre Member (BIF). In the south, the basement rocks have been eroded and subsequently infilled with Tertiary sediments of fluvial and lacustrine origin. The southern pit wall intersects pyritic black shale that has potential for acid generation upon lengthy exposure to air, water and bacteria over a period of time.

The Fortescue River and its main tributaries (Homestead, Shovelanna, Whaleback and Warrawanda Creeks) all join before cutting through the Ophthalmia Range in the 400 m-wide Ethel Gorge. The alluvial-filled palaeovalleys of these creeks form the regional groundwater drainage system. The alluvium reaches a depth of 90 m and groundwater flow is northwards through Ethel Gorge and ultimately to the Fortescue Marshes. The shallow calcrete is an important aquifer that is in places separated from the alluvium by a confining clay sequence. Local, perched aquifers may develop for short periods when the alluvium within the active creek beds is saturated during river flow events. Recharge occurs both naturally through direct rainfall infiltration and river flow, as well as artificially via leakage from Ophthalmia Dam and recharge ponds 3 km upstream of Ethel Gorge (Fig. A9).

Some of the basement rocks, in particular the BIF, form local aquifers associated with mineralisation and structurally induced development of secondary permeability. In the south, the upper portion of the orebody is overlain by permeable detrital scree that lenses into the main alluvial sequence, resulting in hydraulic connection between aquifers (Fig. A10).

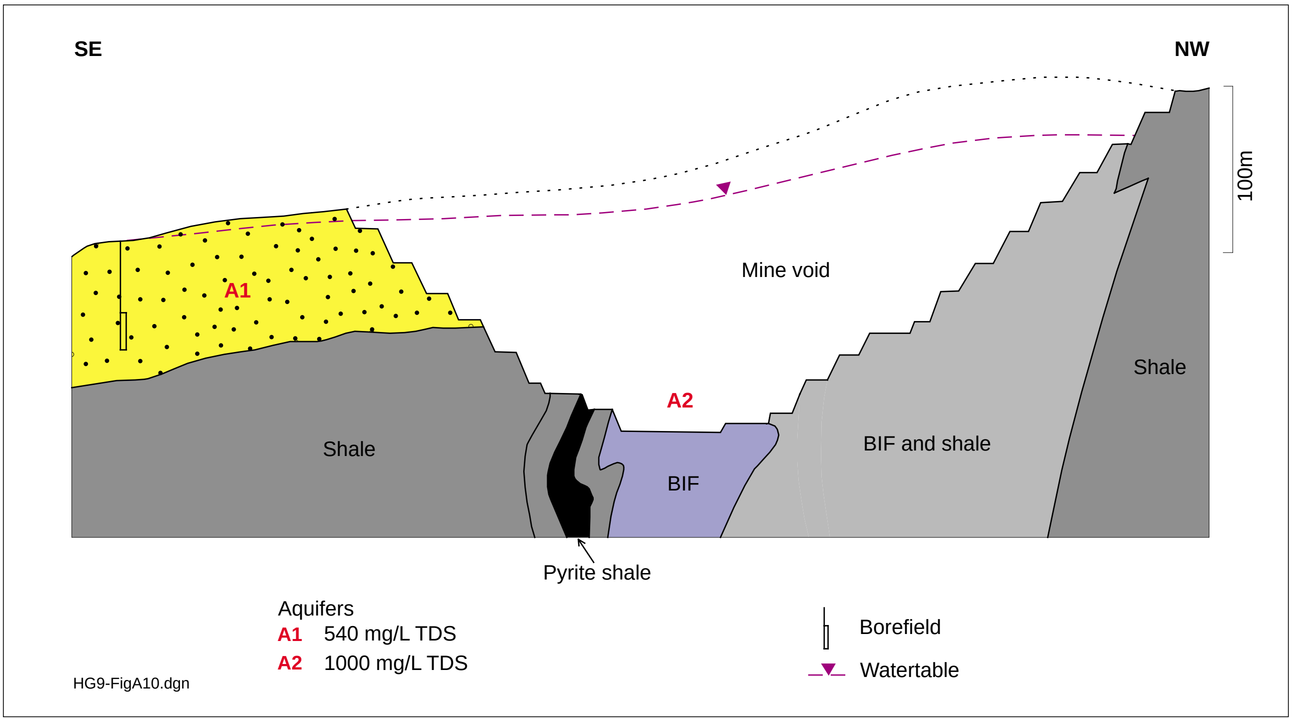

Figure A10. Cross section through Orebody 23 following mine closure

Potable water is supplied to the town of Newman from the borefield along Homestead Creek, 7 km upstream of the proposed mine. The Ethel Gorge borefield, drawing from alluvium, supplies 14 000 kL/day to Mount Whaleback mine. Groundwater throughflow in Ethel Gorge prior to development of the borefield was estimated at 1000–2000 kL/day reducing to 500–700 kL/day on the commencement of abstraction. Evapotranspiration loss is estimated at 10 000 kL/day, as the creek system supports significant numbers of River Red Gum and Coolibah trees.

Potential impact of mining void

Groundwater modelling has indicated that mine dewatering will produce significant drawdowns impacting on the existing Ethel Gorge borefield. Outflow of groundwater from Ethel Gorge to the north will be effectively stopped, except during periods of heavy rainfall where shallow groundwater flows may occur in the alluvium. Throughflow will therefore have to be artificially supported during dewatering activities.

On completion of mining, waterlevels in the aquifer are expected to return to pre-mining levels within three years. The mine void will remain open and gradually infill with water. The lake water will become progressively more saline due to evaporation rising from 1000 mg/L to about 10 000 mg/L after 100 years. Owing to hydraulic connection with the alluvial aquifer, the groundwater salinity immediately outside the pit will also increase in time and a saline plume may move downgradient into the borefield (Fig. A11). Modelling predictions indicate that it may take 30 years for groundwater salinity immediately down-gradient of the pit to increase by 20%, and 100 years to increase by 50%. The overall impact will be limited provided there is adequate groundwater throughflow via artificial recharge from Ophthalmia Dam

The final waterlevel in the pit will be above the exposed Mount McRae Shale (pyritic shales), thus reducing the potential for long-term oxidation and acid production.

Conclusions

Mine closure and the abandonment of the opencut will result in the formation of a pit lake that will become saline over time. The resultant pit lake may adversely affect the adjacent shallow groundwater resource, currently a source of good quality water for urban and industrial use. Impacts may be measurable within 30 years, and could be considered as significant within 100 years of mine closure.

The nature of the mining operation precludes the backfill option. The planned strategy of leaving the void to naturally fill with water therefore appears the most practical. The quick response time of the groundwater system means that compliance monitoring over a short period will permit early checking of modelling predictions. This will allow greater confidence in the long-term predictions and forewarn of any necessity for mitigation measures.

References

BHP, 1997, Orebody 23, Consultative Environmental Review (unpublished).

6 Hope Downs operation

Introduction

Most of the data and information used in this case study on the proposed Hope Downs operation is from Hope Downs Management Services (2000). The Hope Downs Project, 75 km northwest of Newman, is a proposed iron ore mining operation based around the Hope 1 deposit. The project will involve the opencut mining of both the Hope North and Hope South (Marra Mamba) orebodies (Fig. A12). When completely mined, the Hope North pit may have dimensions of 5500 x 250 x 240 m (deep) and the Hope South pit 5000 m x 200 m x 130 m (depth). The Hope North pit will extend 200 m below the watertable, whereas only a small portion of Hope South deposit lies below the watertable. It is anticipated that waterlevels will recover on completion of mining, but high evaporative losses within the pit lakes will prevent complete recovery.

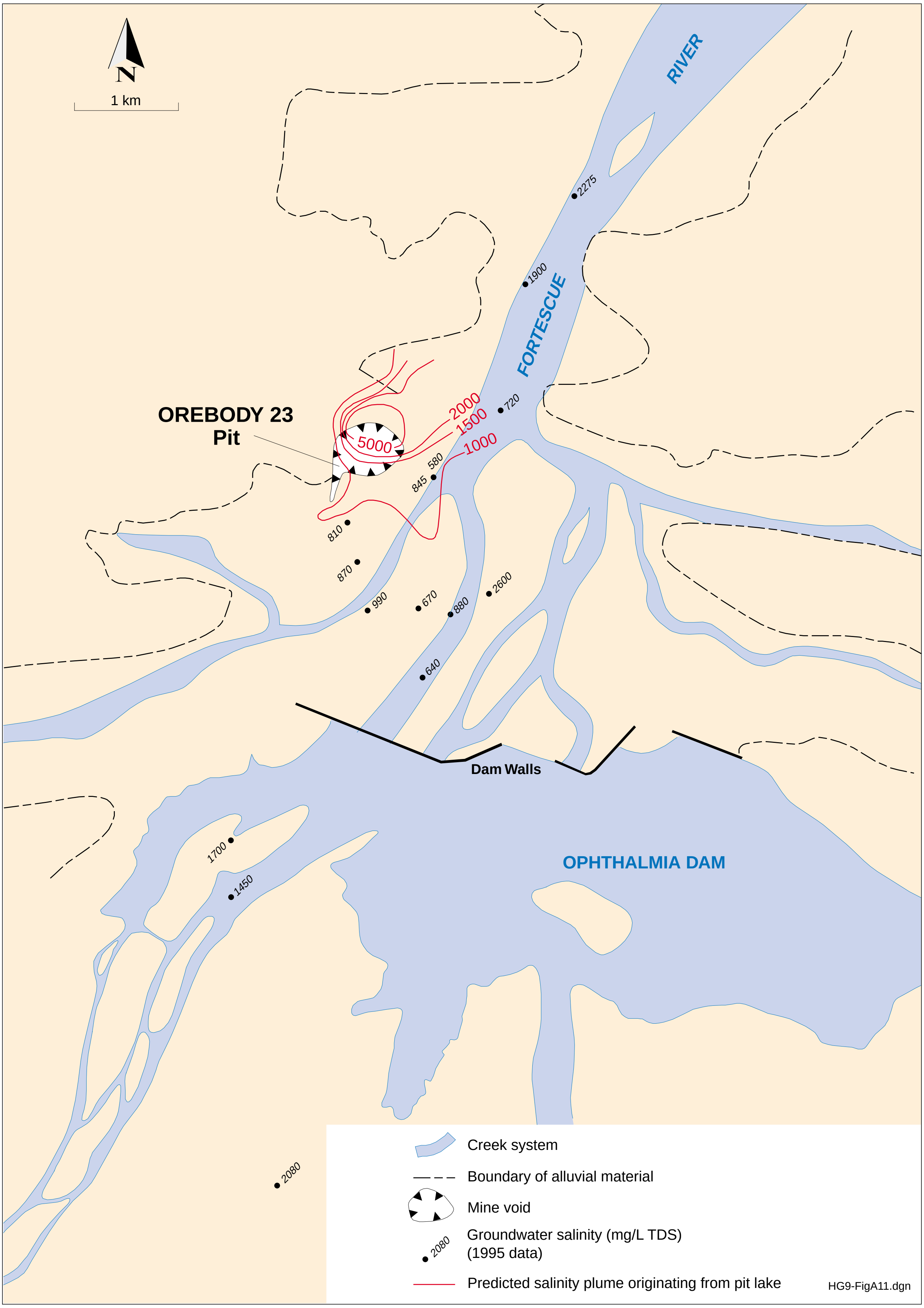

Figure A11. Predicted salinity plume from Orebody 23 after mining

The Hope 1 deposit is located within the southern half of the Weeli Wolli Creek catchment. The mine site comprises two systems of easterly trending hills and ridges with a vast area of outwash plain. Weeli Wolli Creek is an ephemeral stream that commonly carries substantial flood discharge.

The Hope North deposit is about 6.5 km southwest of Weeli Wolli Spring, which is located where Weeli Wolli Creek enters a relatively narrow gorge. The gorge forms the surface and groundwater outlet from the southern half of the Weeli Wolli catchment (Fig. A12). The spring is a permanent surface-water feature that is supported by groundwater discharge. Surface-water flow disappears about 2 km downstream of the spring as a result of seepage and evaporation.

Although the region is classified as semi-arid to arid, it does experience periodic heavy rainfalls during summer owing to both monsoonal effects and cyclones. Annual rainfall of 330 mm is highly variable, ranging from 140 to over 1000 mm, and annual evaporation exceeds 3000 mm.

The area contains two broad vegetation complexes. On the higher ground, there is continuous low Mulga woodland and tree steppe of *Eucalyptus brevifolia* (Snappy Gum) over spinifex. In the creeks, the dominant species are *E.camaldulensis* (River Red Gum), *E.microtheca* (Coolibah) and *Melaleuca argentea* (Paper bark), which are all considered to be phreatophytes.

Geology and hydrogeology

The Hope 1 area is characterised by rocks of the Hamersley Group, including the Brockman Iron and Marra Mamba Iron Formations. The Marra Mamba Iron Formation contains the ore deposits, with most mineralisation confined to the Mount Newman Member and the base of the West Angela Member. The mining areas are located on the northern limb of the Weeli Wolli Anticline and have undergone an additional series of folding. The two deposits also appear to be on a major northeast–southwest structural lineament that dictates the lower Weeli Wolli Creek drainage pattern. It is this lineament that appears to be responsible for the gorge in the Brockman BIF in which Weeli Wolli Spring is located.

The karstic dolomite within the Paraburdoo Member of the Wittenoom Formation is an important aquifer (Fig. A12). Other bedrock aquifers exist within the West Angela Member (where manganiferous) and in fractured Marra Mamba Iron Formation, with the enhancement of permeability related to structural features.

In places, many of these form high-permeability zones that underlie the Tertiary valley-fill sediments. The pisolite and calcrete, where present below the watertable, also constitute a significant aquifer. The aquifer is recharged via direct rainfall infiltration and creek-line infiltration. Groundwater contours show the hydraulic gradients to be fairly steep in the upper catchment but decreasing downstream towards the proposed mines and Weeli Wolli Spring.

The Weeli Wolli Spring has formed by the concentration of flow through a narrow gap in the Brockman Formation and changes in topographic gradient. This “damming effect” of groundwater flow results in an apparent “underground reservoir” that discharges over the shallow basement, thus forming the spring. A linear zone of high permeability is inferred in the basement between the proposed mines and the spring.

Groundwater is fresh and slightly alkaline, although there is increasing salinity (up to 600 mg/L TDS) towards the spring. This is a result of increased evapotranspiration near the gorge, as the shallow watertable supports extensive stands of phreatophytic vegetation.

Both orebodies are significant local aquifers with relatively high permeability. The Hope North orebody is bounded on the southern side by low-permeability BIF, but to the north it is directly hydraulically linked to the regional aquifer. At Hope South the small “pods” of orebody below the watertable are contained within the low-permeability BIF.

Potential impact of mining void

Dewatering will be necessary to maintain dry-mining conditions, as both deposits extend below the watertable (Fig. A13). In order to lower the watertable by 180 m at Hope North, it is anticipated that groundwater abstraction rates of between 30 and

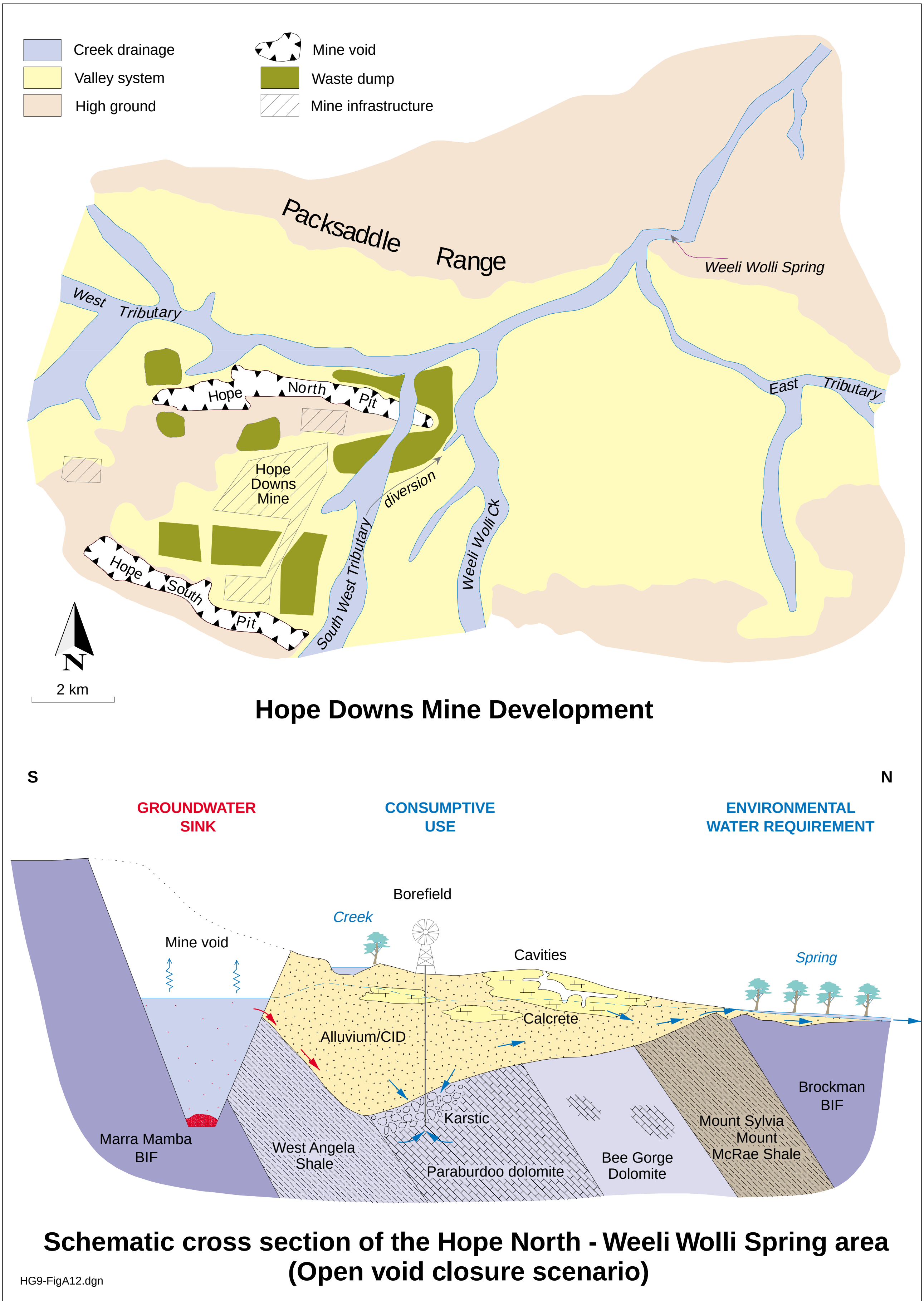

Figure A12. Mine layout and cross section from Hope North to Weeli Wolli Spring

110 ML/day will be required over a period of 22 years. This would lead to a drawdown of about 50 m at Weeli Wooli Spring, with shallow groundwater contribution to the spring ceasing in the first two years.

In addition, dewatering at Hope Downs will also dewater the proposed BHP water supply borefield east of the Mining Area C. This is not a major problem, with the mine-water balance at Hope Downs indicating a dewatering surplus of 90 ML/day after the ecological and mine-water requirements have been met.

The groundwater–spring interaction at the head of the gorge is a critical hydrological factor with regard to the proposed mining of the Hope North deposit (Fig. A13). Weeli Wolli Spring is supported entirely by groundwater baseflow and this ecological water requirement is the major beneficial use of the regional aquifer. The environmental and cultural importance of the spring is such that groundwater abstraction would not be permitted to allow the spring to dry up. The spring will have to be artificially maintained if groundwater abstraction in the catchment up-gradient of the spring results in significant flow reduction. In fact, because of the very high hydraulic sensitivity of the spring, groundwater abstraction would not be allowed for consumptive use close to the spring.

The highly sensitive water balance within the catchment implies that the entire groundwater resource has to be allocated to ecological water requirements. Any modification to the groundwater system will necessitate some form of spring supplementation. During mining, it is possible to use surplus dewatering discharge to artificially maintain spring flow via either artificial recharge into the calcrete (up-gradient of the spring) or direct surface supplementation. However, the major concern is spring supplementation on the cessation of mining.

Groundwater modelling has indicated that it could take 60 years for the waterlevels at the Hope North Pit to return to pre-mining levels with the resumption of natural spring flow. The importation of water from outside the catchment and mining lease is dependent on negotiations with other mining companies. The proponent has made a commitment to artificially maintain the system for possibly twenty years after mining ceases.

After extensive modelling and testing of some 12 different scenarios, the proponent has agreed that the preferred management strategy is:

- Infilling the Hope North and Hope South pits to prevent the development of a ‘groundwater sink’.
- Floodwaters from the South West tributary to be diverted into the backfilled Hope North pit for at least 20 years to enhance waterlevel recovery.
- Importation of 20 ML/day from outside the catchment (possibly Marillana Creek and/or Weeli Wolli CID aquifer) for aquifer re-injection in the vicinity of the Hope North pit.
- Abstracting some 20 ML/day from the dolomitic aquifer in the upper reaches of the catchment for spring augmentation and aquifer re-injection in the calcrete up-gradient of the gorge.
- During mining operations, artificially recharging all surplus water into the dolomitic aquifer in the upper reaches of the catchment.
- If successfully implemented, this strategy should ensure that the spring flow is self-sustaining within 20 years.

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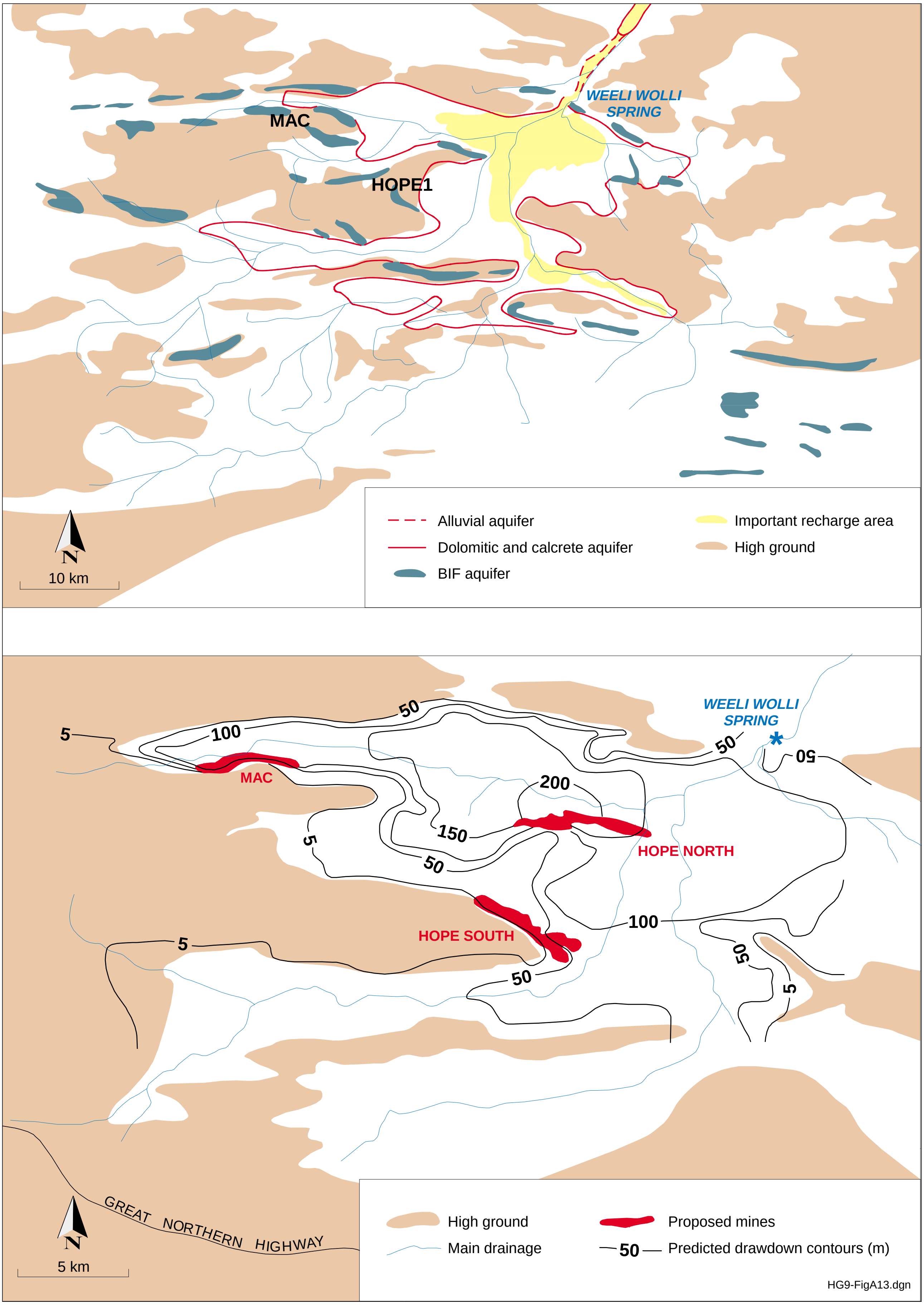

Figure A13. Aquifer distribution and predicted drawdown resulting from dewatering

Conclusions

The possible development of the Hope North mine constitutes one of the most difficult mine void closure scenarios in the State.

- The mine void will be backfilled to prevent the development of a 'groundwater sink'.
- The void potentially has a direct hydraulic link to the adjacent unconfined aquifer.
- The adjacent aquifer is fully allocated to ecological water requirements.
- The linked ecological water use (Weeli Wolli Spring — a spring-fed wetland) has both great cultural and heritage value.

References

HOPE DOWNS MANAGEMENT SERVICES, 2000, Hope Downs Iron Ore Project – Public Environmental Review, August 2000 (unpublished).

7 Yandi operation

Introduction

Most of the data and information used in this case study on the BHP and HI Yandicoogina operations are from various unpublished reports for BHP (AGC Woodward-Clyde, 1995a; BHP, 1998) and Hamersley Iron (A. J. Peck and Associates, 1995; AGC Woodward-Clyde, 1994, 1995b, 1997, 1998).

The Yandi operations are a good example of a 'groundwater throughflow' mine void. A number of mines extract pisolitic ore (CID) from beneath the watertable. The CID formed along the Marillana–Yandicoogina–Weeli Wolli Creek system, which about 150 km northwest of Newman (Fig. A14), and extends over 70 km with a width of 500–700 m and thickness of more than 50 m. Opencut mining is currently taking place at four sites along Marillana Creek, and ultimately mining will remove the entire CID. The very low overburden to ore ratio (0.2:1), though advantageous to mining, represents a disadvantage with regard to the backfilling of final mine voids. Current mine-closure plans have opted for partial infilling of the voids, in order to minimise pit lake surface area and maintain a degree of throughflow within the system. These plans involve the creation of a number of shallow elongated final voids.

Pit E2	2700 x 550 x 45 m	[final water depth 15 m]
Pit C1/2	4000 x 550 x 60 m	[final water depth 17 m]
Pit C5	2000 x 550 x 60 m	[final water depth 7 m]
Junction	7750 x 600 x 35 m	

The climate is semi-arid with very hot summers and mild to warm winters. Rainfall of about 250 mm/yr results from local convective storms and large-scale cyclonic events, and evaporation losses are high (3300 mm/yr). The vegetation is dominated by a tree steppe of Snappy Gum and mulga over spinifex, whereas the creeks contain major stands of phreatophytic vegetation. Apart from mining, land use is pastoral.

Marillana and Yandicoogina Creeks drain the Hamersley Range to the west and south of the mine. The Marillana Creek system drains eastward, where it joins Weeli Wolli Creek, which flows northward before discharging into the Fortescue Valley (Fig. A14). Streamflow is seasonal, with flows after heavy rains; Marillana Creek normally flows for 30 to 60 days a year. Annual streamflow in the area around Yandi can range from negligible to tens of millions of cubic metres.

Hydrogeology

The iron ore deposits (CID) lie within Tertiary palaeochannels that are incised into shale, dolerite and banded iron-formation (BIF) of the Weeli Wolli Formation. The CID consists of three main facies: a basal conglomerate; basal clay pisolite; and the main pisolite ore zone (Fig. A14). The pisolitic units have well-developed joints and solution cavities (providing up to 25% open pore space) and near-horizontal clay layers varying in thickness and lateral extent. Downstream of Junction Deposit, the Marillana Creek CID joins the Weeli Wolli Creek CID before trending northeast towards the Fortescue River Valley. The Weeli Wolli Creek CID is less well defined and at greater depth, and plunges towards the north under the Fortescue River Valley.

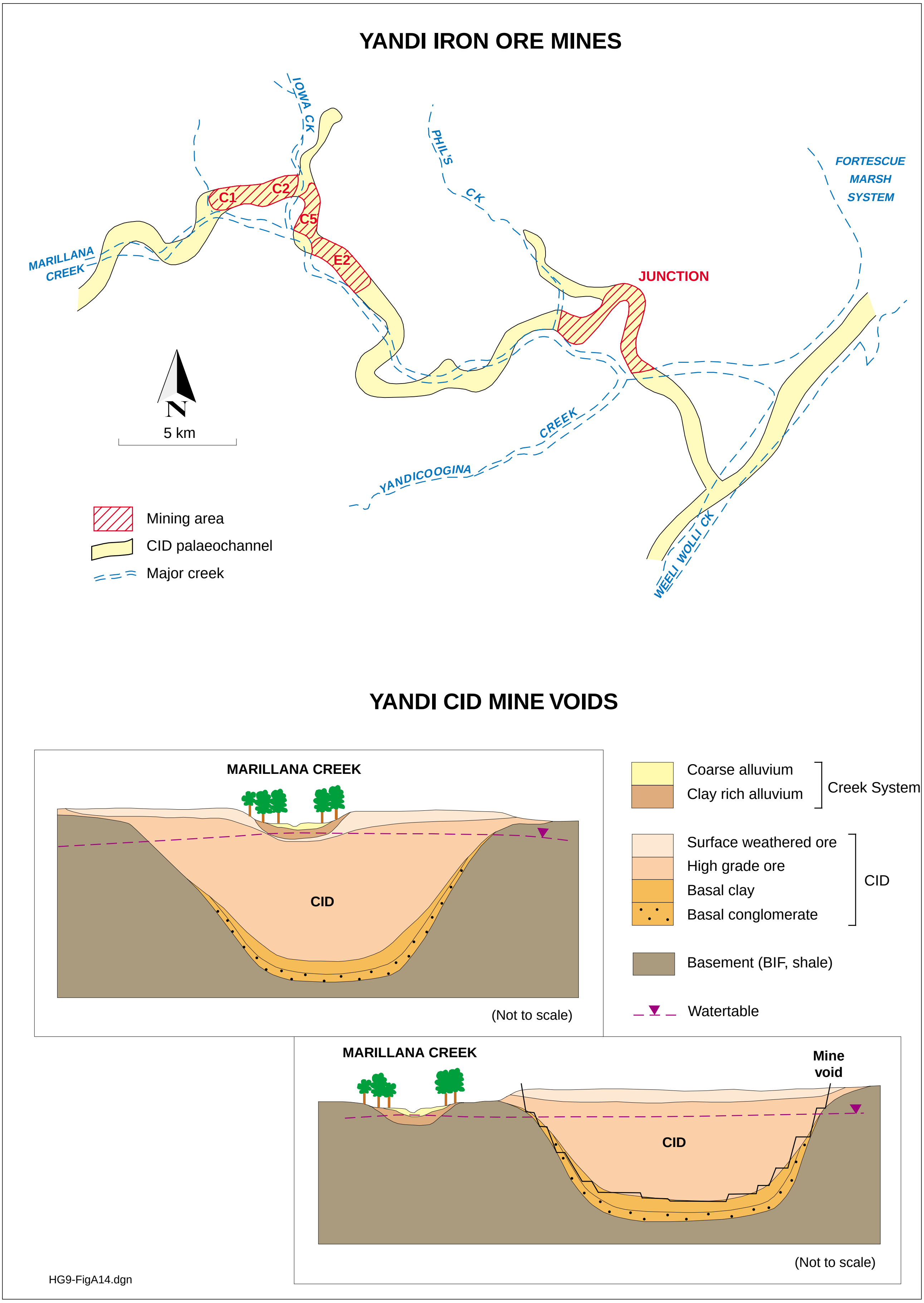

Figure A14. Distribution of mine voids at Yandi iron ore mines

Marillana Creek and other creeks wind along narrow strips of unconsolidated Quaternary alluvium. The alluvial bed within Marillana Creek varies in width from 150 to 400 m with depths of 5 to 20 m. The shallow alluvial aquifer associated with the various creeks is estimated to have a throughflow in the order of 5 m^3/day forming recharge/discharge points where the creeks cross the CID aquifer (Fig. A14).

The CID is the main aquifer with an estimated throughflow of 2.5 to 3 ML/day. The water within the CID is fresh, in the order of 500 mg/L TDS. A difference in salinity and water chemistry in the CID between Marillana Creek and Weeli Wolli Creek suggests that contributions due to throughflow may be small. The CID aquifer behaves as a fractured-rock aquifer, but over the long term it may show an unconfined response.

The basement rocks (Weeli Wolli Formation) contain fractured-rock aquifers with hydraulic conductivity much lower than that of the CID or creek alluvium. The fractured-rock aquifer is highly localised and capable of providing significant bore yields.

Potential impact of mining voids

The Marillana Creek system is an important source of surface runoff to the Weeli Wolli Creek system, as well as a source of recharge to the Marillana Creek CID aquifer. The CID aquifer contains fresh groundwater that is an important groundwater resource. The contribution of the Marillana Creek CID aquifer to the throughflow in the whole CID aquifer would appear to be relatively small.

The mining of pisolitic ore will effectively remove the aquifer. Modelling indicates that dewatering will result in significant drawdowns, but that waterlevels will recover within 15 years of the cessation of mining. Full recovery of waterlevels will be prevented by evaporation from the relatively shallow water bodies in the mine voids.

There will be evaporation losses from all pits, including the Junction mine, where the infill material extends above the expected watertable. A total of 10 000 kL/day could be lost to evaporation, in which case the mine voids will act as local groundwater sinks. However, apart from Pit C5, the impact will be small enough for an infrequent flood event to replenish aquifer levels and maintain adequate throughflow in the CID aquifer.

In the long term evaporation of the pit lakes will result in an increase in salinity, as water is lost through evaporation and salt is left behind. Modelling indicates that the salinity of the pit lake water in mine void C5 (groundwater sink) will increase steadily from 500 to 14 000 mg/L after 250 years; at mine void E2 (partial groundwater throughflow) from 500 to 1600 mg/L after 90 years, stabilising at about 1800 mg/L; and at Junction mine (groundwater throughflow) to 2500 mg/L. The salinity of the groundwater leaving the Marillana Creek CID is not expected to exceed 2500 mg/L and this should be significantly reduced through mixing once it enters the main Weeli Wolli Creek CID aquifer. The degree of mixing will be dependent on the ratio of throughflow between the aquifers and will require a better understanding of the throughflow in the Weeli Wolli CID. Based on the predicted post-closure configuration, water quality in the Weeli Wolli CID should reach equilibrium within a short period of time (100 years).

Conclusions

Mine void closure strategies at the Yandi operations will result in a number of different hydrogeological voids. As much of the Marillana Creek CID aquifer will be removed during mining operations, closure strategies will have to ensure adequate groundwater throughflow to protect the down-gradient Weeli Wolli CID aquifer and maintain the beneficial use of the groundwater resource.

After mine closure, compliance monitoring of bores within Marillana and Weeli Wolli Creeks should detect changes in water quality. If closure predictions are not met, there is scope for implementing actions to mitigate any adverse environmental effects. Degradation of water quality beyond the compliance standard (should it occur) would not be irreversible. As the system will be managed as a groundwater throughflow system, decreasing evaporative loss in the voids should improve water quality with subsequent flow-on effects.

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8 Plutonic gold operation

Introduction

The Plutonic gold operation is located about 180 km north of Meekatharra. Mining operations commenced in 1990 with surface and underground workings. Surface mining operations comprise 27 opencut pits with the gold ore processed at a central mill (Fig. A15). The size of the mine voids is highly variable with the largest pit, Main pit, having dimensions of 1200 m by 800 m and depth of 175 m. Gold mineralisation occurs within shallow laterite and deeper, highly deformed mafic volcanics. It has been confirmed in pits where dewatering has ceased that the waterlevel recovers to partially fill the voids. The case study is focused on two smaller opencut pits: Salmon pit and Perch pit, which exhibit different hydrogeology and mine closure options.

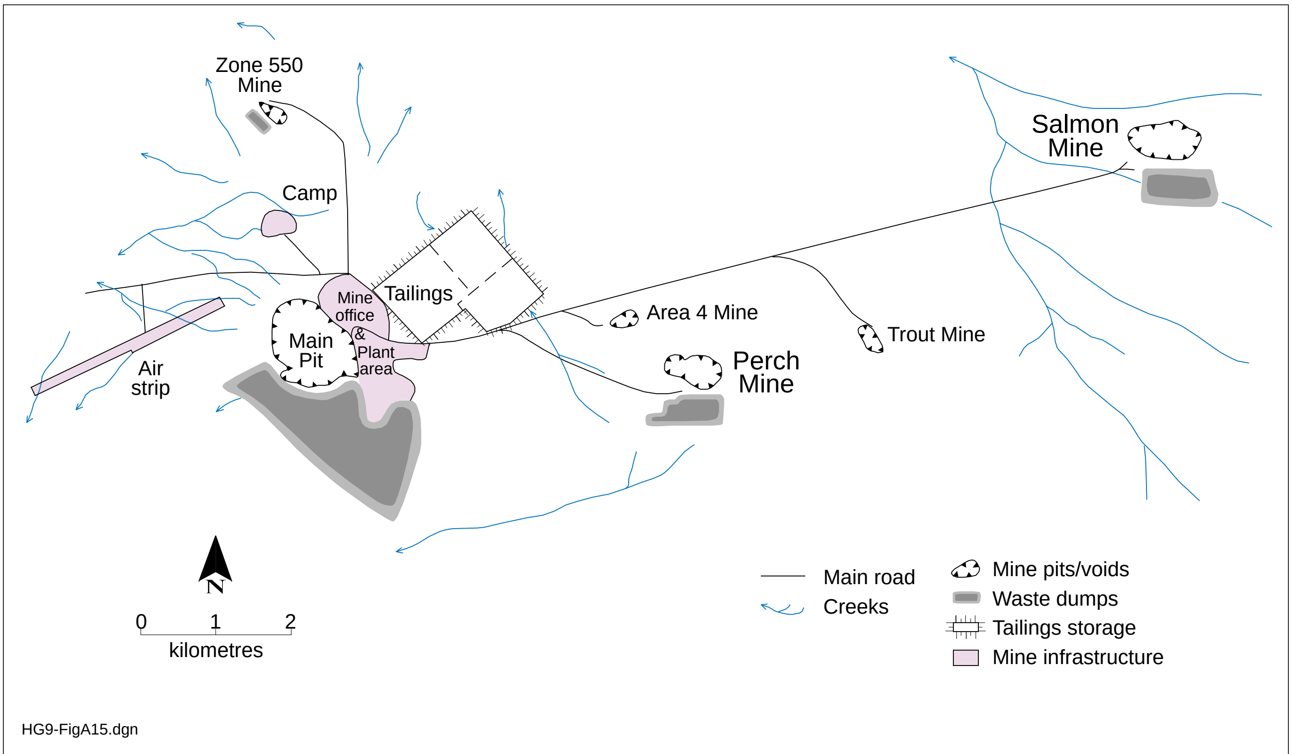

Figure A15. Location of mine voids at Plutonic gold mine

The climate is arid with an average rainfall of 225 mm/yr and average evaporation of 4100 mm/yr. Rainfall occurs primarily during the summer–autumn months from tropical rain depressions or cyclonic activity. The maximum temperature between December and March frequently exceeds 40˚C.

The topography of the mine site is characterised by a low-relief alluvial plain comprising minor ephemeral watercourses that drain toward the middle branches of the Gascoyne River. Prior to mining, the area was used largely for cattle and sheep grazing.

Geology and hydrogeology

All the mining at Plutonic occurs within an Archaean granite–greenstone terrane. Most mineralisation is associated with the Plutonic Greenstone Belt, part of

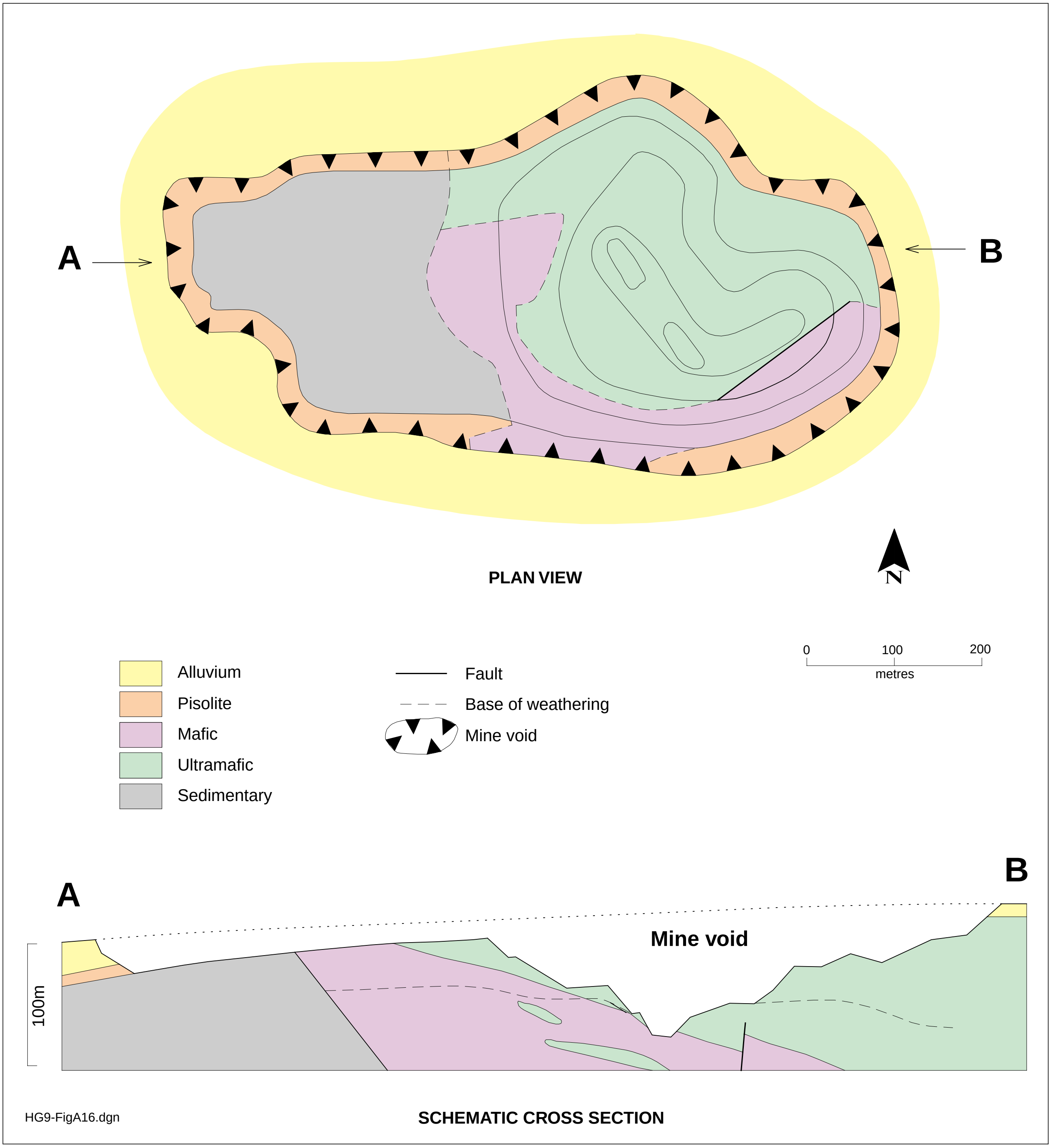

Figure A16. Geology of the Salmon mine void

the Marymia Dome, which is a remnant basement feature within the Proterozoic Capricorn Orogen. The north-easterly trending greenstone sequence has a strike length of about 50 km comprising ultramafic volcanics, tholeiitic basalt and metasedimentary rocks.

The geology of the Salmon pit comprises an upper alluvial cover, up to 30 m thick, overlying a discontinuous pisolitic laterite horizon. The laterite, developed on the underlying Archaean rocks (Fig. A16), appears to be variably reworked into the alluvium. The greenstone rocks (basement) comprise two major units: gently-dipping mafic rocks characterised by siliceous intrusions and extensive faulting, and underlying ultramafic units with clayey weathering products and less fracturing.

The alluvium and laterite are hydraulically connected, forming an unconfined to semi-confined aquifer. The waterlevel is generally 5 m below ground level with regional groundwater flow in a north-westerly direction. Groundwater resides primarily in the basal pisolitic laterite with well-defined paths for groundwater movement. Groundwater recharge mechanisms are direct infiltration of rainfall and streamflow during flood events.

Groundwater occurrence in the greenstone rocks is associated with siliceous intrusion and fracturing. The fractured-rock aquifer is semi-confined with indirect recharge via leakage from the alluvial aquifer and adjacent permeable units. The transmissivity of the fractured-rock aquifer is lower than that of the overlying pisolitic laterite. Most aquifers contain fresh to saline groundwater with salinity often increasing with depth. Other water quality considerations are that arsenic and nitrate concentrations often exceed drinking-water guidelines.

In contrast, Perch pit is characterised by numerous structural features. A major shear is evident along the contact between the mafic (mineralisation host) and the hangingwall ultramafic unit in the northern margin of the pit (Fig. A17). In the south of the pit, an easterly trending fault marks the contact between the footwall ultramafic unit and a granite pluton. Several sinistral faults also transect the pit in a north-easterly orientation. A steep dipping, easterly trending Proterozoic dyke intrudes the mafic unit in the north of the pit.

Groundwater occurrence is associated with structural features derived from several phases of brittle deformation. The overlying saprolitic and clayey alluvium act as a semi-confining layer The pre-mining waterlevel was about 40 m below surface. The groundwater salinity is generally less than 600 mg/L, although there are slightly elevated pH, arsenic and nitrate levels.

Potential impact of mining voids

All mines at Plutonic encounter localised fractured-rock aquifers that will contribute to the mine void with groundwater. The rate of flooding varies between mine voids with Salmon and Trout pits quickly flooding due to direct hydraulic connection between the unconfined alluvial aquifer and mine voids.

The mine voids will act as ‘groundwater sinks’ with evaporation from the pit lakes exceeding water inflow. There are large portions of Salmon and Perch mine voids that will remain dry due largely to mine void geometry (Figs A16 and A17). Modelling has indicated that the pit lakes will become more saline at a annual rate of 200 mg/L; hence, a millennium may pass before any significant environmental effects could be measured.

Location, in respect to surface drainage features, is the major difference between the Perch and Salmon pit voids, which required different mine closure strategies. Perch pit is located on a localised catchment divide, whereas Salmon pit occurs within an alluvial plain between two well-defined creeks that feed into the Gascoyne River (Fig. A15).

Dewatering at Perch pit produced an ellipsoidal drawdown related to the identified structural features, while the waterlevel was effectively unchanged away from the pit. The final void appears to be hydrogeologically isolated with potential for water or mine-waste storage. Perch pit and its satellite pits are currently used for gold tailings storage (Parsons Brinckerhoff, 2002).

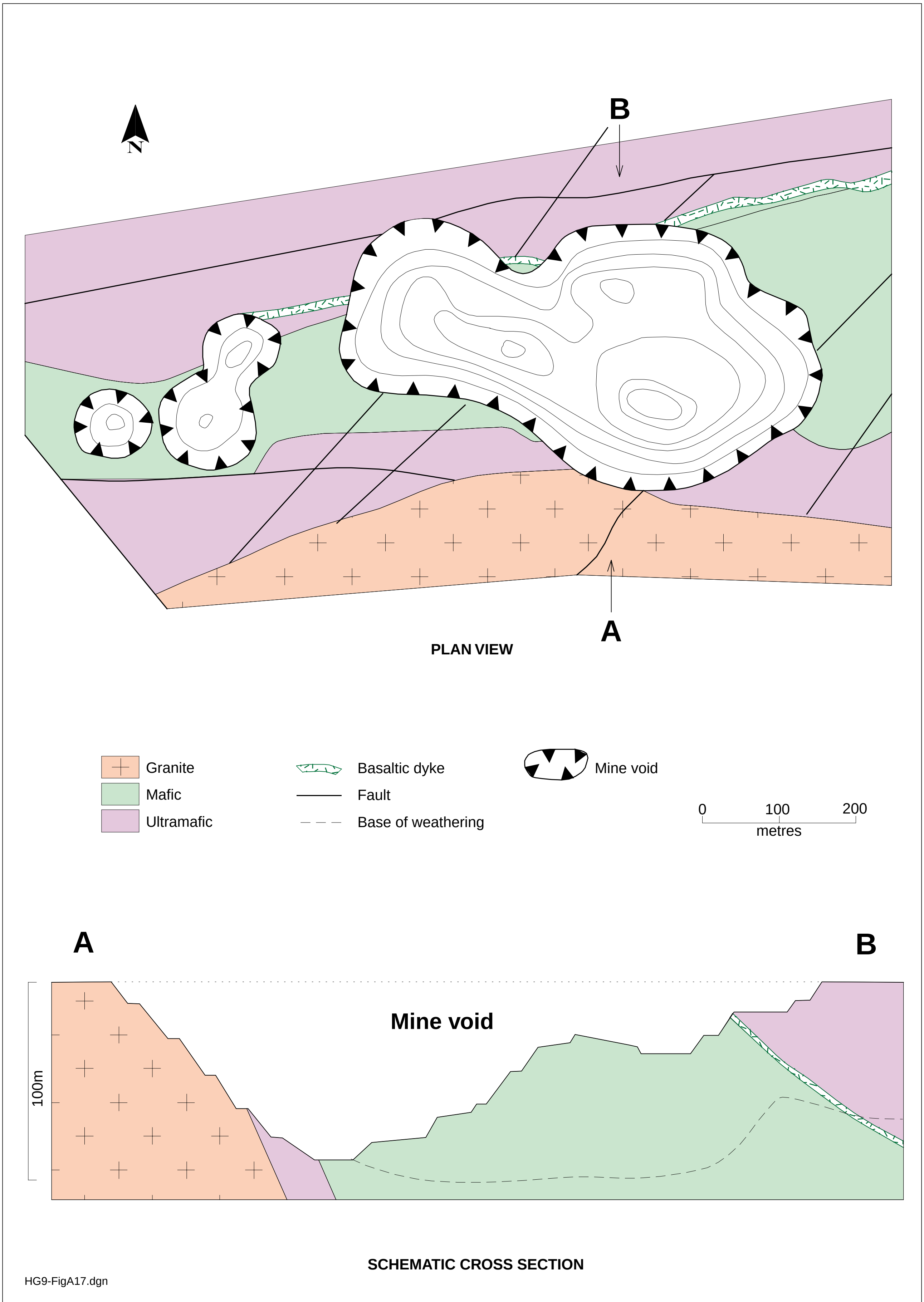

Figure A17. Geology of the Perch mine void

Salmon pit is highly susceptible to periodic flooding as happened during Cyclone Bobby in February 1995. There is a high probability that the final void will invariably flood from surface water runoff unless the final pit closure bund is engineered to withstand a one in 500 year flood event. Another option may be to design the final void as a ‘throughflow’ void by diverting the creeks. This will ultimately result in the void filling with water and provide seasonal flushing of the system. The frequency of flooding appears to be one in four years, depending on the presence of cyclones and tropical depressions.

Conclusions

Final void size and remoteness from the main mining operations ensures that backfilling with excavated waste is not considered a viable option. The most practical closure option was initially thought to be allowing the mine voids to slowly flood with water.

An additional option at Salmon pit is engineering a ‘throughflow cell’ by diverting the adjacent creeks, which would alleviate the potential of the void to become a hypersaline-water point source for the Gascoyne River. Although, there are important ethnographic issues that must considered prior to implementing creek diversion. Pit lakes in the remaining mine voids will become progressively saline (over hundreds of years) with potential as water-storage facilities. The shallow voids, if not backfilled, have potential as storage facilities for in-pit tailings or stock water. In-pit tailings storage is a preferable option for those voids that are positioned close to existing mine operations, such as Perch pit.

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9 Marymia gold operation

Introduction

The information provided in this case study was sourced from the original Notice of Intent document and a technical paper, both by Chris Lane of Soil and Rock Engineering (Lane, 2000).

The original Marymia gold operation, located 200 km northeast of Meekatharra, commenced mining in

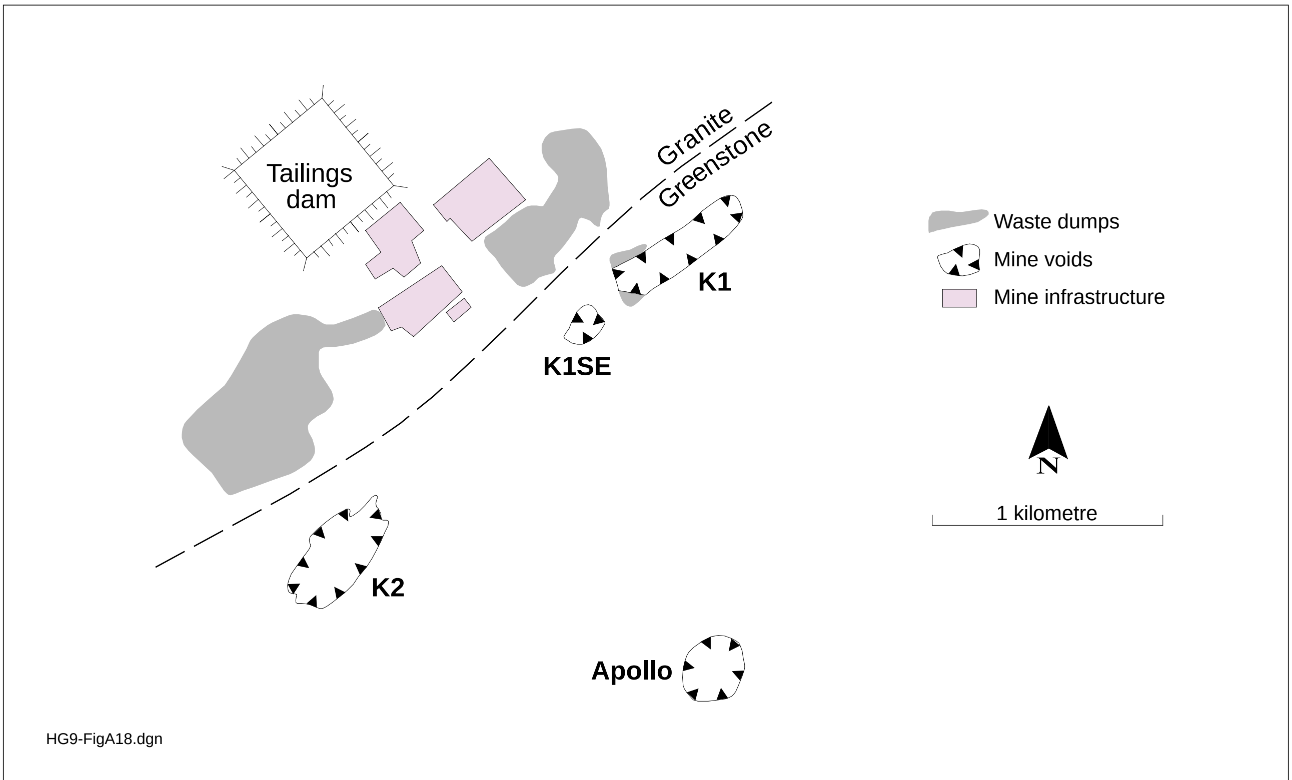

Figure A18. Location of mine voids at Marymia gold mine

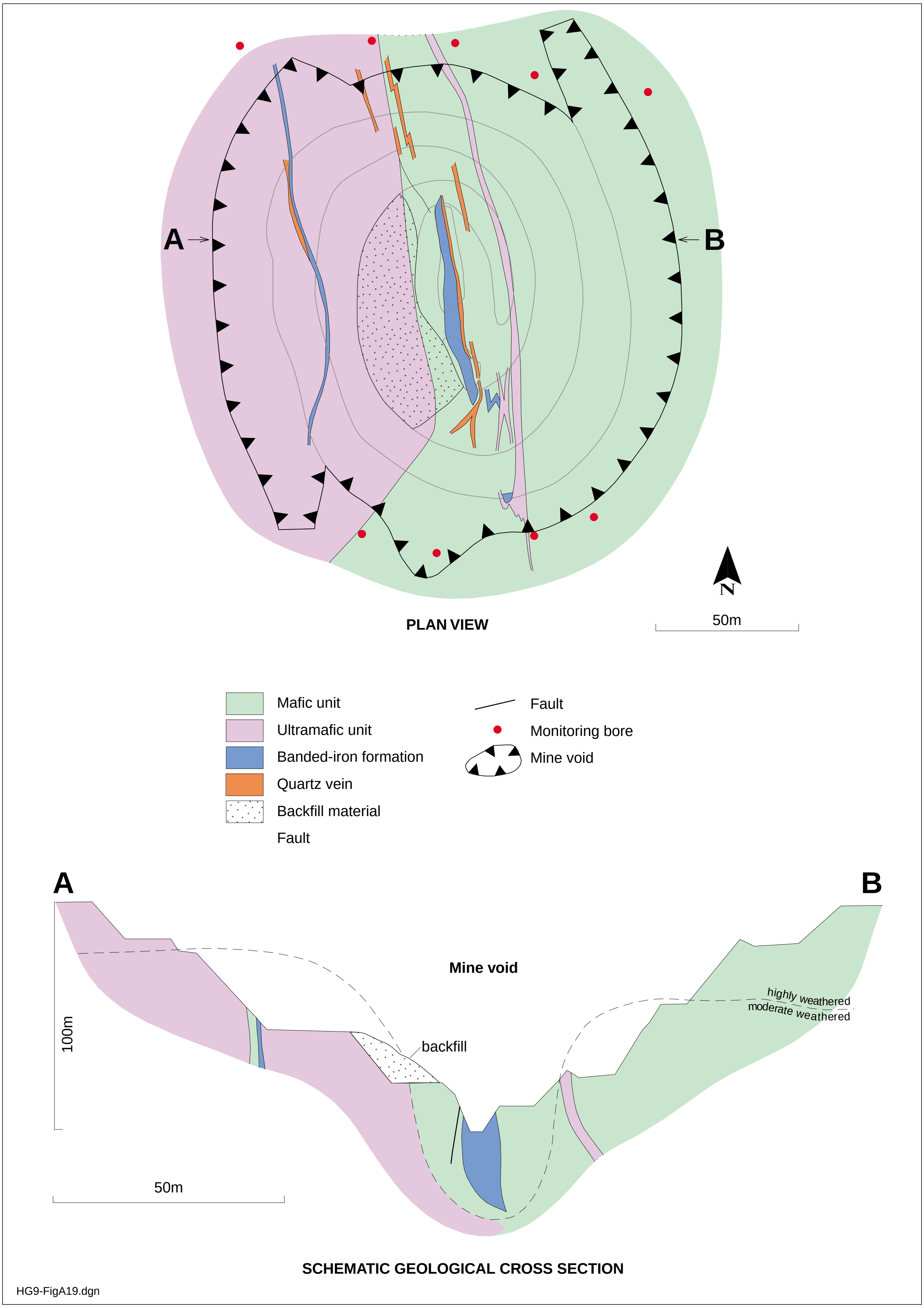

Figure A19. Geology of the K1SE mine void

1992 and ceased in 1998. Marymia is now operated by Barrick Gold who have plans to re-mine certain areas. This case study will focus on the previous owner's (Resolute Resources Ltd.) handling of tailings disposal as part of the mine closure strategy. In 1994, investigations were undertaken to evaluate the potential of in-pit tailings disposal at the mine. It was identified that ore from the Marwest pit contained fibrous actinolite and tremolite with the resultant tailings requiring containment in a sealed environment. At the same time, the K1SE pit located close to the plant was completely mined (Fig. A18). Deposition of tailings from Marwest pit into K1SE pit commenced in December 1995.

The climate is arid with an average rainfall of 230 mm/yr and average evaporation of 3800 mm/yr. Rainfall occurs primarily during the summer–autumn months, predominantly from tropical depressions or cyclone activity. The topography of the mine site is characterised by a low-relief alluvial plain comprising minor ephemeral watercourses that drain south-eastwards into Lake Gregory. Prior to mining, the land was used was sheep grazing.

Geology and hydrogeology

All mining at Marymia takes place within the Plutonic Greenstone Belt, one of two greenstone belts in the Marymia Dome, which is a remnant basement feature within the Proterozoic Capricorn Orogen. The north-easterly trending greenstone sequence has a strike length of about 50 km and comprises ultramafic volcanics, tholeiitic basalt and metasedimentary rocks.

The K1SE opencut pit had final void dimensions of 170 m by 150 m and a depth of 50 m. There were four major geological units intersected during mining; a highly sheared talc chlorite schist, mafic amphibolite, BIF (hosting the mineralisation) and massive hangingwall mafic rocks. Shearing along lithological contacts is common with a pervasive foliation, sub-parallel to the shearing, within the talc chlorite schist (Fig. A19).

Groundwater was only encountered within the BIF towards the base of the pit. The watertable is about 50 m below ground level and no major dewatering was required during mining. Groundwater salinity is generally less than 1500 mg/L TDS.

Geotechnical suitability of pit for tailings disposal and system design

A geotechnical inspection showed that no cracking, indicative of potential large-scale wall failure, was present around the pit crest, haul road or berms. Tests confirmed the durability of the wall materials when subjected to cycles of wetting and drying. Some minor wall failure was anticipated during deposition, as tailings and ponding water against the highly weathered clayey materials may result in strength loss due to material softening.

The final dry density and water recovery characteristics of the tailings were assessed to determine the preferential mode of tailing deposition. The maximum water available for recovery (52%) was available within 24 hours of deposition, assuming that tailings velocity was low in order to minimise turbulence. Water release would be rapid allowing for water recovery via a decant system, thus alleviating the necessity for an underdrainage system.

The high water recovery and limited storage of the tailings indicated that only a pontoon-mounted pump for water return was required. Discharge of the tailings was from a single outlet initially from the haul road and later from the pit rim. A set of nine groundwater monitoring bores were constructed to the north and south of the pit within the expected flow path (Fig. A19). The bores were designed for the multiple purposes of monitoring and recovery (if tailing water was affecting groundwater resources).

Performance of the discharge system

Tailings were discharged from an open-end line directed onto the ground above the supernatant waterlevel, which enabled the tailings to enter the pond at low velocity. No major wall failures were observed during tailings disposal.

The return-water volumes, as a percentage of water in the tailings slurry, ranged from 5% at the start of in-pit disposal to 74% after four months. Two months after operations ceased, the average dry density of the tailings was 1.4 g/cm^3 confirming that the final dry density prediction of 1.64 g/cm^3 was achievable.

Groundwater monitoring showed rising waterlevels in all bores resulting from tailings deposition, in particular along the shear zone that passes through the pit in a north–south direction. Rising groundwater salinity (about 3000 mg/L TDS) and cyanide concentrations (about 120 mg/L) were observed. The hazardous asbestos-type material was stored wet beneath a constant cover of water, until finally covered by fresh earth on completion of the tailings operation.

Conclusions

The in-pit tailings disposal proved to be extremely cost-effective, with considerable savings in capital and operational costs, compared with above-ground tailings storage (TSF) option. The greatest benefits for tailings disposal into K1SE pit were environmental including:

- Safe storage of hazardous waste;
- No necessity for land clearing for a surface TSF;
- No aesthetic impact which is normally associated with a surface TSF;
- Backfilling of a final void; and
- Reduction in raw-water and reagent consumption.

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10 Mount Magnet gold operation

Introduction

The Mount Magnet gold operations, owned by Harmony Gold, is located 500 km northeast of Perth. In 1888, gold was first discovered in the area and mining has taken place ever since. At present, the mining operations extend over 60 km^2 comprising about 30 opencut pits (Fig. A20). Underground workings have also been established in several of the pits with further underground potential beneath the main ridge to the northwest of town.

The climate is semi-arid with an unreliable rainfall of 230 mm/yr and evaporation of 2600 mm/yr. Rainfall occurs during the autumn and winter months (April to August) related to southwesterly cold fronts and during summer (December – March) related to cyclonic storms.

The physiography is characterised by an ancient peneplain which drains in a southwesterly direction. Rugged ridges of steeply dipping banded iron-formation and rounded hills of granitic rocks provide moderate relief. There are a number of ephemeral, sheet-wash drainage features (part of Boogardie Creek) to the southwest of the operations (Fig. A20). Vegetation comprises sparse mulga and other low scrub. The landscape has been subjected to both intensive pastoral and historical mining.

Geology and hydrogeology

Regional geology is dominated by a northeast-trending greenstone belt, comprising deeply weathered (up to 100 m) banded iron-formation, and mafic and felsic volcanics. The weathering profile comprises laterite and saprolitic clays, which are locally overlain by alluvium, colluvium and lacustrine deposits. Primary mineralisation is associated with differential fracturing and shears, particularly in the banded iron-formation. Secondary mineralisation related to supergene enrichment also occurs in the residual lateritic duricrust, mottled clay horizons and overlying pisolitic gravel unit.

Groundwater occurs in fractured-rock and minor unconsolidated alluvial aquifers. Aquifer permeability and storage is closely related to regional faulting, such as the Mount Magnet and Boogardie Faults, and various structural features including fractures, joints and shear zones. Fracturing is better developed in the felsic rocks than the mafic rocks. The alluvial aquifer within the drainages comprises clay, silt and sand. The Genga Borefield provides the Mount Magnet town water supply, with abstraction from both the alluvial and fractured-rock aquifers.

Dewatering of mining operations within Boogardie Creek (such as Brown Hill, Milky Way, Franks Tower and Lone Pine) required in-pit and perimeter production bores. Most groundwater was encountered at the base of oxidation, which ranges from 35 to 45 m below ground level. In the deep pits, such as Quasar, there was considerable groundwater flow observed from fractures and shear zones.

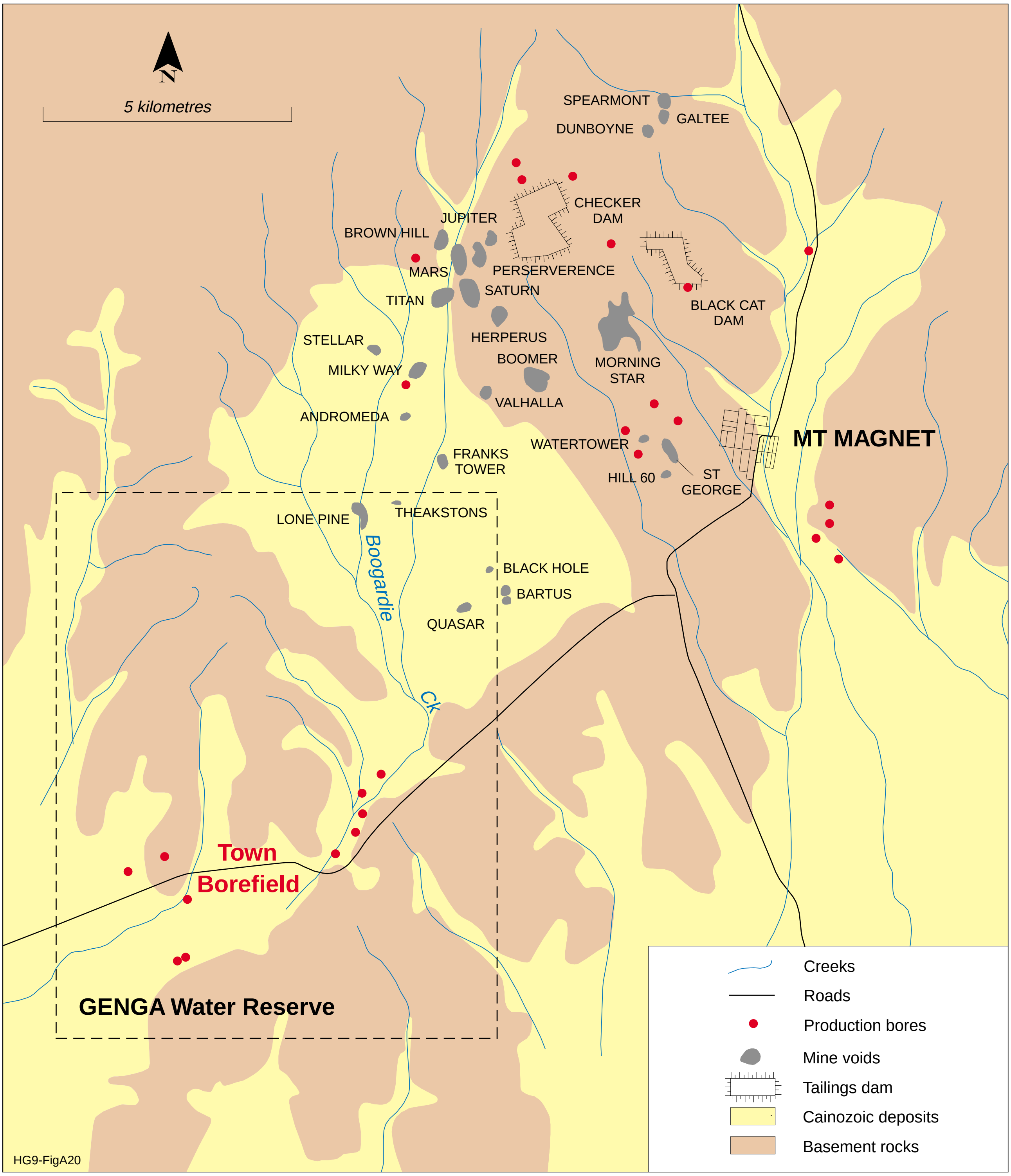

Figure A20. Location of mine voids at Mount Magnet gold mine

Rainfall infiltration is the major source of aquifer recharge. The alluvial aquifer in the Genga Borefield also receives recharge from periodic surface runoff along Boogardie Creek. Groundwater salinity typically ranges from 700 to 1800 mg/L, with the lowest salinity beneath rocky pediments on the catchment boundaries. In the deeper, fractured-rock aquifers, groundwater is often stratified with lower salinity groundwater from rainfall infiltration overlying brackish to saline water.

Potential impact of mining void

Most final mine voids within Boogardie Creek are relatively shallow, extending only to the base of oxidation. In contrast, a number of pits, such as Quasar and Bartus, extend into the fresh bedrock and intersect fractured-rock aquifers (Fig. A21).

On cessation of dewatering, it is anticipated that the voids will flood with groundwater. Groundwater inflow is largely from the fractured-rock aquifers and permeable features in the weathering profile. The rate of pit inundation is expected to be slow, particularly in the clayey weathering zone. After reaching a new equilibrium, the mine voids may act as ‘partial throughflow’ types with some pit water flowing into the nearby shallow aquifer. Salinity in the pit lakes will progressively increase and ultimately become hypersaline. Monitoring of several pit lakes has shown salinity increasing by about 15% over three years as a result of evaporation and saline groundwater inflow from the fractured-rock aquifers.

Increasing pit lake salinity is a potential threat to the surrounding low-salinity shallow aquifer, particularly if voids act as ‘throughflow’ types. Another concern is the cumulative impact of the numerous mine voids (potential hypersaline point sources) in a relatively small area, which are located 5 km up-gradient of the Genga Borefield (Fig. A20). In order to remediate and prevent ongoing problems, mine management has initiated investigations and development of various initiatives, such as:

- Shallow voids, where possible, to be backfilled with waste rock during the excavation of nearby mines; e.g. Theakston and the southern portion of Lone Pine pit were completely backfilled to resemble a low, dome-shaped hills;
- Pits to be used for the storage of dewatering discharge with the water pumped back to the plant for process water requirements. The Quasar, Bartus and Frank’s Tower pits are examples of excess water storage;
- Surface water flow to be diverted into opencut pits that are favourably located with respect to creeks, such as the Spearmont, Brown Hill, Milky Way and Lone Pine pits; and
- Continuing groundwater and pit lake monitoring for refinement of the predictive model, prior to mine closure.

Conclusions

At Mount Magnet, there are numerous mine voids in a relatively restricted area that also serves as the same catchment for a town water supply. Most of these mine voids have the potential to become ‘partial throughflow’ types resulting in possible contamination (salinity-related) of the surrounding shallow, potable groundwater resource.

Current mine management strategies include backfilling of voids and temporary use of voids for water storage. Backfilling is cost effective only where waste rock is available from nearby mining operations and the shallow voids have been completed mined. Creek diversion is an attractive closure strategy for some voids, resulting in a degree of seasonal flushing of the pit lakes and ensuring that water entering the nearby shallow aquifer has acceptable salinity levels (Gerrard, 2002).

The company is undertaking regular monitoring of water quality in and around the mine voids, in particular those receiving surface-water flow. The monitoring data will provide valuable information for developing closure plans for the mining operations, which is especially important considering the cost of backfilling voids should this become necessary.

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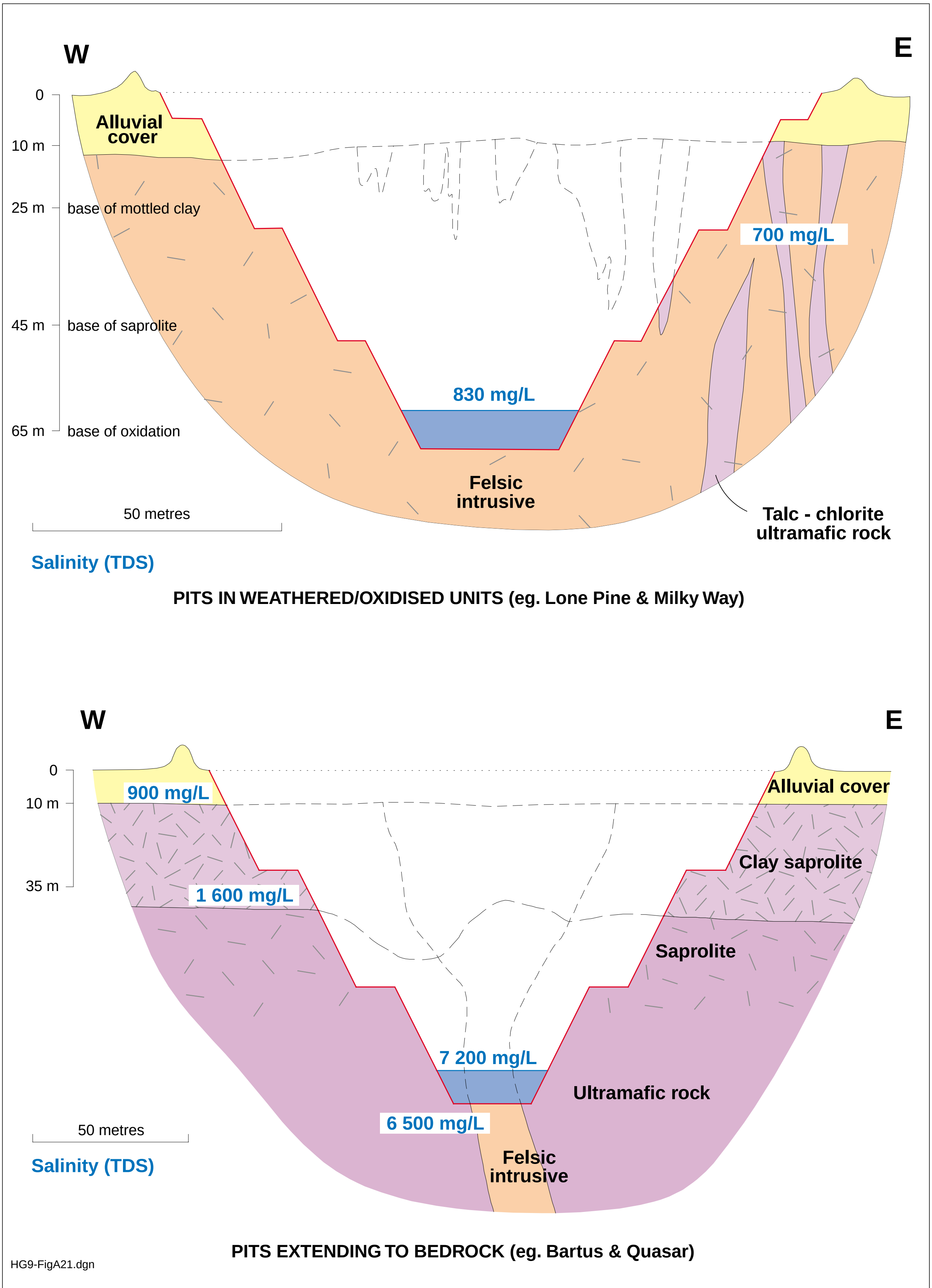

Figure A21. Mine void geology and groundwater salinity at Mount Magnet gold mine

11 Mount Keith nickel operation

Introduction

The Mount Keith nickel operation is located about 70 km north of Leinster in the Northeastern Goldfields. In 1968, nickel sulphides were first discovered in the vicinity of Mount Keith, although resource development did not commence until 1993. The size and shape of the low-grade nickel orebody makes it amenable to opencut mining, with an expected mine life of 20 years. Mining is planned in stages to maintain a constant ore:waste stripping ratio. The pit stages involve cutting back the east and west walls to widen and deepen at each previous stage (Fig. A22). The current pit (Stage E) is about 1800 m by 1000 m, orientated north–south, and a depth of 240 m. The final pit void will have dimensions of 2500 m by 1700 m and a depth of 500 m.

The pit extends below the watertable with mine dewatering achieved by small sumps, horizontal drainholes and two perimeter production bores. The base of the final excavation will be about 480 m below the pre-mining waterlevel. It is anticipated that on cessation of dewatering, waterlevels will slowly recover to partially fill the void.

The climate is semi-arid to arid with an average rainfall of 220 mm/yr and evaporation exceeding 3500 mm/yr. Rainfall is highly variable, with most precipitation during the summer months related to cyclonic and thunderstorm activity.

The climate regime imposes severe restrictions on the quality and quantity of water available to the mining operation. There is no permanent surface water in the area; hence, local groundwater resources meet all mine water requirements. Groundwater is abstracted from a number of borefields within palaeochannel aquifers (Fig. A22). Land use is devoted to mining and pastoral grazing.

Geology and hydrogeology

The Mount Keith pit is located within the Agnew–Wiluna Greenstone Belt, which comprises ultramafic intrusives, mafic volcanics, felsic volcanics and metasedimentary rocks. Nickel mineralisation is hosted within the ultramafic rock. The geology is structurally complex, with vertical to steeply dipping structures (Fig. A22). Localised weathering of dunite (ultramafic) has formed a siliceous caprock. The depth of weathering varies from 20 m to over 100 m.

Outcrop is generally poor with an extensive cover of thin clayey to gravelly sheetwash and alluvial sediments. Ferruginisation has indurated the alluvium, with a hardpan present in places beneath or at the surface. There are also a number of Tertiary palaeochannels that contain clay overlying coarse-grained sand (Fig. A22).

Groundwater occurrence is associated with secondary permeability features, such as geological structures, lithological contacts and weathering. Most shear zones are filled with talc–serpentinite or clayey materials and are only considered local aquifers. Lithological type at Mount Keith has limited effect on groundwater occurrence, with lithological contacts, faulting and shearing forming the most important aquifers. Bore yields are more consistent in the hangingwall volcanics, and more variable, though locally larger, in the footwall sequences. Groundwater salinity ranges between 2000 and 4500 mg/L.

Prior to mining, the siliceous ultramafic caprock aquifer was dewatered over eight months. The pre-mining waterlevel at Mount Keith was about 20 m below ground level. Waterlevels near the pit are currently depressed owing to dewatering, and the modified hydraulic gradient is towards the pit. There is minor seepage from lower walls in the pit with additional water anticipated during cutbacks at higher elevations in the hangingwall and footwall sequences. Subhorizontal drainholes are also used to relieve the water pressure behind the pit walls. Mining into the weakly oxidised rocks below the watertable has encountered negligible groundwater flow.

Potential impact of mining void

The Mount Keith pit does not intersect any significant regional aquifer. It is anticipated that on cessation of dewatering, the final void will slowly fill with groundwater and the pit lake will reach a new equilibrium. High evaporation rates will ensure that the final void acts as a ‘groundwater sink’ with the pit

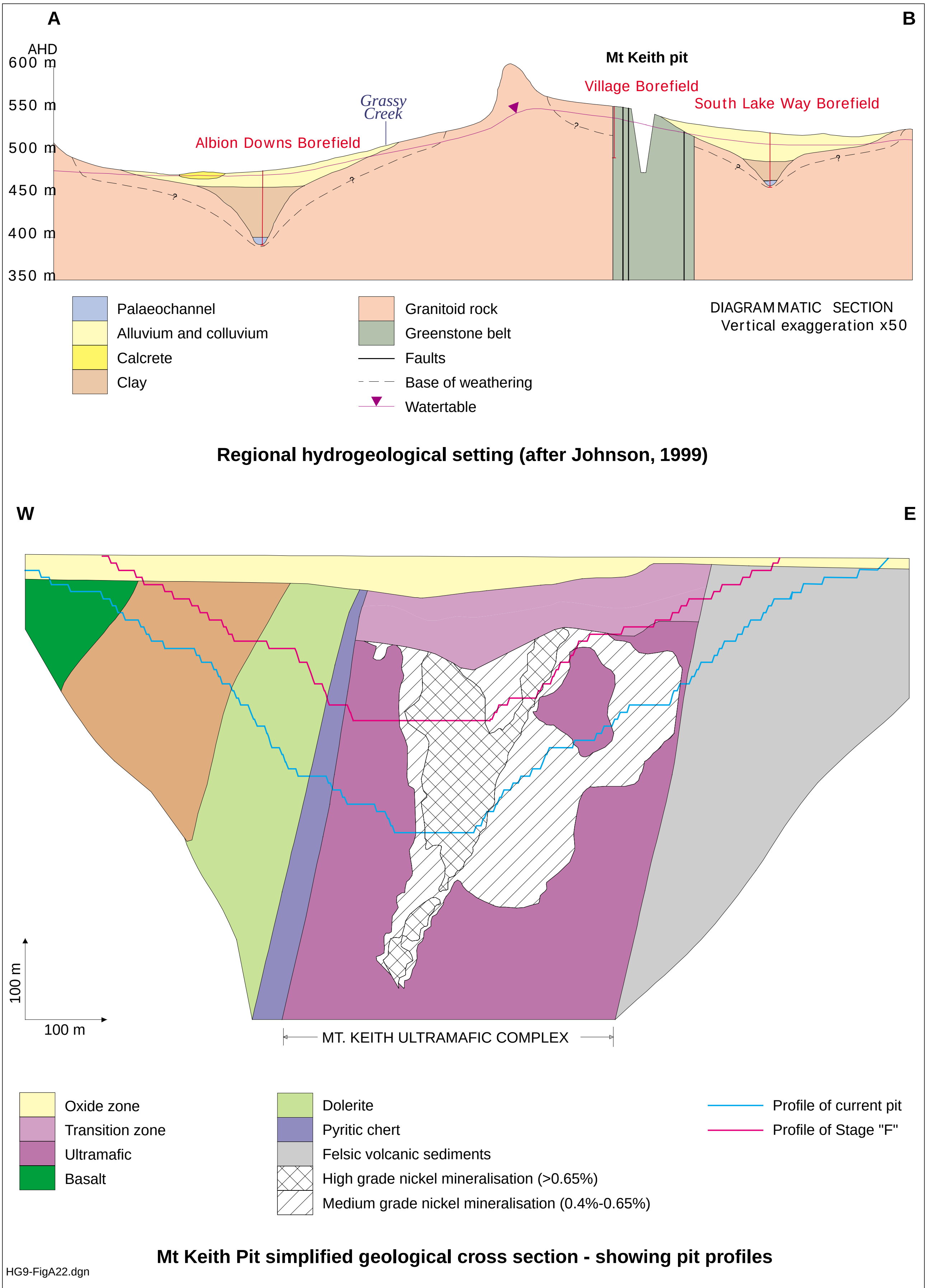

Figure A22. Regional hydrogeology and in-pit geology at Mt Keith nickel mine

lake becoming progressively more saline. The pit is isolated from any drainages or tailings storage facilities and will not receive significant inflows of stormwater. The movement of hypersaline groundwater from the pit lake will be confined to the greenstone rocks associated with permeable zones derived from faulting and fracturing.

The chert along the western contact is sulphide-rich and has potential for acid-generation, particularly when the waterlevel is recovering within the pit. However, the narrowness of the chert and discontinuous nature suggests there will be no problems with acid mine drainage.

Conclusions

Owing to the vastness of the final mine void, backfilling is not considered a viable option. The nature of mining will also not permit partial backfilling during the life of the mine. The most suitable closure option is to allow flooding of the pit. The water quality of the local aquifer is brackish, so any future water usage will be restricted to limited irrigation, stock watering and mining. The pit lake will become more saline over time (hundreds of years), although it will not have an impact on any regional groundwater resource. The final void may also serve as a water storage facility for any future mining.

12 Agnew gold operation

Introduction

The Agnew gold operation is located about 30 km southwest of Leinster in the Northeastern Goldfields. The Agnew plant was commissioned in 1986 to process ore from the Emu pit. Mining from the Emu pit ceased in 1992, although there are current expansion plans being considered to resume mining for another two years. At present, the Redeemer and Crusader underground mines are the only operational mines. The mining operation comprises three major mining areas:

- Emu opencut pit (void dimensions of 1000 m x 250 m) and associated underground mine;
- Redeemer opencut pit (void dimensions of 750 m x 400 m) and associated underground mine; and
- Cox opencut pit (void dimensions of 300 m x 250 m), Deliverer opencut pit (void dimensions of 200 m x 200 m) and Crusader underground mine.

There are also a number of smaller opencut pits in the area (Fig. A23) including Hidden Secret (1 km west of the plant), Turret pit (4 km east of the plant) and Genesis pit (2.5 km northwest of the plant).

This case study will focus primarily on the Emu pit, which is also known as AG pit. Emu pit currently extends to a depth of 70 m with a proposed cutback expansion widening and deepening the void to about 120 m below ground level. The intention of the cutback is to breakthrough into the previous underground workings. There is also the possibility that the northern end of the final void may be partially backfilled.

The climate is semi-arid with an unreliable rainfall of 200 mm/yr and evaporation rate of about 3000 mm/yr. Rainfall occurs predominantly during the autumn and winter months (April to August), although there are infrequent seasonal cyclones in the summer.

The key physiographic features are ancient internal-draining systems, known as palaeodrainages, that contain numerous salt lakes. The Agnew area is located high in the landscape with the Emu pit on a catchment divide between two ephemeral drainages that flow westward into Scotty Creek. Vegetation is dominated by low woodland and shrubland. Land use is largely related to mining and a declining pastoral industry.

Geology and hydrogeology

All mines lie within the Norseman–Wiluna Greenstone Belt of the Eastern Goldfields Province. Emu pit is located within the north-plunging Lawlers Anticline, which comprises a sequence of ultramafic rocks overlain by ultramafic-derived conglomerates and arenaceous metasediments of the Scotty Creek Formation (Fig. A23). The Archaean basement rocks are concealed beneath alluvium, colluvium and lacustrine deposits of Cainozoic age. Gold mineralisation is associated with quartz breccia lodes, quartz stockwork veining, disseminated arsenopyrite developed at the lithological contact

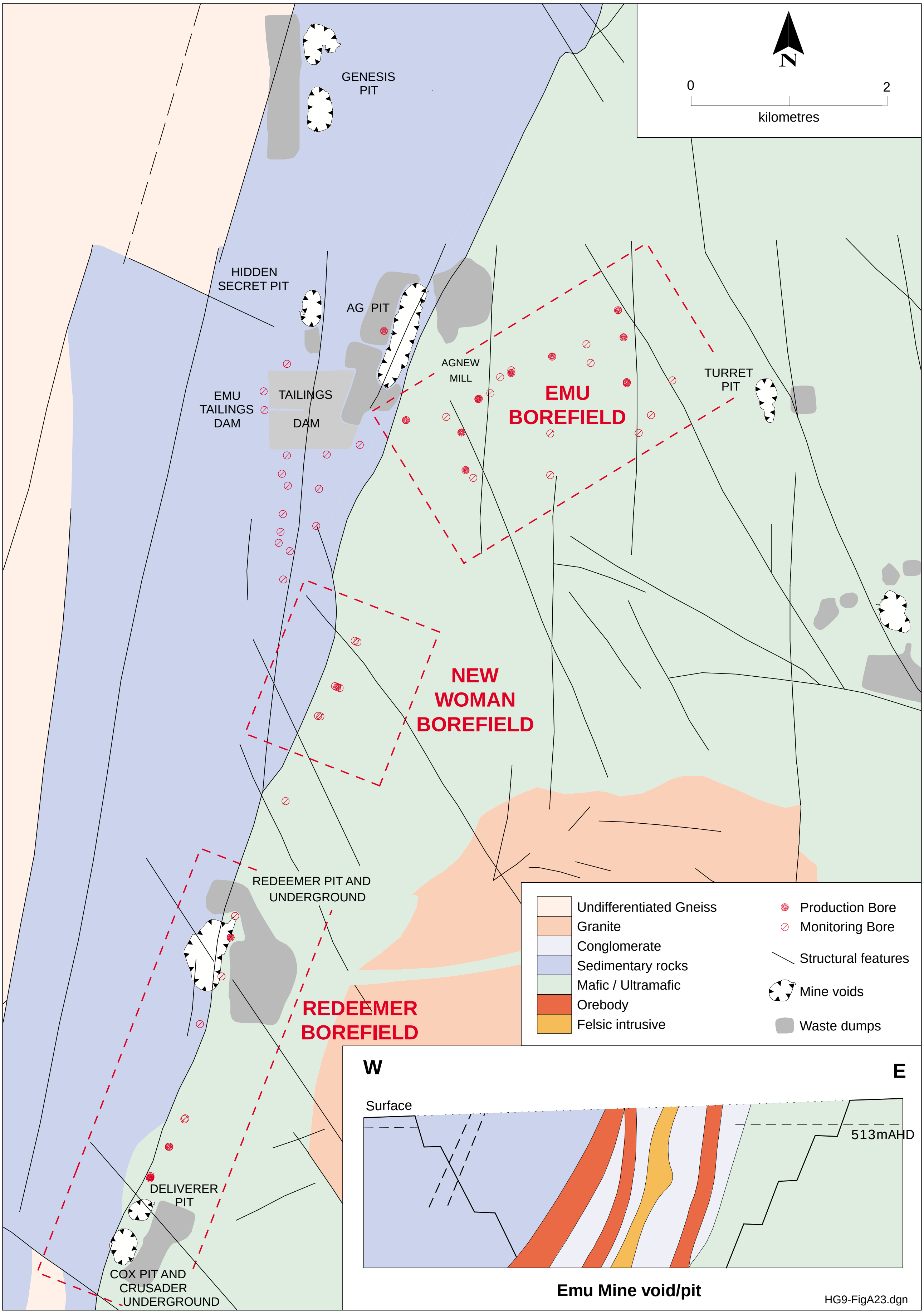

Figure A23. Regional geology of the Agnew gold operations

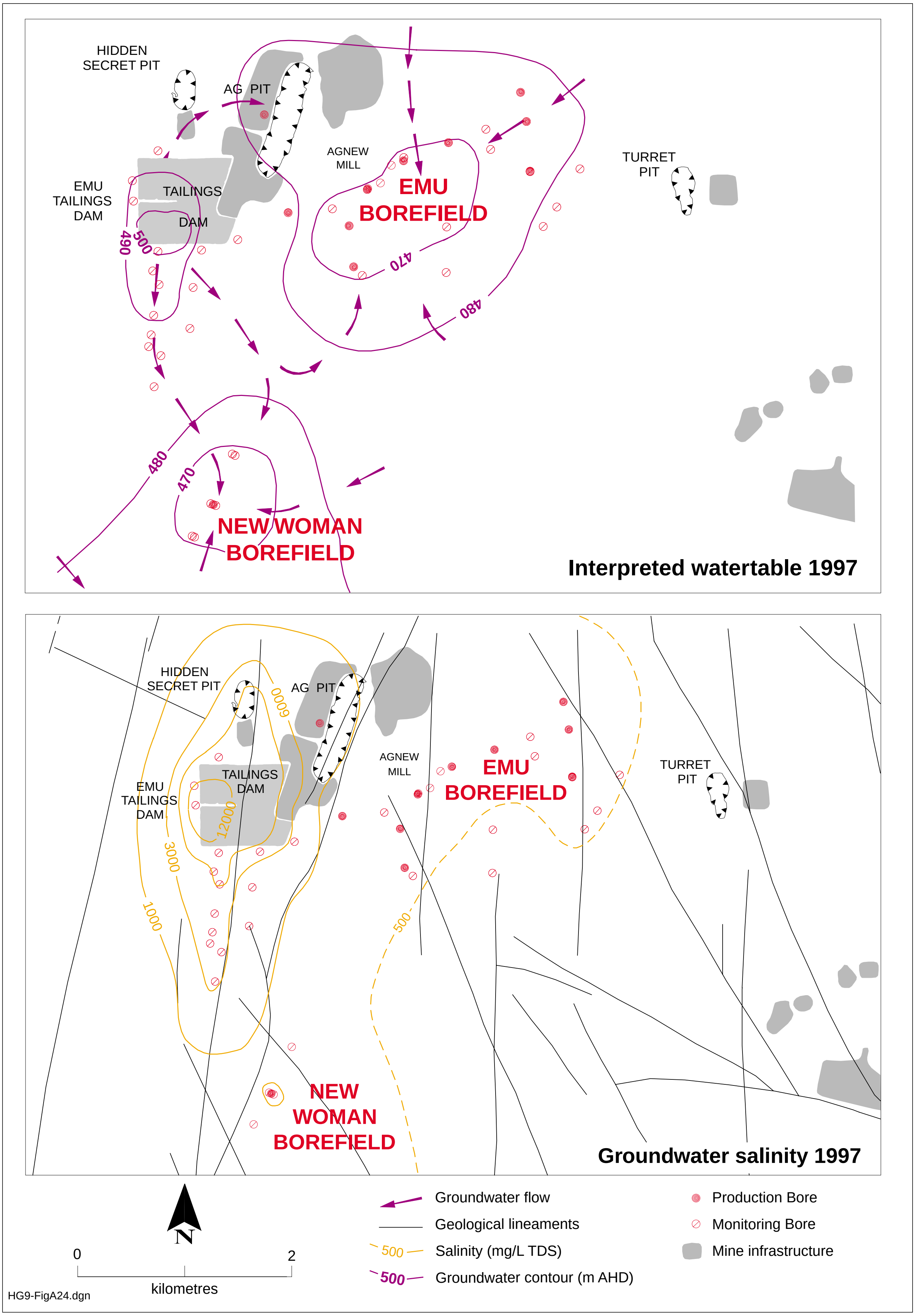

Figure A24. Groundwater levels and salinity in the vicinity of Emu pit

with the ultramafic conglomerates, and discrete lodes within the arenaceous metasediments.

Two significant aquifers have been identified in the vicinity of Emu pit:

- vuggy, siliceous caprock aquifer developed through preferential secondary weathering of specific ultramafic rocks (dunite); and
- fractured-rock aquifers associated with structural features, such as faults, joints and shear zones, particularly in metasediments.

Both aquifers are site-specific and highly localised. The New Woman and Emu borefields, the principal sources of potable and process water, are developed in the siliceous caprock aquifer (Fig. A23). Groundwater abstraction from these borefields has locally depressed the watertable (Fig. A24). In 1998, the watertable was about 20 m below surface to the south of Emu pit. Fresh to brackish groundwater ranging from 500 to 1600 mg/L is abstracted from the Emu and New Woman borefields. In contrast, groundwater in Emu pit, derived from the underground workings, has a salinity between 7000 and 9600 mg/L TDS and a pH range of 7.1 to 7.7.

Potential impact of mining void

Emu pit is considered hydrogeologically isolated from any significant groundwater resource. The southeastern side of the pit does intersect the ultramafic unit and there is potential for hydraulic connection with the caprock aquifer in the Emu borefield. The orebody contains primary sulphide with acid-generating potential; however, all sulphidic material occurs in the ore and will be removed from the pit.

On the completion of mining and dewatering activities, the pit will start flooding with water. The rate of flooding will be relatively slow until abstraction ceases from the Emu borefield. The groundwater flow pattern suggests that leachate from the tailings dam will enter the pit lake, although any leakage will cease when the TSF dries out.

The pit extension will form a direct connection with the old underground workings resulting in an increase in pit lake salinity. The high evaporation rates experienced in the area will ensure that the final void serves as a ‘groundwater sink’, although there is potential for brine formation leading to the development of a high-density saline plume that could move along strike within the fracture zone.

Conclusions

It is anticipated that following mine closure, the Emu mine void will act as a ‘groundwater sink’. The water quality of the pit lake will be influenced by evaporation, as well as by seepage from the tailings dam and saline water from the underground workings. The preferred mine closure option is for the final void to reach steady-state and continue to act as a ‘groundwater sink’, which will restrict movement of the final hypersaline waterbody and preserve water quality in the caprock aquifer (Emu Borefield). It is important to note that groundwater abstraction from New Women Borefield has the potential to induce north–south flow between the Emu and Redeemer mining areas.

13 Leinster nickel operation

Introduction

Leinster nickel operation is located 18 km north of Leinster in the Northern Goldfields. Mining began in 1974, initially with opencut pits, and progressed to underground operations. There are currently two underground mines, Perseverance and Rockys Reward, as well as the proposed Harmony opencut mine (Fig. A25).

The Harmony deposit, the focus of this case study, is located 2 km north of the existing Rockys Reward opencut. The deposit was discovered in 1998 and is to be mined using conventional opencut methods to produce a final void with dimensions of 1650 m by 400 m and a depth of 185 m. Following the opencut mining (about six years of mine life), there is potential for underground development at the southern end of the pit. The mine will extend below the watertable and dewatering will be required. There is scope for backfilling in the northern end of the pit with waste rock from the Stage 3 cutback (Fig. A25).

The climate is semi-arid to arid with an average rainfall of 230 mm/yr and high evaporation of 2650 mm/yr. Rainfall is highly variable, with intense

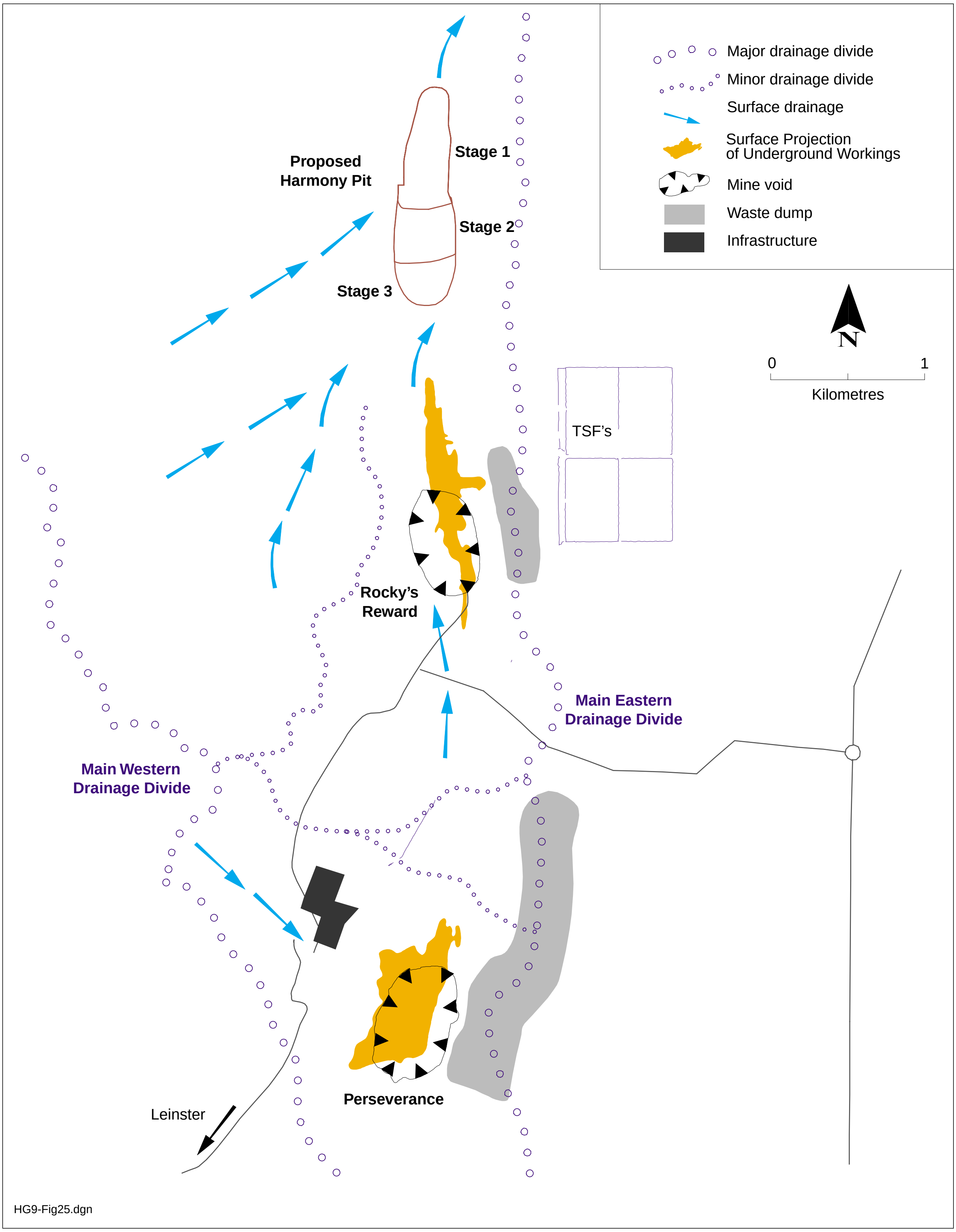

Figure A25. Location and drainage at Leinster nickel operation

rainfall events during summer related to cyclonic and tropical activity.

The deposit occurs beneath a north-flowing drainage with low northerly striking ridges to the east and west. The creek that flows across the deposit has most of its catchment area in the southwest (Fig. A25). Three diversion channels will divert runoff around Rockys Reward pit and the proposed Harmony pit. Further downstream, the creek feeds into the Lake Miranda–Calowindi Well area, which comprises large calcrete deposits that are recharged from surface runoff. Land use is related to mining and pastoral grazing activities.

Geology and hydrogeology

The Leinster mines are located within the Agnew–Wiluna Greenstone Belt. Nickel mineralisation occurs as a discrete massive sulphide and disseminated zone within steep, westward-dipping ultramafic rocks over a strike length of about 1500 m. The hangingwall and footwall lithologies are commonly ultramafic and metasedimentary rocks. Perseverance Fault is the major regional geological structure. The ore deposit contains multiple steeply-dipping faults and gently folded mineralised surfaces that have been structurally truncated at depth (Fig. A26). Two easterly trending dolerite dykes cross the centre of the deposit. The lithologies are deeply weathered to a depth of 100 m.

There are two main aquifers within the proposed Harmony pit; cavernous and fractured siliceous ultramafic material within the weathering profile, and fracture zones in the hanging-wall metasedimentary rocks. The siliceous ultramafic aquifer occurs as a narrow strip along the strike length of the deposit with a maximum depth of 75 m and poorly defined width of about 40 m. Two adjacent dolerite dykes (Fig. A26) act as groundwater barriers. The southern portion of the aquifer is in hydraulic connection with the Rockys Reward underground mine. At present, there is little information about the fractured-rock aquifer in the metasedimentary rocks.

Groundwater in the vicinity of the Harmony deposit is generally fresh, up to 850 mg/L, reflecting direct recharge from the creek system into the siliceous ultramafic aquifer. In contrast, the neighbouring Rockys Reward (4900 mg/L) and Perseverance (103 000 mg/L) mines encounter saline to hypersaline groundwater.

Potential impact of mining void

Development of the Harmony deposit has the potential to impact on local surface and groundwater resources. The pit will be positioned within a narrow, moderately-incised drainage that captures flow from minor drainage channels and sheet-flow runoff from local ridges. The diversion channels will ensure that surface runoff will continue to flow northward into the Lake Miranda–Calowindi Well area. With respect to groundwater, the limited extent of the siliceous ultramafic aquifer means that the aquifer will be completely dewatered during mining.

In considering mine closure, the final void at the Harmony deposit must be assessed in conjunction with the neighbouring Rockys Reward mine. On cessation of both mining operations, the Harmony pit will slowly fill with groundwater. The pit lake waterlevel will not recover to pre-mining levels owing to high evaporation rates and reduced local recharge. The stormwater diversion is designed to cope with a 100-year flooding event to ensure that no surface runoff will enter the void. There is potential for saline groundwater from the adjacent Rockys Reward void and underground workings to impact on the final water quality of the Harmony pit lake.

Acidity is another important mine closure issue with the mine encountering sulphidic shale, which has acid-generating potential. The oxidised, gossanous nickeliferous material found in the ultramafic unit has low acid-generating capacity. It is considered that the most appropriate remedy is either to backfill that portion of the void containing the acid-generating material, or to ensure that it is submerged beneath water.

Conclusions

Mining at the Harmony deposit has the potential for short-term impacts on both the local surface water and groundwater resources. The final void should partially fill to form a pit lake, which will become progressively more saline. Over time, and depending on hydraulic connectivity, the pit lake may cause a

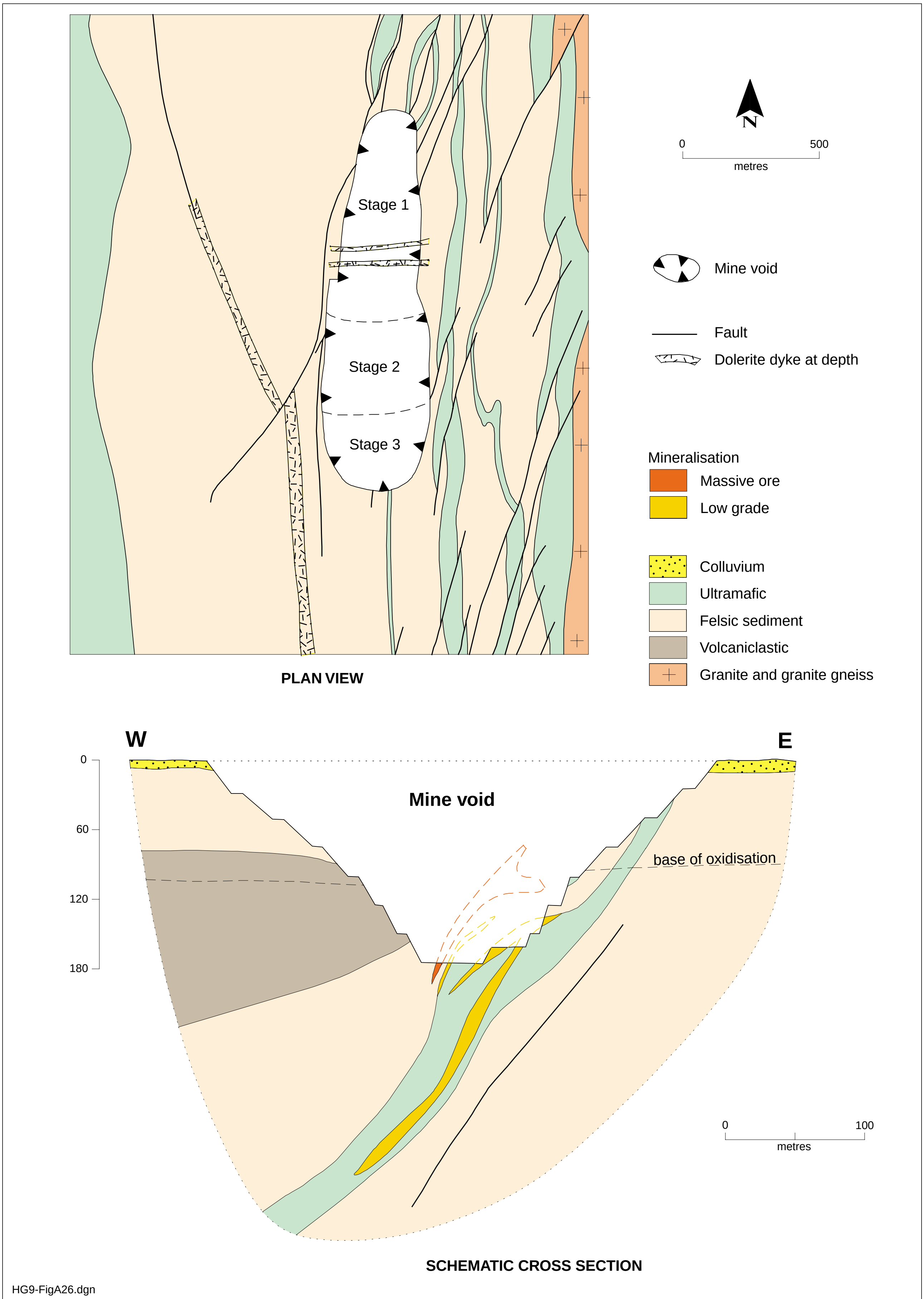

Figure A26. Geology of the Harmony mine void

deterioration in the surrounding groundwater quality, thereby impacting a nearby brackish groundwater resource.

The preferred mine closure option is to partially backfill the final void with waste rock from Rockys Reward mine, which will continue operating after the Harmony pit has closed. The main assumption is that the Harmony pit will be 'sterile', or devoid of mineralisation, and thus considered a final void. Another option may be the rediversion of the creek system through the final void. This will require further modelling as surface flow may not be sufficient to maintain a full void on an annual basis, and the capture of all excess flows may impact on downstream areas. Both of these options will eliminate any threat from potential acid-generation.

14 Red October gold mine

Introduction

The Red October gold mine is located on the western shore of Lake Carey, about 80 km south of Laverton, in the Northern Goldfields. The deposit, discovered in 1994, lies within greenstones of the Archaean Yilgarn Craton. Opencut mining commenced in 1999 and ceased after two years, resulting in a final void of 600 m by 600 m and a depth of 100 m.

The climate is arid with hot dry summers and cool winters. Light winter rainfall is associated with southerly low-pressure cold fronts, whereas summer rainfall is mainly from thunderstorms or tropical rain depressions. The average rainfall is 225 mm/yr and evaporation is about 3000 mm/yr.

The pit, within the lakebed of Lake Carey, between Angelfish and Treasure Islands, approximately 5 km offshore (Fig. A27). Lake Carey is a large ephemeral saline lake situated within an ancient palaeodrainage system. Surface water drains into the lake from the surrounding low-lying terrain. During severe flooding events, there may be interconnection between lakes resulting in southward movement of water towards the Eucla Basin.

Land use comprises low-intensity pastoralism and significant mineral exploration. There are also a number of other mining operations present along the northeastern shore of Lake Carey, such as Granny Smith and Sunrise Dam.

Geology and hydrogeology

Gold mineralisation at the Red October is related to a steeply dipping mafic/ultramafic contact within the Yandal Greenstone Belt (Fig. A28). The hanging wall comprises a mixed pyroxenite–peridotite ultramafic and Mg-rich basalt sequence with minor interflow sediments and discontinuous sulphide-rich graphite shale. The footwall consists of a massive Mg-rich basalt. The brecciated quartz–carbonate orebody is about 650 m in length and steeply dipping to the northwest.

At the surface, there are lake sediments of clay and sandy silts, up to 10 m thick, with interbedded gypsum horizons. Beneath the lake sediments are transported Tertiary fluvial deposits, up to 30 m, that rest on weathered (saprolitic) basement rock. The weathering of the basement rocks often extends to 70 m below surface.

The local groundwater system broadly comprises three hydrogeological units :

- upper zone of lake sediments and Tertiary deposits;
- middle zone consisting of weathered basement rock; and
- deep zone of fractured rock.

The pre-mining waterlevel was at, or close to, the lake surface. The highest permeability and groundwater flow is associated with the base of oxidation. Initial modelling indicated that the rate of water entering the pit would be less than 2.6 ML/day. Modelling has also indicated that the cone of depression within the lake sediments may extend 600 m from the pit. Following mine closure, it is anticipated that there will be 95% recovery of waterlevels within 12 years. Groundwater is hypersaline, in the order of 210 000 mg/L TDS.

Potential impact of mining void

The hydrogeological processes associated with the final mine void are directly related to salt lake hydrology. Prior to rainfall, the lake typically has a thin salt crust developed on clay via groundwater discharge from a shallow watertable beneath the lake surface. The variable and intermittent nature of surface-water flow into Lake Carey indicates that the salinity of the pit lake will vary significantly.

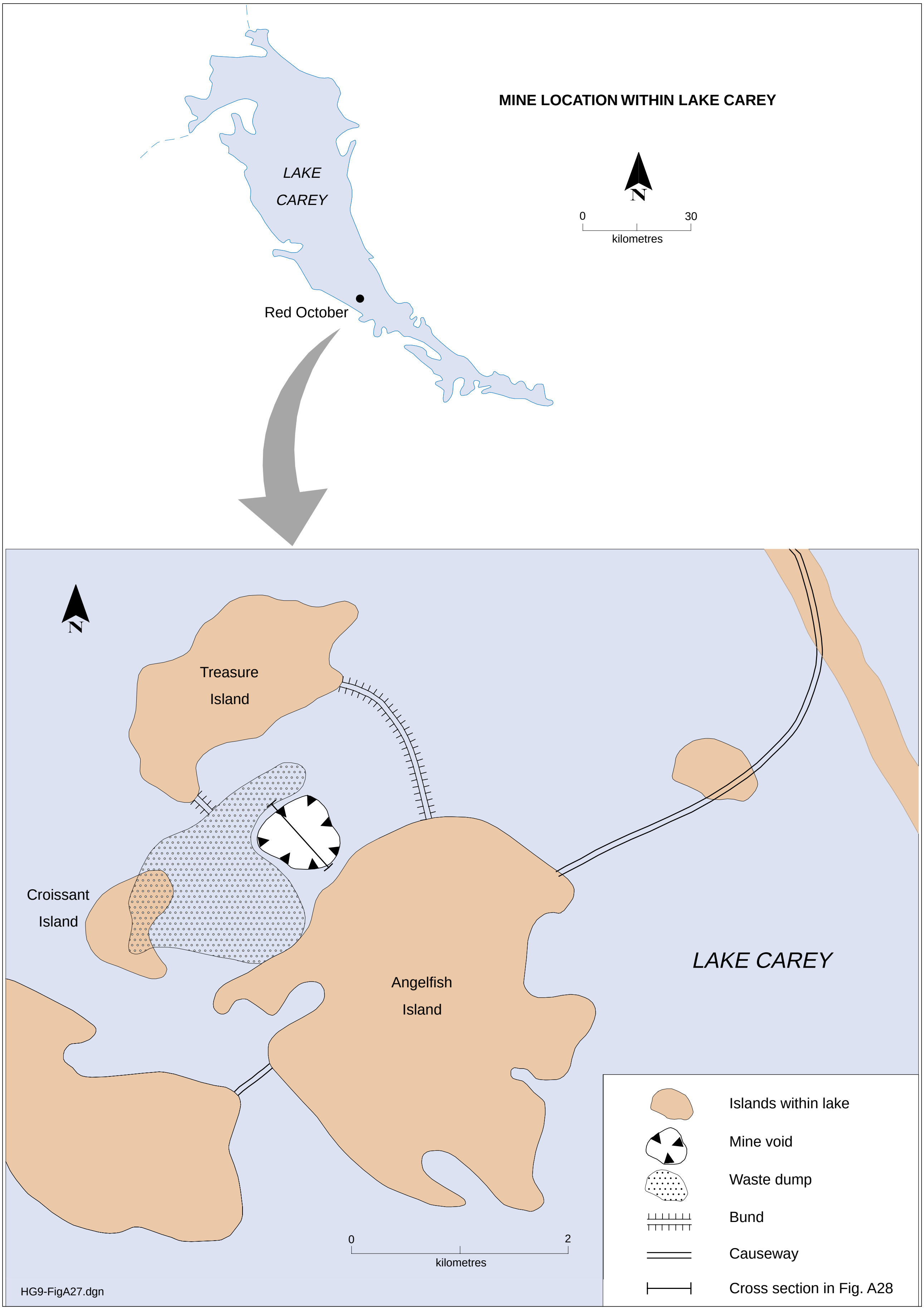

Figure A27. Location of Red October gold mine within Lake Carey

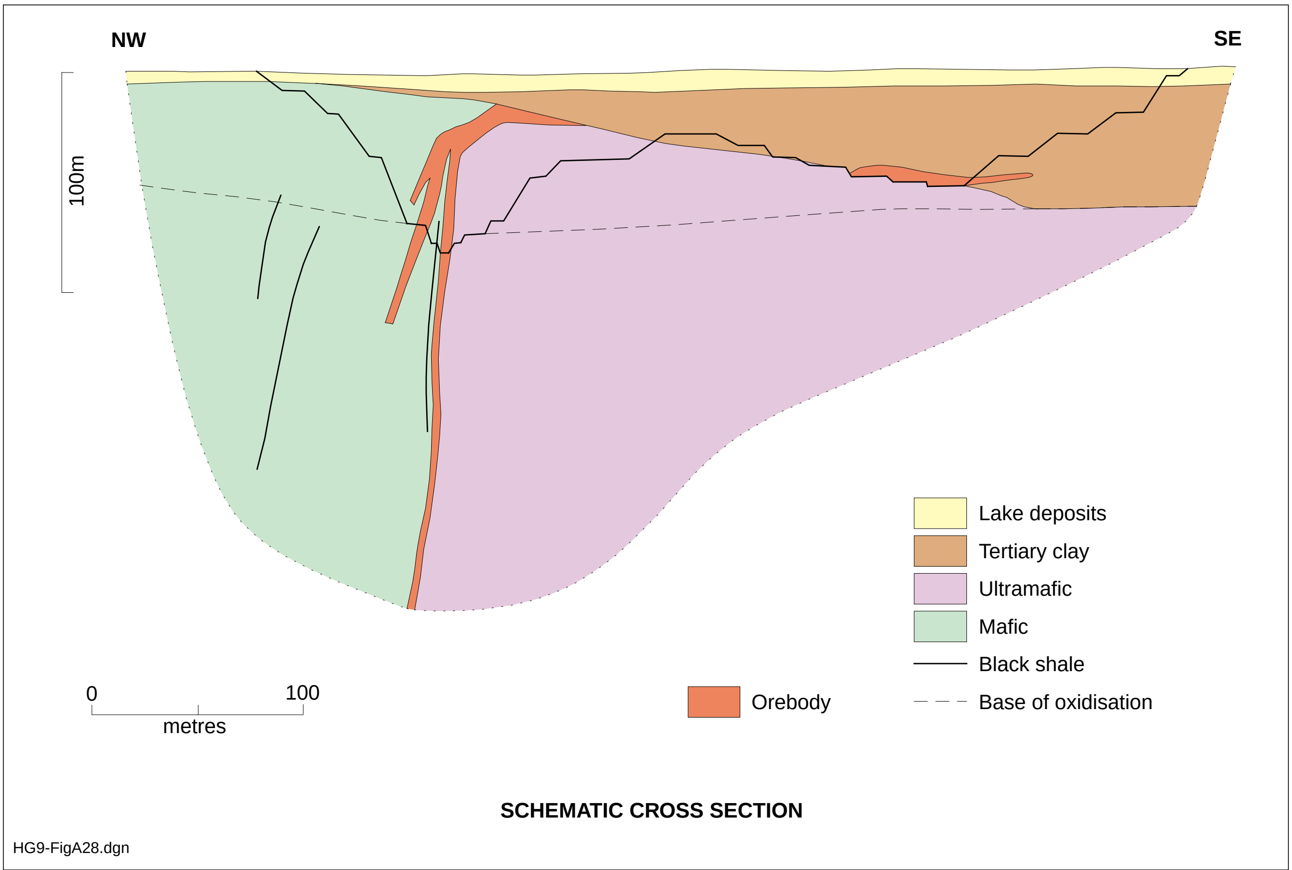

Figure A28. Geology of the Red October mine void

In planning for mine closure, mine management has outlined the following objectives :

- minimise the risk to the public by ensuring the physical and chemical stability of all disturbed areas;
- return the mine site to a condition that will support activities consistent with multiple land uses;
- re-establish stable topographic conditions that will support a self-sustaining native vegetation that is consistent with the nominated land use;
- minimise on-site impacts by controlling infiltration, erosion, deflation, sedimentation and degradation of drainage;
- employ rehabilitation methods that are technically effective and cost efficient, which rely on proven engineering practice and do not require ongoing maintenance after closure.

In order to meet the objectives, there were two alternative proposals: (1) ‘closed option’ (where a bund is constructed around the pit to isolate the pit from the surface of the lake), and (2) ‘open option’ (where the pit remains open to the lake). A comparison between the two options is highlighted in Table A4.

Conclusions

The final mine void is very small compared with the size of Lake Carey. The groundwater resources in the vicinity of Red October are hypersaline and any impact from the final void, if it is allowed to fill with water, will be negligible on the beneficial use (mine process water) of the groundwater resource. Therefore, public safety and aesthetics are the major mine closure priorities.

Table A4. A framework for comparing potential impacts of void closure options for the Red October mine.

Closed void	*Open void*
Characteristics	**Characteristics**
• The final void is a closed system isolated from the lake by an earth bund	• Final void open to lake surface water
• No mixing of lake and void water	• No control over mixing of lake and void waters
Features	**Features**
• Open pit enclosed by rock-armoured earth bund designed to handle at the minimum a 1 in 100 year flood event	• Open pit with contoured (reduced batter angle) of the upper levels of the pit to several metres below the expected final resting waterlevel
Issues	**Issues**
• Erosion or destruction of bund by flooding	• Stability of the contoured batter
• Erosion/stability of steep batters	• Impacts of mixing void water with the lake water
• Aesthetic impact of bund	• Aesthetics of man-made beach system surrounding the pit
• Poor water quality of void water	• Stability of batter once pit lake level has stabilised
• Mixing of void and lake water in the event of erosion of the bund	
• Permanency of option (bund unlikely to remain stable over long term)	
• Remedial action difficult to implement	
• Responsibility of long-term maintenance	

15 Broad Arrow gold operation

Introduction

The Broad Arrow gold operation is located about 38 km north of Kalgoorlie in the Goldfields region. Gold was first discovered in the area in 1893, and the several small underground operations in the vicinity ceased mining in 1918. It was not until 1986 that mining recommenced with the development of the Victory, Talbot and South Talbot opencut pits.

In 1998, mining returned to the South Talbot deposit with the development of the Broad Arrow pit. There are proposals to extend the Broad Arrow pit in a southerly direction that will effectively join the Broad Arrow (stage 1) and Victory voids (Fig. A29). Stage 2 operations will require dewatering and produce a final void with dimensions of 450 m by 250 m and a depth of 120 m. It is proposed that waste rock from the pit extension be will used to backfill the Victory and Broad Arrow stage 1 pits, while the Talbot Pit will be used for water storage during mining.

The climate is semi-arid to arid with an average rainfall of 260 mm/yr and evaporation of 2850 mm/yr. Rainfall is often well distributed throughout the year, with intense rainfall associated with summer thunderstorms and winter frontal systems.

The landscape is slightly undulating, with waste dumps from old mining operations forming the most prominent landforms. There are a number of small creeks which feed into a local drainage to the west of the mine. Human activity in the area over the past 100 years has largely removed all native vegetation.

Geology and hydrogeology

The Broad Arrow deposit is located within the Norseman–Wiluna Greenstone Belt. The in-pit geology consists of volcaniclastic tuff, shale, dolerite, basalt and carbonaceous shale (Fig. A30). Gold mineralisation is associated with arsenopyrite and hosted within a system of quartz–carbonate veins in the dolerite. The weathering profile is deep and extends to 150 m below surface, particularly within shear zones.

Regional groundwater resources are largely associated with palaeochannel aquifers and specific fractured-rock aquifers. In the vicinity of Broad Arrow, groundwater occurs in fractured-rock aquifers associated with northerly trending joints in the shale and carbonate veining in the dolerite. The main in-pit aquifers are mineralised dolerite (orebody), lithological contacts, and material at the base of the weathering profile between 60 m and 150 m. The pre-mining watertable was about 50 m below surface. Groundwater is typically saline to hypersaline, up to 50 000 mg/L, with high concentrations of arsenic.

Potential impact of mining void

The pit is in a relatively confined area that has already experienced considerable mining activity. Theer are five mine voids and waste dumps within an area of 2 km^2, which is immediately adjacent to major roads, a railway line and a village. The development of the Broad Arrow stage 2 pit is an extension of an existing mining development.

Additional dewatering will be required for the pit extension, and this will cause the cone of depression to deepen slightly and shift about 500 m to the southeast. There is little potential for acid-generation, as the depth of oxidation extends to 80 m below surface and most arsenopyrite is restricted to the ore zones. On completion of dewatering, the final void will act as a ‘groundwater sink’ and slowly fill with water to develop a pit lake. This water will only be suitable for industrial (mining) usage, as the groundwater is largely hypersaline. It is anticipated that the pit lake water will become progressively more saline due to evapoconcentration.

Conclusions

Although the Broad Arrow operations will create an additional mine void, this will provide the mining company with the opportunity to rehabilitate existing mine structures (voids and waste dumps). On completion of mining and dewatering, any remaining voids will slowly fill with water that will become progressively more saline. The final pit lake is not a major hydrogeological concern, as the area contains no significant groundwater resources. The main benefit in backfilling the Broad Arrow stage 2 void with material from the existing waste dumps or tailings dam would be purely aesthetic.

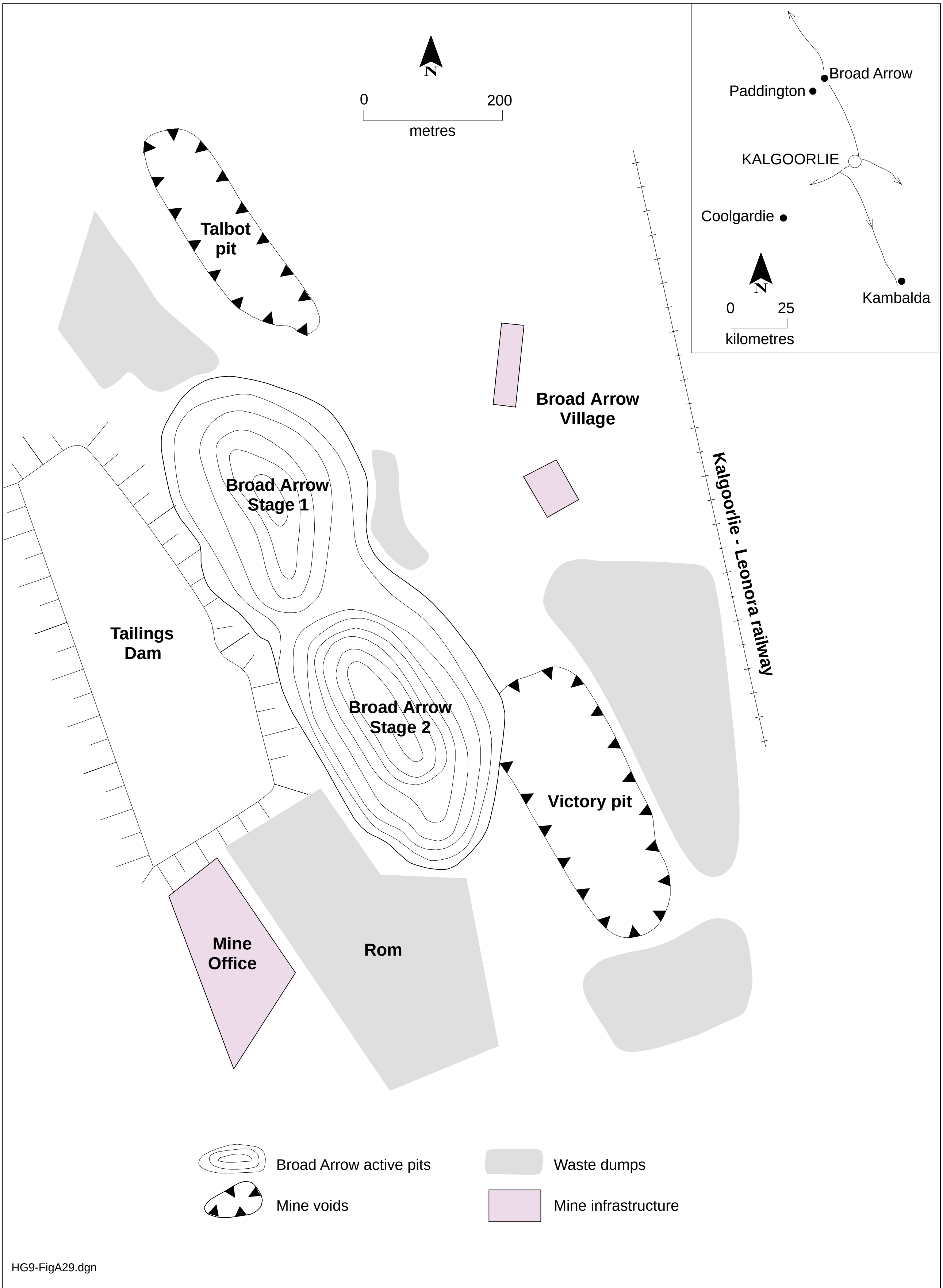

Figure A29. Location of mine voids at Broad Arrow gold mine

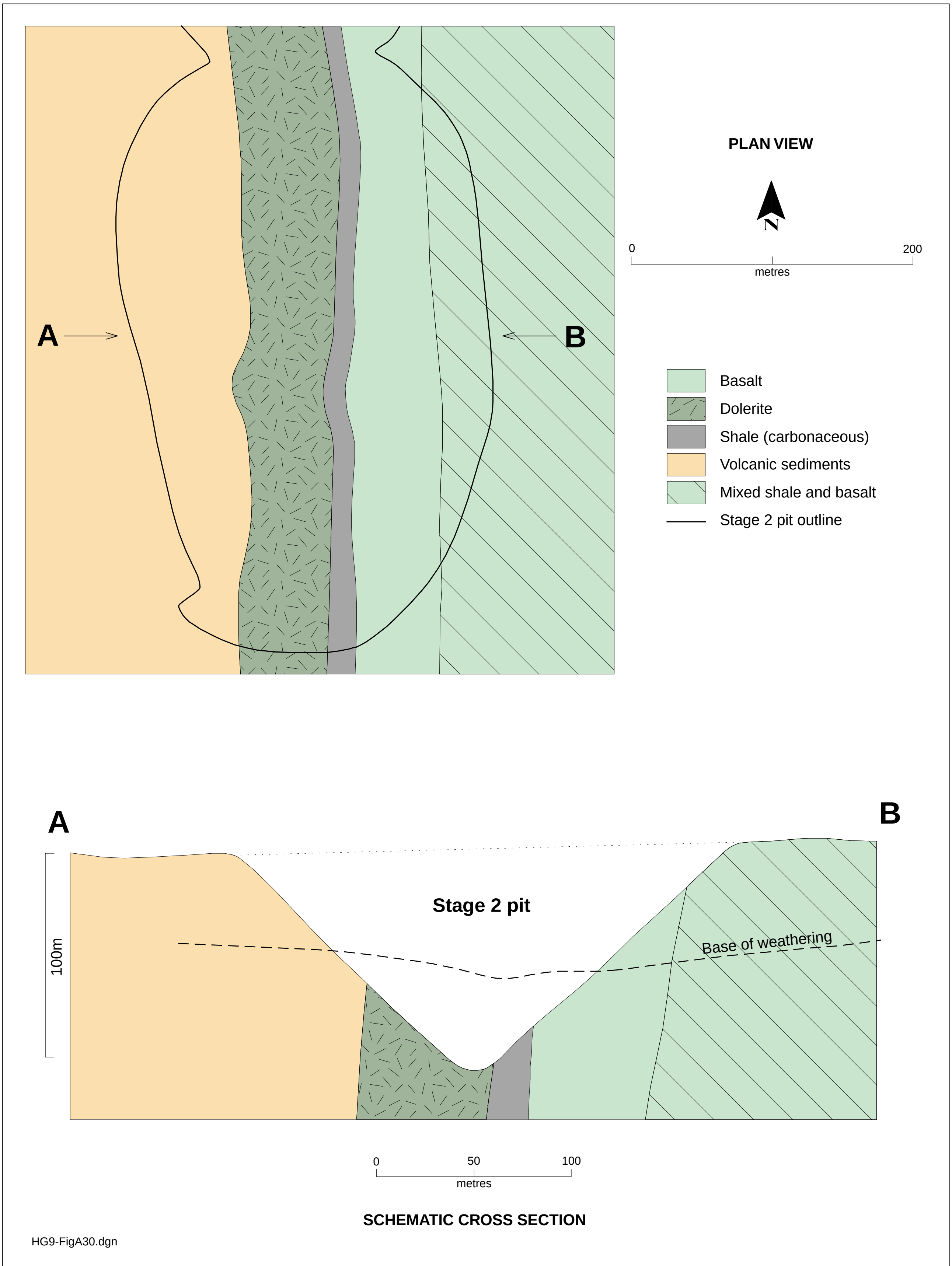

Figure A30. Geology of the Broad Arrow mine void

16 St Ives – Revenge gold mine

Introduction

The information provided in this case study was sourced from the original Public Environmental Review document (Dames and Moore, 1999) and an internal WMC Exploration report by Berry (1999).

The Revenge mine, part of the St Ives gold operations (SIGM), is located 20 km south of Kambalda. At present, SIGM comprises three operating mines and another 13 mine voids within a 30 km radius (Fig. A31). The Revenge mine is located within Lake Lefroy at the eastern end of the main causeway and Delta Island. Mining at Revenge commenced in 1989 and ceased by mid-1998. The mine is surrounded by a 6 m-wide causeway (bund) which is about 1.2 m higher than the lake surface. The final void dimensions are 750 m by 350 m with a depth of 70 m. Underground mining was completed with a connecting drive into the pit, which was designed for free drainage of pit wall flows into the workings.

The climate is semi-arid, with an average rainfall of 255 mm/yr and an evaporation rate of 2000 mm/yr. Most rainfall occurs between February and August from winter cold fronts and infrequent summer tropical depressions. Intense rainfall events often cause flooding of the salt lakes.

Lake Lefroy, a large flat salt lake, is about 43 km long and 13 km wide and forms part of a chain of lakes that drain the eastern edge of the Great Western Plateau. Salt-dominant vegetation covers most of the area. Land use is largely devoted to pastoral and mining activities, although large tracts of land remain vacant Crown land or reserves.

Geology and hydrogeology

The Revenge mine lies within the Archaean Norseman–Wiluna Greenstone Belt. The in-pit geology comprises the Defiance Dolerite and Paringa Basalt with associated felsic porphyry volcanics (Fig. A31). The orebody exists within a shear zone, a splay of the Boulder–Lefroy Fault that contains multiple quartz veins. The basement rocks are concealed beneath some 10 m of Tertiary sediments comprising low-permeability silts and clays.

Groundwater occurs both in the lake sediments, and fractured-rock aquifers related to the mineralised orebody and intruded porphyry dyke. Water flow into the pit reached a maximum of 2500 m^3/day during the life of the underground mine. The total inflow comprised an accumulation of numerous minor inflows via structural defects, deeper portions of the weathered profile, and unsealed exploration drillholes. Groundwater in the Revenge pit and underground workings is hypersaline, up to 335 000 mg/L, as a result of evaporation from the surface of Lake Lefroy.

Potential impact of mining void

Revenge pit can be identified as a ‘water sink’ within a ‘regional water sink’ (Lake Lefroy), as the lake is the terminus of the catchment area. Groundwater flow into the mine void will continue at a rate of 2500 m^3/day with the pit lake level stabilising to within 5 m of the lake surface. Groundwater modelling indicates that the level of the pit lake will reach steady-state in 5 to 10 years.

As the Revenge pit will act as a surface water and groundwater sink, it is anticipated that salinity of the pit lake will progressively increase via evapoconcentration, resulting in the gradual deposition of crystalline salt, particularly gypsum and halite. Monitoring in the nearby North Orchin pit (Fig. A31) has shown a 40% increase in salinity over a period of three years. The hypersalinity of groundwater ensures that the only beneficial use is for mining-water purposes and, as such, any salinity increase in the final void will have no adverse impact on groundwater suitability.

Acidification of the pit water is not considered a significant mine closure issue at Revenge because of the following characteristics:

- Flooding of the pit to above the base of oxidation will occur relatively quickly;
- The absence of throughflow in the mine; hence, no net flux of water or oxygen;
- The ionic strength of the hypersaline water will buffer any changes in pH;

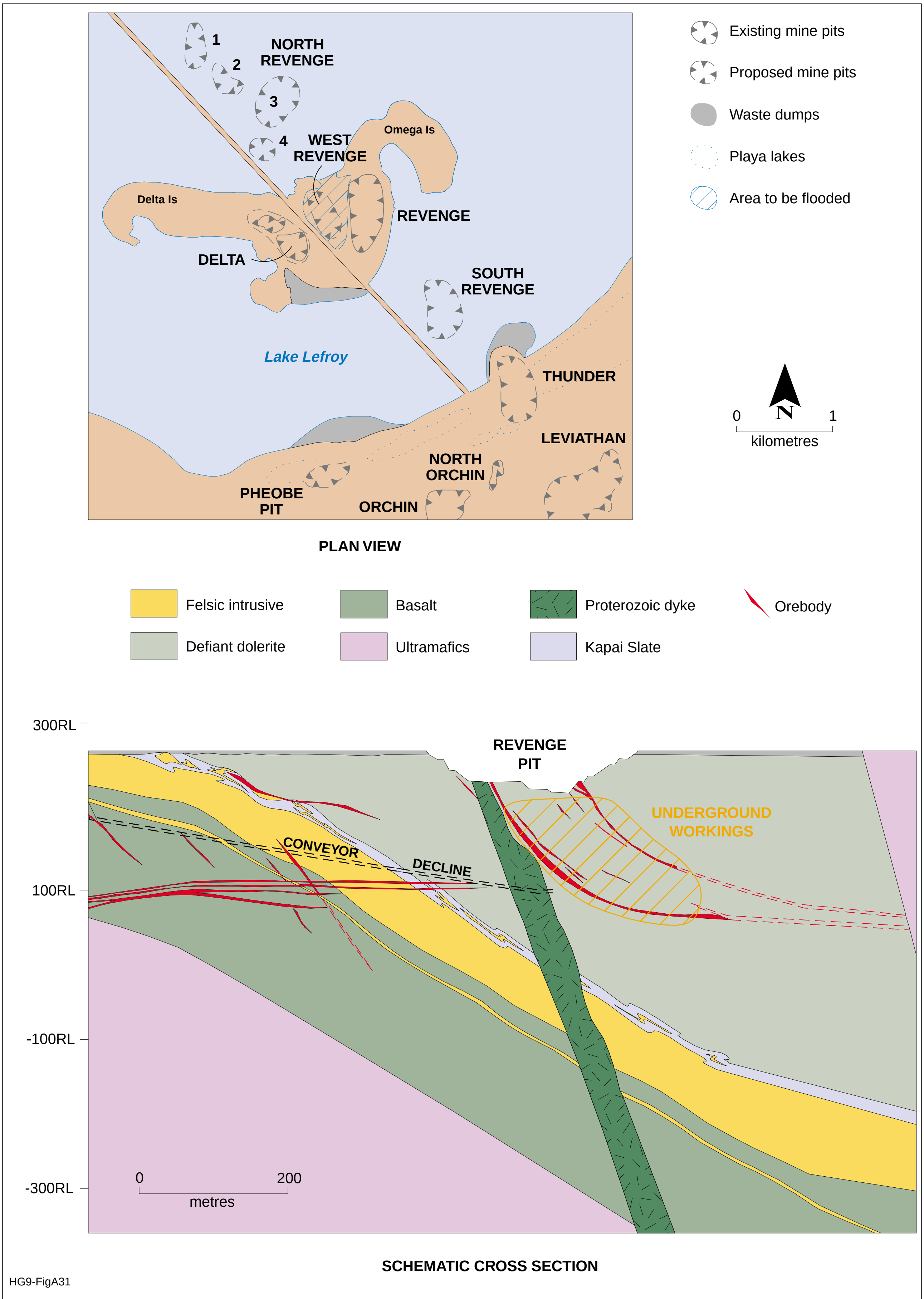

Figure A31. Location and geology of the Revenge gold mine

- The removal of potential acid-generating material associated with sulphide-bearing quartz veins in the orebody; and
- Most material with acid-neutralisation capacity, associated with alteration zones around the orebody, is largely unmined and remains in-situ within the pit wall.

Conclusions

Salt-dominant vegetation types are revegetating the outer causeway and the inner bund surrounding the pit. The bund will therefore form a long-term stabilised barrier which further isolates the pit from the lake bed.

Since closure, the mine void has continued to act as a ‘water sink’ with very low flux rates relative to the overall water budget for Lake Lefroy. The void will act as a salt depository, although the mass of salt ‘locked up’ in the void will be very small compared with the overall salt store in the lake and surrounding areas. The salt and water balances are currently being studied by CSIRO.

Further mining in the vicinity of Revenge pit (Fig. A31) may enable the company to backfill the final void. The current closure strategy for SIGM is that all mine voids in the lake environment will be backfilled; hence, only North Revenge pit 3 and Delta Cutback will not be backfilled. The West and South Revenge pits are to be flooded by breaching the bunds to produce shallow lagoons in the lake.

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BERRY, K., 1999, Revenge pit closure – Preliminary Comments on Water Issues: WMC Exploration (unpublished)

17 Eneabba West mine

Introduction

Iluka Resources Limited is currently decommissioning the Eneabba West mine, which is located on the Swan Coastal Plain, about 140 km south of Geraldton and 25 km inland from the coast. The mine is part of a regional mineral sands operation throughout the Eneabba area. The Eneabba West orebody comprised a sequence of five mineralised strands that were mined using a large bucket-wheel dredge that pumped sand to a floating concentrator for processing. The concentrator uses water in wet-gravity spirals to separate the heavy-mineral fraction from the less-dense clay and sand that form the tailings. The wet tailings were pumped into mined pits to commence the rehabilitation process. Dredging commenced in 1990 and ceased in November 1999 when the ore reserves were exhausted. The orebody and mining operations were on private agricultural land, which had been previously cleared of native vegetation.

The Mediterranean climate is characterised by hot, dry summers with frequent strong winds and short mild winters. Average rainfall is 530 mm/yr, with most occurring in the winter months. Temperatures often exceed 40°C during summer months and evaporation is about 1500 mm/yr.

The mine site is located on the Eneabba Plain, which gently slopes to the west and north. Landforms are characterised by low dunes of sandy, infertile soils. There are no permanent watercourses in the vicinity of the mine, although the mining area is traversed by two creeks that flow during the wet months into Lake Indoon (an important local recreational facility) and Lake Logue, 5 km west of the mine (Fig. A32). Vegetation comprises a low shrubland heath with nature reserves on either side of the mine.

Geology and hydrogeology

Regional geology comprises Late Tertiary to Quaternary superficial sediments overlying the Cattamara Coal Measures of Jurassic age. Superficial sediments consist of sand, silt and clay of thickness varying from 3 m in the southeast to 24 m northwest of the mine. The mineral sands were dredged from these superficial formations.

The superficial sediments form a shallow unconfined aquifer underlain by the Cattamarra Coal Measures, which is a significant regional aquifer. Groundwater in the superficial aquifer is brackish (up to 2000 mg/L TDS) with groundwater flow towards the southwest. The Cattamarra Coal Measures aquifer is

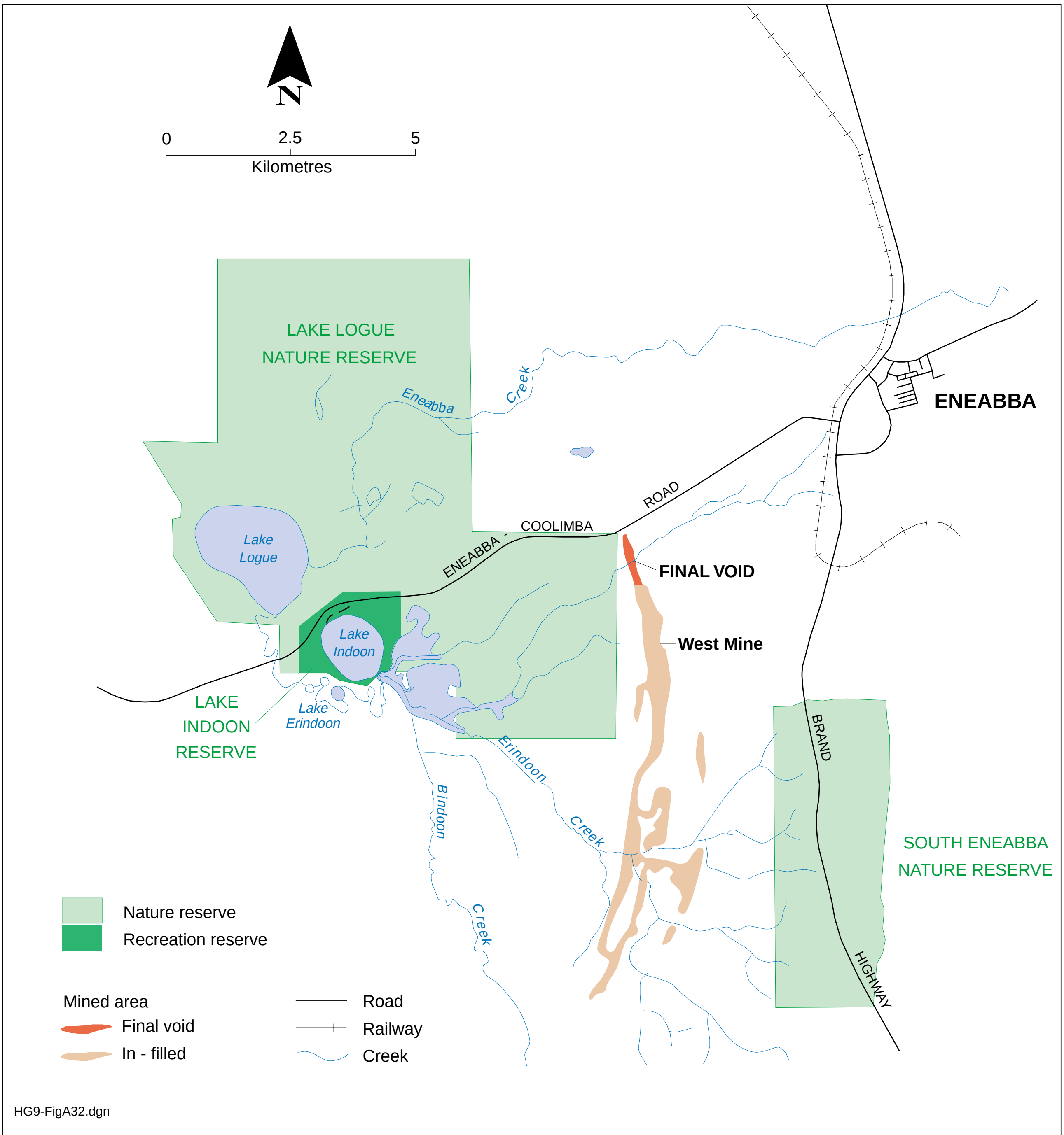

Figure A32. Location of the Eneabba West mineral sands mine

generally confined, except in the vicinity of the West Mine borefield where waterlevels have been lowered in both aquifers from groundwater abstraction.

Potential impact of mining void

Dredging continued to the base of the superficial sediments. Groundwater from the Eneabba West borefield was used to supplement seepage into the dredge pond. Separate ponds were created by placing sandy overburden in narrow causeways across the main pond, with individual ponds infilled with tailings. The tailings, varying in width from 150 m to 1500 m, were deposited over a 9 km length crossing the pre-mining groundwater flow direction.

At the completion of rehabilitation, there will be a final void with dimensions of 1300 m by 100 m wide and a depth of 30 m (Fig. A33). The void will slowly flood with groundwater with modelling predictions

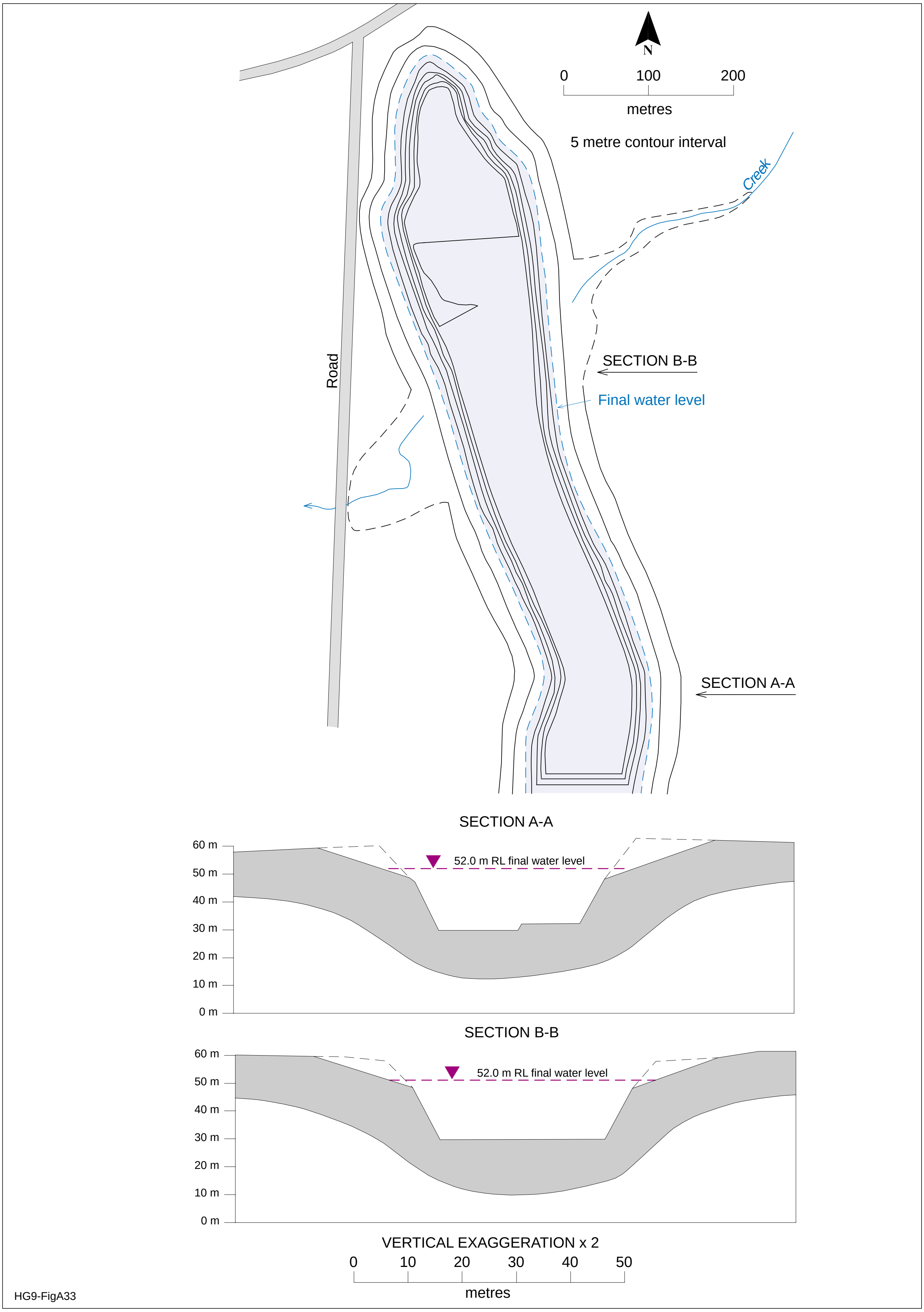

Figure A33. Geometry of the final void at Eneabba West mine

indicating about 40 years to reach equilibrium. In order to shorten the recovery period, the company plans to initially artificially recharge the final void for two years (groundwater to be abstracted from the Yarragadee Formation, east of Eneabba West). The reasoning for rapid recovery and equilibration of waterlevels in the final void was to minimise the impact of temporary lowering of waterlevels on phreatophytic flora within the adjacent Lake Logue Nature Reserve, as well as to minimise the potential for sub-aerial erosion of the final void embankments.

As evaporative loss from the pit lake is high compared with rainfall recharge, the final void acts as a 'groundwater sink'. Salinity in the pit lake is expected to increase from 2000 to 3000 mg/L over ten years and reach nearly 9000 mg/L after 100 years. Artificial recharge into the final void will have a temporary effect on lake salinity with no effect on long-term water quality in the void. The pit lake may develop salinity and temperature stratification within the waterbody, which may result in problems of eutrophication and algal blooms. It is possible that a layer of relatively clear, low-salinity water will develop over cooler, more turbid water of higher salinity.

The main considerations of the final mine closure strategy's were minimising impacts to phreatophytic vegetation downstream of the void, and creek diversion around the void into its original course. A number of detailed studies were undertaken to develop void rehabilitation options, including creek diversion into the mine void to assist with dilution.

Potential impact of tailings

An important mine closure issue is the potential change in waterlevel and groundwater flow due to the low-hydraulic conductivity of the tailings. Studies have shown that the hydraulic conductivity of the tailings may range from 0.8 m/day with minimal consolidation, 0.08 m/day under average consolidation to 0.009 m/day where consolidated by a 15 m of overburden load equivalent. In contrast, the hydraulic conductivity of the superficial sediments ranges from 0.5 to 2 m/day. There are long-term concerns of declining waterlevels to the west of the mined area and increasing waterlevels to the east. The waterlevel may increase to within 2 m below surface in low-lying areas along Erindoon Creek resulting in potential salinity problems. Final remediation will comprise construction of a single lake (4 ha in area) and the planting of phreatophytic vegetation in the eastern areas, where rising watertables are predicted.

Conclusions

Following rehabilitation at Eneabba West, there will be one long, thin void with all remaining mine voids backfilled with saturated tailings. The final void and the backfilled areas will probably impact on the local groundwater system. The final void will act as a 'groundwater sink' with artificial recharge under consideration to minimise short-term impact on phreatophytic flora in the nearby nature reserve. Salinity within the pit lake will increase over time, although the rate of increase may be slowed with diversion of seasonal stormwater flow from a local creek.

The backfilled pits will probably impede groundwater flow, which will result in waterlevel changes and potential salinity concerns. However, this problem has been addressed with the construction of an artificial lake and the planting of phreatophytic trees in specific areas. Iluka Resources Limited has a distinct advantage as it will continue operating in the area for many years, and there are opportunities to monitor its planned closure strategy and make any modifications.

18 Collie Basin coal operation

Introduction

Since 1898, coal has been mined in the Collie Basin from 25 underground and 14 opencut pit collieries. Most of these mines are not currently operational; the first opencut pit was officially closed in 1997. The Collie Basin is a small, shallow intra-cratonic Permian sedimentary outlier within Archaean granitic rocks. The Permian sediments comprise numerous coal measures which also form a complex multi-layer aquifer system containing significant fresh groundwater resources. All the mines extend below the watertable, with the pre-mining watertable and groundwater flow patterns being significantly altered as a result of dewatering.

The Collie Basin is located in the higher rainfall region of the State, with an average rainfall of 850 mg/L and an evaporation rate of 1600 mm/yr. The south branch of the Collie River, in the vicinity of the mining operations, flows only for about half the year.

The case study is focused on mine closure of the WO5 Mine, which comprises six individual mine voids with the largest (WO5B) covering an area of 920 000 m^2 and reaching a depth of 80 m (Fig. A34). All of the voids, located alongside the south branch of the Collie River, extend below the watertable and are slowly filling with water. Over time, and without intervention, the pit lake water will become more saline and acidic.

Geology and hydrogeology

The Collie Basin has an elongate, bilobate structure (Cardiff and Premier Sub-basins) containing an outlier of Permian sediments surrounded by Archaean granitic rocks (Fig. A35). The Permian sediments are further subdivided into the younger Collie Group and the older Stockton Group sediments. The basin margins, delineated by normal faults, are sub-parallel to the elongate axes of the basin. The Permian sedimentary sequence is weakly folded and transected by numerous normal faults that form complex graben structures. The Permian sediments do not outcrop, but subcrop beneath up to 20 m of Cretaceous Nakina Formation consisting of sandstone and mudstone, and Tertiary to Recent deposits of alluvium, colluvium and laterite.

The superficial units constitute a shallow unconfined aquifer with permeable zones in the laterite and sandy beds that are recharged by winter rainfall. Downward hydraulic heads between the unconfined aquifer and the underlying Permian aquifers imply recharge to the deeper aquifers from the unconfined aquifer. Groundwater discharge into local streams and wetlands is non-perennial and fresh. The Nakina Formation is unsaturated over some parts of the basin; hence, the watertable is within the Permian sediments.

Sandstone beds within the Collie Group are major sedimentary aquifers in the Collie Basin. Coal seams and associated mudstone, clay and shale beds form confining layers of low permeability. Groundwater occurrence and flow are controlled primarily by the presence and nature of the sandstone aquifers, as well as by local structures. Individual aquifers are limited in their areal distribution by fold structures and faults. The groundwater is fresh (less than 500 mg/L) with a pH of less than 6.0. The groundwater quality varies with different aquifer settings, proximity to recharge, or discharge zones and land use.

Both the shallow unconfined aquifer and deeper Collie Group aquifers are presnt in the vicinity of WO5B mine void. Prior to mining, the groundwater flow direction in the shallow aquifer was controlled by the surface topography and subcrop zones of the Collie Group aquifers. Dewatering over several decades has produced an elliptical zone of depression. In the past, annual abstraction has exceeded recharge resulting in ‘mining’ of the groundwater resource and inducement of leakage from the shallow aquifers. Groundwater flow in the basin is complex owing to discontinuities in the geological structure caused by faulting, wash-outs and mine workings. Faults affect groundwater flow in various ways. Some are permeable and others are impermeable, depending on the contact between strata in these areas.

The close proximity of the WO5B mine void to the Collie River is a key factor in consdiering closure options. Streamflow in the river has also been affected by the dewatering activity. The increased leakage of river water into the underlying aquifer and reduced groundwater inflow has probably contributed to the ephemeral nature of the river pools adjoining areas of groundwater abstraction. The loss of the permanent pools is believed to have had serious biological consequences, both on animal populations and the ecology of the river system.

Potential impact of mining void

Dewatering of underground workings at the WD2, WD6 and WD7 mines near the WO5B void has resulted in lowering of the pre-mining waterlevels. The watertable has been further modified by dewatering associated with the opencut mining. The rate of inundation and final pit lake level are dependent on the water-balance characteristics of each void, in particular inflow of groundwater and runoff.

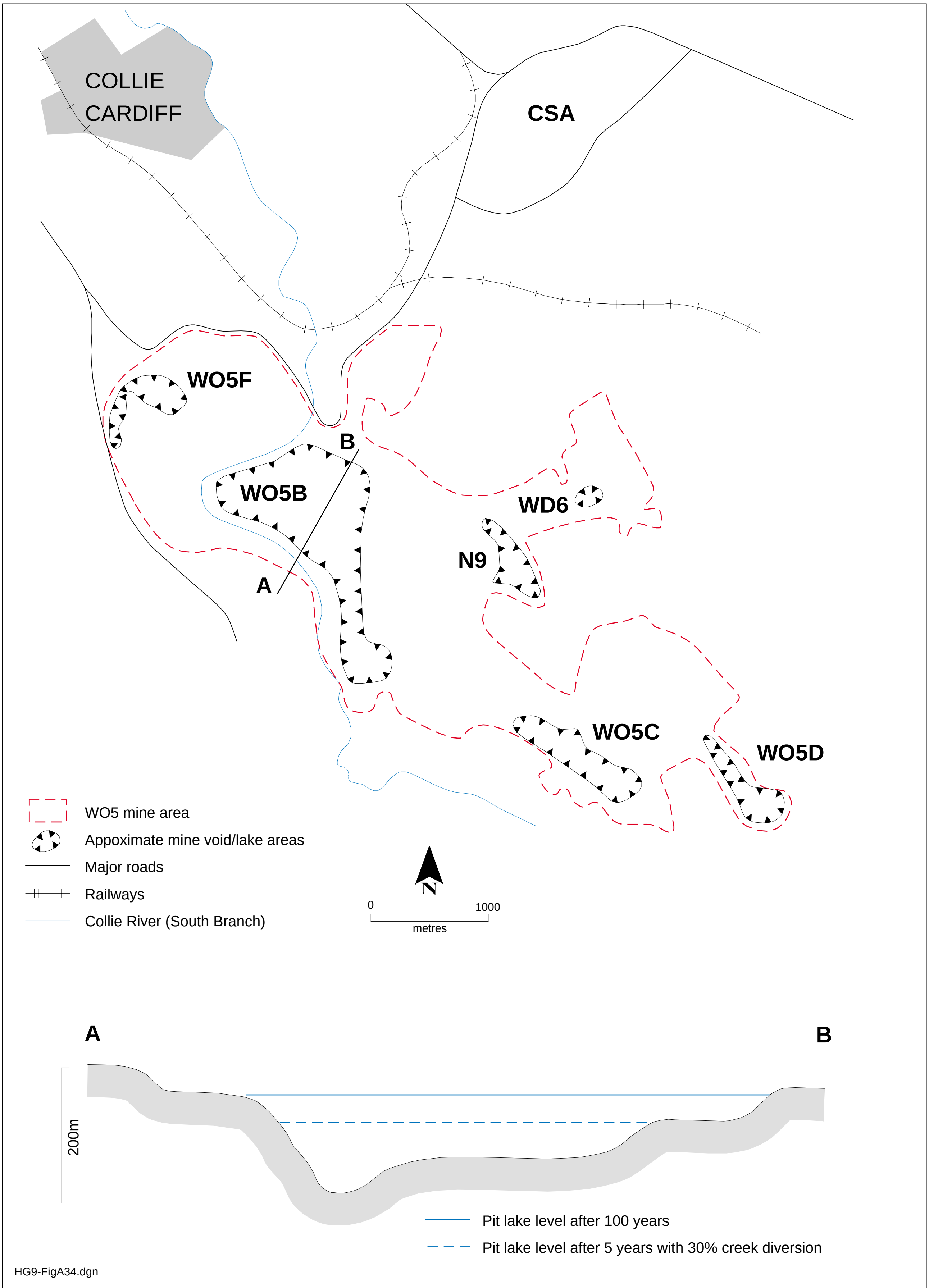

Figure A34. Location of the WO5B mine void, Collie Basin coal operations

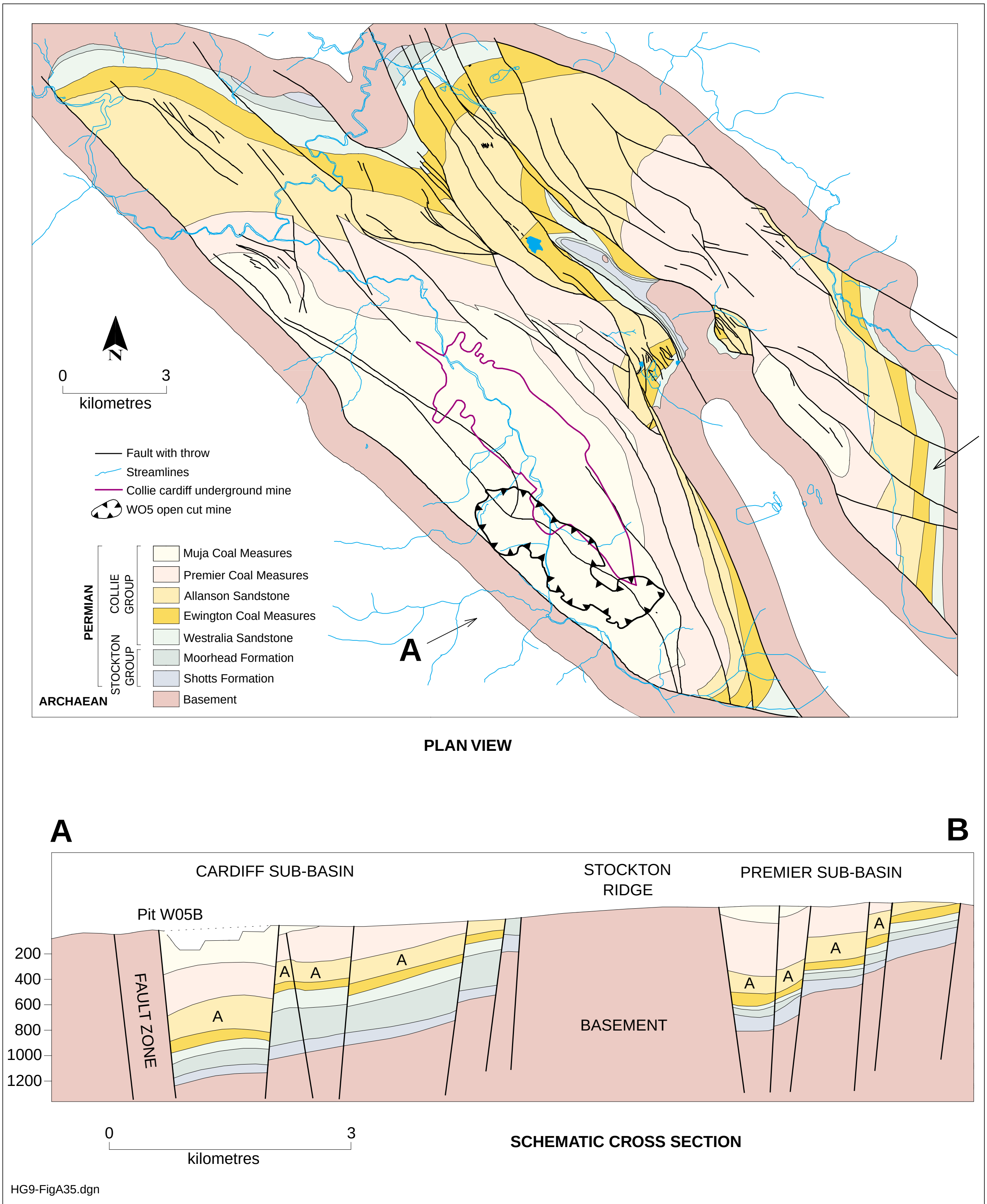

Figure A35. Geology of the WO5B mine void

An assessment of the largest void, WO5B, indicates that waterlevel recovery, to within 5 m of the ground surface, in the pit may take 100 years. Studies have shown that the pit lake will never naturally overflow in a mature reafforested catchment setting, and that lake salinity will progressively increase over the 100 years from about 500 mg/L to 3000 mg/L. The pH of the existing groundwater is lower than 4 and will be similar in the pit lake. The pit water balance will be influenced by the regional lowering of the watertable through ongoing dewatering and water-supply abstraction.

One mine closure option is streamflow diversion. The diversion of the south branch of the Collie River into the final void would accelerate lake inundation and promote seasonal topping-up and overflow of the lake. This option may also facilitate more rapid recharging of depleted deeper aquifers. Studies have shown that a partial diversion, 30% of river flow, would result in void inundation within five years rather than the expected 100 years. The option of streamflow diversion has dramatic effects on the evolution of lake quality. This closure option would ensure that the salinity of the void water will be similar that of the river (1200 mg/L). Rapid filling of the void, and consequent submergence of backfilled overburden, would also inhibit further formation of acid.

Conclusions

The closure strategy of mine voids in the Collie Basin must consider various social and environmental factors. It is not possible to entirely backfill the opencut mines and there will thus be numerous final voids following mining. As all mine voids extend below the watertable, they will flood with water, and the resultant pit lake will increase in salinity. The diversion of water from the river system into the voids is the preferred long-term closure option. In addition, this option may also have a short-term benefit as it may assist recharging the groundwater system, and reduce the demand on the groundwater resources if the voids are used for water-supply storage.