# CHAPTER SIX

# CONCLUSIONS AND RECOMMENDATIONS

**Plate 6.1. Aerial Photo of Phosphate Hill PG Stacking Facilities**

**Cells 1 (south) to 4 (north), with Galah North pit and fertilizer plant, 1 July 2003**

## 6.1 CONCLUSIONS

When the WMC Fertilizers' plant at Phosphate Hill, north-western Queensland, commenced operations in late 1999, very little was known about the by-product of the phosphoric acid production process, phosphogypsum (PG). One set of samples was taken early in 2000 (during the plant commissioning period) by the Company's gypsum stack consultants, Ardaman and Associates, Inc., which were analysed for some major elements and subjected to engineering tests. No other work had been done on the material.

It was known from the pre-planning stages of the operation that PG would be produced in large quantities and was initially to be stored in above-ground stacks, as occurs elsewhere in the world. This study was instigated in early 2000 with two purposes in mind:

(a) to fully characterise the PG produced at Phosphate Hill; and
(b) to provide a preliminary assessment of the material's suitability as mine backfill.

The PG was sampled in three states:

(i) hemihydrate ($CaSO_4.0.5H_2O$) filtercake, derived from the phosphoric acid plant filtration system immediately after acidulation of the parent phosphorite;
(ii) PG slurry, consisting of recycled acid process water, small amounts of hemihydrate and dominated by dihydrate PG ($CaSO_4.2H_2O$); and
(iii) dihydrate PG that had been stored in the stacking facility for several months and had been drained of most of its pore fluids.

The slurry was sampled over a period of 12 months. This time frame was chosen to assess if there was any seasonal variation in the PG produced. It also saw the use of several ore parcels from different sources in the mine and gave the opportunity to assess any differences in PG derived from changing ore sources.

One of the major findings of this study is that the PG produced at Phosphate Hill is notably different to that produced elsewhere. This is most obvious in the comparison of gypsum content, whether as dihydrate, hemihydrate, anhydrite or any combination of the three, against $SiO_2$ and other acid insolubles. PG analyses available in the literature for material produced at foreign plants shows that $SiO_2$ levels in those sources generally account for less than 1% of the total whereas at Phosphate Hill it forms between 20% and 30%. $P_2O_5$ content is also consistently higher in the Phosphate Hill material, where accepted acid recoveries in the PAP of around 90%, along with the accepted sources of loss of $P_2O_5$ to gypsum (in the co-crystallisation of phosphatic mineral species, the presence of unreacted rock, as pore or crystal- bound fluid and from mechanical losses during processing), result in $P_2O_5$ forming an average of 2% to 3% of the total material sent to the stack, compared to 1% or less elsewhere.

The elevated levels of both $SiO_2$ and $P_2O_5$ can be initially attributed to the make up of the ore body. The Monastery Creek Phosphorite Member contains a much higher volume of $SiO_2$ than ore bodies mined elsewhere. This is due to the many chert and highly siliceous siltstone and shale beds found within the ore sequence that cannot be separated out during crushing and processing. Much of this material is also phosphatised to a low degree which, when combined with undigested phosphorite, co-crystallised phosphates and pore-bound phosphatic liquids, accounts for the elevated levels of $P_2O_5$ within the PG. Increased $SiO_2$ may also result from the presence of soluble silicates (*e.g.* fluorosilicic acid and alkali fluorosilicates created during and after acidulation) held in the pore spaces of the PG.

Apart from a lower pH level within the stack liquids, other physical and chemical characteristics of the Phosphate Hill PG are similar to those found elsewhere. It is very fine grained, with the majority of crystal sizes falling between 2 and 200 microns. Monoclinic crystal shapes display tabular, rhombic and lozenge shapes and massive aggregates are common, as elsewhere. However, acicular crystals were rare and the "swallow-tail" twins noted in other PG were not seen in the Phosphate Hill product. $Al_2O_3$ was slightly elevated, probably derived from the clay content within the siltstones and shales, but other major element levels, including F, were similar to PG from other sources. The lower pH is derived from the relict acids contained within the PG and the recycled acid process water used to re-slurry the HH before deposition on the stack.

Trace element analyses had not previously been done on the material at Phosphate Hill. This study has shown that most of the trace elements identified in the local PG fall within similar ranges to those found elsewhere. The exceptions are elevated levels of Ba, Co, Mn, Pb, Sc, Ti and Y. This again will be a reflection of the primary and alteration mineralogy of the parent phosphorite, which contains barite ($BaSO_4$) and gorceixite ($BaAl_3(PO_4)_2(OH)_5.H_2O$), pyrolusite ($MnO_2$), a number of mica-group minerals (as discussed above) and unidentified amphiboles, the dissociated ions of which may have re-precipitated as complex phosphates in the gypsum. Many of the trace elements found in other PG products have either not been identified or are at very low levels in the Phosphate Hill PG. These include the heavy metals Cd and Hg.

In-depth mineralogy assessments had also not been done on the Phosphate Hill PG, beyond identifying hemihydrate and dihydrate gypsum and quartz. The results of this study also revealed some differences in the Phosphate Hill PG. Consistently identified within the material were a range of clays, generally consisting of smectite ($(\frac{1}{2}Ca,Na)_{0.7}(Al,Mg,Fe)_4[(Si,Al)_8O_{20}](OH)_4.nH_2O$) and clinoptilolite ($(Na,K)_6[Al_6Si_{30}O_{72}].24H_2O$), as well as unidentified amphibole/s and micas. Although only paragonite ($NaAl_2(Si_3Al)O_{10}(OH)_2$) was definitively identified within the latter mineral group, muscovite ($K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$) and glauconite ($(K,Ca,Na)_{\sim1.6}(Fe^{3+},Al,Mg,Fe^{2+})_{4.0}Si_{7.3}Al_{0.7}O_{20}(OH)_4$) are also known to regularly occur within the ore body and thus may be expected to form part of the "mica" contained within the PG.

The unidentified amphibole was also a semi-consistent component within the PG, occurring in 9 of 24 samples. Believed to be sourced from the basement granitoids of the Kalkadoon-Leichhardt Block and the Proterozoic metamorphosed marine sediments of the Plum Mountain Gneiss and Corella Formation, this mineral has also not yet been identified within the ore. Its presence within the PG may result from concentration during the crushing/acidulation/filtration cycle of the fertilizer plant. It is recommended that more work be done to confirm the existence of this mineral and to not only identify the chemical type of the amphibole but its provenance. None of these minerals (clays, micas and amphiboles) have been identified as forming part of the PG in analyses available from other sources.

Moisture retention falls after the first flushing event but afterwards shows a tendency to increase over further episodes. However the fall on flush 5 for the “old” DH suggests that more work may need to be undertaken over a longer period to see if the long-term trend continues upwards or decreases again for all species of PG. This may have implications on the amount of fluid that can be absorbed in the long term by the PG and thus how much leachate may be produced. As the decrease in moisture retention in flush 5 occurred after further input of fluid into still damp material (unlike other flushes which were done on largely dried material) it may also have implications for the amount of water retained/leachate produced during above-average wet seasons (such as that of 1999/2000 and the current season 2003/2004) with much more closely spaced, higher volume rain and flood events, than that produced during the infrequent events during drought periods. This can be expected to lead to pulses of contaminated fluids entering the aquifer during wet season flood inundation of the fill with possibly little or no input during droughts, resulting in a much longer overall period of contaminated leaching compared to stacks located in consistent, higher-rainfall areas where any leachate could be expected to reach equilibrium much sooner.

Clumping of aggregates appears to continue in HH while cementing occurs within DH with continuing addition of water until the hydration of all gypsum species is complete. The HH appears to form larger aggregates with each leaching event, resulting in a coarse, sand-like material that is only semi-consolidated. The DH, in contrast, consolidates and hardens into a more impermeable material. This has implications for the porosity and permeability of long-term disposal facilities and the amount of potentially contaminated leachate that may be available to infiltrate the local aquifer as a HH disposal site may remain porous or even increase in porosity while a DH disposal site would decrease in porosity and significantly slow the progress of leachate through the fill material.

There appears to be little or no variation in PG produced either according to season or source of ore. Gypsum species chemistry and morphology remained the same, irrespective of the weather conditions or the source of the ore (hard, less altered Galah pit phosphorite or softer, more weathered Brolga pit ore), as did the content of other minerals (quartz, clays, micas and amphibole). The main effect seen during the 12 month sampling cycle was a slight change in the overall composition and chemistry of the PG that can be attributed to declining production conditions in the phosphoric acid plant in the lead up to the major shutdown in 2001. This is directly attributable to loss of efficiency in the recovery processes within the plant, particularly in the areas of acid produced from rock input and the recovery of acid in the filtration system. This confirms the point noted in Becker (1989) that the correct setting and performance of the phosphoric acid plant is essential not only for phosphoric acid production but for clean and consistent PG production.

In common with other sites that have been the subject of studies, such as the deposits in Florida, Africa and the Middle East, radionuclides are present in the Phosphate Hill PG. These include U-238, Po-210, Pb-210, Ra-226, Rn-222 and an unidentified isotope of Th and are all sourced from the parent ore. The majority of the uranium follows phosphate into the fertilizer product, while Ra-226, Po-210 and Pb-210 tend to report to the gypsum stack. Po-210 is also suspected of being present in the gas by-products of the acidulation process in the phosphoric acid plant while Ra-226 may possibly accumulate in plant scale. Th was split between the PG and fertilizer. Radon was detected in the gypsum but the levels were little different to those measured at the mining camp and were of levels so low as to not be of concern, as is the case for the other radionuclides However, the major finding of the follow-up analyses contained as part of this study is that U-238, Po-210, Pb-210 and Ra-226 appear to be concentrating in the stack fluids. This is believed to be due to the practice of recirculating the fluids through the re-slurry/stack/drain system and may be of long-term concern to the operation. This is not an issue that has been identified in other reports on PG radioactivity and will require follow-up work.

The second section of this project focussed on the applicability of the PG for use as a mine backfill material. To that end, dissolution column experiments were set up using hemihydrate, newly-deposited dihydrate and aged dihydrate. Water was added to the columns to simulate the natural weather conditions at Phosphate Hill, *i.e.* a number of large rain events separated by drying periods over the equivalent of about two years (or two wet seasons) or to replicate the complete inundation of PG fill by either seasonal flood events or by recovering groundwater levels. The PG was analysed before and after the dissolution exercise and the leachate itself was also analysed.

Leachate from both HH and DH PG is dominated by $SO_4$, Total P and Ca with lesser amounts of Al, Fe, Y and Mn. This is representative of gypsum dissolution being the primary source of contamination within the leachate, with input from interstitial phosphates in their various forms. The low pH of the initial flushing events can be related to the mobilisation of the relict process acids contained within the pore spaces of the PG. The levels of all elements continue to fall with ongoing flushing events. This results in the leachate becoming more benign over time with cumulative leaching events. pH levels rise towards neutrality and electroconductivity falls until it approaches the level of the input fluid (*i.e.* rainwater or groundwater). Radionuclides also rapidly decrease with flushing. All of this suggests that the first two to three flushing events are likely to carry the majority of the pollutants into the aquifer.

Of interest in this case is the consistent spike observed in the results (EC, major and trace elements and radionuclides) from the newly-deposited DH PG. If this is not the result of analytical error then it would mean that this particular type of PG does not release many contaminants during the first input of fluid. This is not reflected by a high level of water retention in the first water input, as retention rates for this material actually increase over time. It is an area that may require further study should there be any plans to use this material as backfill.

The pumping of PG slurry directly into the mine void would be expected to result in immediate contamination of the local aquifer as the slurry liquids either came into direct contact with the groundwater or infiltrated through the highly transmissive Beetle Creek Formation into the aquifer. This would be followed by episodes of decreasing leachate contamination as surface or ground water interacted with the material in the pit, until neutralisation was achieved, which could possibly take decades or centuries. As such, slurry is deemed to be unsuitable for use as backfill under any conditions. Utilising dry PG alone as mine backfill, whether as HH or DH, would also be expected to result in several episodes of decreasingly contaminated leachate infiltrating the local groundwater until an equilibrium was reached within the stacked material.

The major and longest-term contaminant to be sourced from PG in the present stacks or any form of it used as backfill is likely to be sulphate derived from the partial dissolution of the PG. Because of its small crystal size and contained relict acids the PG has a higher dissolution rate than naturally-occurring gypsum and will release sulphate much more readily. While other potential contaminants, such as relict acids, phosphorous and radionuclides appear to be removed early in the leaching process, sulphate derived from gypsum will continue to be an issue as the PG dries, consolidates cracks and weathers. The study results show that levels of sulphate of concern to both humans and livestock occur at low to moderate levels of mixing of leachate with aquifer. As this particular aquifer is essentially a closed system, the potential pollutants can be expected to concentrate in the long term, probably within the southern part of the aquifer, and cannot be easily treated or removed. The high transmissivity of the aquifer is likely to cause contaminants to be drawn to any pumping activity.

The use of PG slurry as backfill would be expected to create problems over the short to medium-term as there would be a constant input of highly acidic, contaminated fluids until such time as the backfill operations in that part of the pit were completed and the contained fluids had completely drained. Using HH or DH PG would not have immediate effects but would certainly provide problems in the medium (decades) to long (centuries) term, dependent on weather conditions and the speed of recovery of the aquifer SWL to pre-mining levels. Acid leachate containing high levels of sulphate and low to moderate levels of phosphate and radionuclides would be discharged into the aquifer after inundation events and with the interaction of a recovering SWL and PG backfill in mining voids. A level of equilibrium would be reached after an indeterminate time, particularly in relation to radionuclides and phosphate, but the dissolution of gypsum would be likely to continue for longer and at higher levels, as it makes up the dominant portion of the PG. Water quality on recovery of the aquifer after mining is expected to be lower than it currently is; the addition of contaminant derived from PG used as backfill will considerably worsen the problem.

Many of these concerns can be minimised or negated by the use of liners, cappying and/or the interlayering of neutralising (calcareous) material within the construction of the in-pit gypsum storage facility. When these options are studied other factors come to the fore. These include the practicalities of moving any tupe of gypsum to the final storage area within the pits; the time frame for access to the pit voids; engineering difficulties associated with site preparation and construction; fleet consideration s for moving gypsum and sourcing and moving neutralising material; the likelihood of requiring substantial infrastructure changes; and the economics of all of these.

Legal environmental requirements add to the challenges of using PG as backfill, as do the concerns of the local stakeholders, particularly pastoralists and indigenous groups. Both of the latter already express grave concerns about the Company's use of the groundwater resource and are unlikely to approve any method of PG disposal that has the slightest possibility of polluting the aquifer and thereby creating problems for management of their stock. Finally, recent changes to the Company's closure strategy means that voids must be left in the completed pits to assist in the rapid recharge of the aquifer, severely restricting the areas available for backfilling.

The combination of all of these factors suggests that, even with remediation measures in place, it is unlikely to be politically, financially or environmentally sound for WMCF to use any form of PG as mine backfill, unless it is on an extremely limited basis.

## 6.2 RECOMMENDATIONS

The results of this study show that PG in any of its form is unlikely to be a suitable material for general use as backfill in mine voids. The only circumstances under which it may be used in this manner would be in shallow areas of the pit that are well above the recovered SWL. Even then, it is recommended that the area be either lined and capped to minimise ingress of water and egress of leachate and/or that any stockpiles be built in a layer-cake manner, including layers of calcareous material to provide a neutralising agent for any contaminated fluids. The latter requires investigation into whether methods can be found to achieve this result without the engineering and practical problems associated with repeated movement of equipment over a PG floor.

It is recommended that a small, controlled trial of in-pit disposal be carried out, using the aforementioned methods and a number of the potential neutralizing agents, to assess their effectiveness before any final decisions on in-pit disposal are made. Full feasibility studies, including engineering, environmental and economic factors, should also be undertaken before any final decision occurs.

Should the long-term strategy for PG storage at Phosphate Hill be to continue with the present use of pond-and-pile stacks with proper containment of drained fluids, then trials of closure strategies that include capping and revegetation, and methods of containing and neutralising any fluids that do continue to drain, should be carried out in the immediate (<10 years) future.

A further recommendation is to continue to monitor radionuclide activity in the recycled fluids utilised in the re-slurrying process. The change in levels of U-238, Ra-226, Pb-210 and Po-210 from 2000 to 2003 is considerable with the concentrating effects of recycling likely to continue. It is essential that the Company continue to monitor the stack fluids for these radionuclides and consider strategies for dealing with the highly acidic stack liquors should radionuclide levels rise to levels of concern.

Further research should be instigated specifically to examine radionuclide transport and behaviour in the leachate. The scope of this study did not allow for such analyses on the small volume of leachate gathered. However, it is an issue to foreign producers and should be examined by WMCF, particularly if there are any plans to attempt in-pit disposal of the PG.

Another possible research project would be to fully identify the mineralogy, chemistry and provenance of the minor components of the PG. These include the clays, micas, amphibole and, particularly, the co-precipitates, in order to assess whether they would have an impact on the leachate derived from the PG.

This study has provided important base-line information on the PG produced at Phosphate Hill. That information should now be used for developing strategies for dealing with the material for the life of the operation. As well as continuing the current storage method it is suggested that options for reuse be thoroughly investigated, in order to reduce by the greatest possible amount the volume of PG that will be permanently stored on site.