Chapter 8. Discussion.

8.1. Introduction.

Three methods have been used in this study to assess the extent to which the research question, "How much can the properties of the regolith be inferred using surface measurable features?", is satisfied at Weipa. First, the spatial association analyses assessed the extent to which the regolith is controlled by modern hydrological processes, as modelled using local watersheds. Second, the ANN analyses assessed the degree to which there are global relationships between regolith properties and topography and vegetation. Third, the GWR analyses were used to assess the effect of any small scale, local, variations in these relationships.

The general implication of the results is that there are distinctly localised variations, of the scale of hundreds of metres, in the relationships between regolith properties and surface measurable features. This chapter discusses the reliability of these results, their implications in the study area, and their implications for addressing similar research questions in other locations.

8.2. Model Error.

This section discusses sources of error introduced to the results through the analysis methods used. Through this it will become easier to identify effects the landscape has had on the inferred relationships and therefore the extent to which the research question has been addressed.

This section is structured with the three analysis methods discussed in their own sections. However, one overarching consideration for all of the analyses is that of relative enrichment, and this is discussed first.
8.2.1. Relative Enrichment.

The mineral data used in this study are percentage by volume of bauxitic pisoliths. Consequently, it is possible for one or more regolith properties to partly control the response of the remaining properties for a sample point. For example, a high percentage of $\text{Al}_2\text{O}_3$ leaves little volume for the remaining minerals, and so they will have low values for that sample. Also, when a mobile mineral is leached from a pisolith, the relative abundance of the less mobile minerals will increase as a result.

The Weipa bauxite is assumed to have developed through a process of desilicification (Tilley, 1998). Given this, many of the relationships identified between the mineral properties and the surface measurable features may be through the removal of $\text{SiO}_2$ from the bauxite profile, particularly for less mobile properties such as $\text{Al}_2\text{O}_3$ and $\text{TiO}_2$.

In this dataset the main evidence of relative enrichment is between $\text{Al}_2\text{O}_3$ and $\text{Fe}_2\text{O}_3$, as they occupy most of the sample volume. Consequently, one is often small where the other is large. The effect of relative enrichment is also obvious in the $\text{TiO}_2$ variogram. It shows a similar relationship to the response of $\text{Al}_2\text{O}_3$ and $\text{Fe}_2\text{O}_3$ at the global scale. $\text{TiO}_2$ has a very low mobility, being effectively immobile in the short term, and so this must be the result of relative enrichment processes.

The hydrous content of the pisoliths also occupies up to 25% of the sample volume. By occupying such a proportion of the sample it may also cause some of the relationships identified between the mineral properties and drainage lines by controlling the response levels of the other variables. This may partly explain the differing patterns of local clustering shown by each of the mineral properties. Ideally this data would be made available for future studies.

It should be noted that, for the GWR analyses, the parameter estimates vary spatially for all variables, and that there are clusters of positive and negative associations for each independent variable. Some relationships may be explained by relative enrichment processes, for example a positive association with $\text{Al}_2\text{O}_3$ occurring in the same location as a negative association with $\text{Fe}_2\text{O}_3$. What is interesting is that these relationships differ across the landscape. This, with the extent of the clustering of the parameters, is further indication that there is spatially
localised variation in the relationship between regolith properties and surface measurable features.

8.2.2. Spatial Association.

Issues of model error for the spatial association analyses centre on the comparability of the distance metrics used in each of the sampling methods and the reality of the zones of modern hydrological control identified by comparing the results of the watershed and geometric sampled $G_i^*$ analyses.

As noted in Section 6.2.1.1, the distance metrics used in the sampling methods for the spatial association statistics differ. This difference may have some effect on the results, but it appears to be limited. The variograms show no obvious evidence of control by drainage distance being greater, and the spatial contiguity and geomorphic position of the $G_i^*$ results indicate that the results are not artefacts of the differing distance metrics. There also appears to be a credible interpretation of the zones of modern hydrological control.

There is the possibility that the zones of modern hydrological control identified in the analysis are in part related to the spatial density of sampling. However, an inspection of the $G_i^*$ surfaces, both original and comparison, shows that they occur through a variety of different sampling densities without changing their spatial pattern.

Similar patterns to the zones of modern hydrological control are observed when the results of the wedge samples are compared with those for the circular sample. However, these tend to be smaller in extent than those calculated using the watershed sampling, and are clearly related to the orientation of the wedge. Also, when they are aggregated they show a similar pattern to the zones of modern hydrological control inferred through watershed sampling. This indicates that the watershed sampling does adapt to the processes controlling anisotropy as they change across the study area. It also indicates that the wedges could be oriented to maximise the $G_i^*$ response through experimentation, however such an approach addresses the symptoms of analysis error, and not the cause.

The spatial association analyses therefore have some limitations, but the general results obtained appear to be sufficient to use in the interpretation of the research
question. The error in the analyses using vegetation and topographic indices now needs to be assessed.

8.2.3. The ANN Model.

The ANN predictions show some large errors when predicting the interval variables, and a high degree of variability when predicting the presence/absence of bauxite. This section discusses the reasons for model errors in the ANN analyses, for both the binary and interval analyses.

8.2.3.1. Binary Predictions.

The binary predictions for presence and absence of pisolithic bauxite have achieved accuracies of between 72% and 92% correct for each class (Section 7.3.1). This is a good achievement when compared with the interval ANN predictions, but there is still between 8% and 28% of the variation unexplained despite the apparent differences in the vegetation response to presence/absence of bauxite (Figure 3.2).

The results of the two presence/absence analyses show also that most of the confusion is over one section of the dataset, that of the non-pisolithic bauxite. The presence/absence analyses have not been able to separate non-pisolithic from pisolithic bauxite, and it appears there is little difference in surface measurable features between such factors.

Another major reason for the error in the presence/absence analyses appears to be due to a mixed zone of bauxite and non-bauxite in the southern part of the Andoom Peninsula. Here the Depth to Ironstone changes markedly within short distances, often with adjacent cells having values of two metres and zero metres. Although the exact cause of the alternations is difficult to identify, it may be due to surficial erosion exposing the crests of undulations in the ironstone layer.

The results for the presence/absence analyses have implications for other regolith models with such a simple classification task. The ability of these methods to identify such abrupt regolith changes in landscapes with more subtle variation, particularly in the vegetation response, indicates a major challenge that may be
encountered by other workers in this field. This is particularly the case when the regolith variation is intermixed as in the south of the Andoom Peninsula.

8.2.3.2. Similarity of Conventional and Multi-Scale Interval Analysis Results.

The results for those ANNs trained using the multi-scale geomorphometric indices are very similar to those trained using conventional indices. These similarities are both spatially and in the error matrices, with accuracies within 1%-5% of each other at the fourth error tolerance. The exception to this is in East Andoom, where the multi-scale predictions showed greater spatial variation for Fe$_2$O$_3$ and the conventional predictions showed greater variation for SiO$_2$.

The multi-scale indices allow a better representation of landscape form, and so there must be some reason for this lack of predictive difference from the conventional indices. Possibly it is because the Weipa landscape is so flat, but it may also be related to the way the multi-scale indices were presented to the ANNs during training. The multi-scale indices are highly correlated, as they are calculated for increasing spatial lags of the same base data. While such correlations can still be informative in a geomorphic sense, they are poorly dealt with in the ANN analyses.

Within an ANN, and any other similar analysis system, the independent data are used only as a series of axes by which to separate the values of the dependent variable, or to define relationships describing how the dependent variable changes. Indices for each scale in this study were presented to the ANNs as individual nodes in the input layer and, as these layers are highly correlated, they will have an artificially increased impact on the error minimisation. This is because network training has many similar axes by which to separate the data. Much of the training effort would thus be occurring in a relatively small section of the weight space, and potentially little effort would be spent adjusting weights in the other regions of the weight space.

As a consequence of training with correlated data, it becomes even easier for the ANN to bias to the modal response than when using the less correlated conventional indices. Some method of better presenting correlated data to the
ANN during training is needed, possibly by training the ANN using parameters from mathematical functions fitted to the multi-scale indices.

8.2.3.3. ANN Analysis Summary.

The binary prediction accuracies appear high, but in reality miss up to 28% of the variation in a simple presence/absence classification. The results of the interval ANN analyses show a general pattern where the predictions have biased to the modal response. This is partly a result of the global error minimisation used during training, and affects both the conventional and multi-scale predictions. While this implies that the equal area distribution of training data has not been effective, other experiments with the dataset (Section 7.3.2.3) have shown that good predictions remain difficult to obtain using a spatially implicit approach. The GWR model error is discussed next.

8.2.4. Geographically Weighted Regression.

The GWR predictions are consistently better than the ANN predictions. They show a greater degree of variation spatially, as well as a closer fit to the training data in the error matrices. This implies there are local variations in the relationship between regolith and surface measurable features, and that these have not been discerned by the ANN analyses. Those GWR analyses used directly with the independent variables are more accurate than the spatially adjusted ANN predictions.

GWR appears, therefore, to be a very useful approach to analysing the regolith. This is because it does not apply global relationships across the dataset, and instead adjusts to changing conditions on a local basis. This includes secondary effects caused by other processes, as these can change the response of the variable analysed. This can be useful in many cases, as one may not have a variable available for analysis, but it may be possible to model its effect through localised variation of a secondary variable.

For the GWR analyses it is possible that there are errors caused by the number of independent variables used. This is because there may be cases where there are no relationships between the regolith and some of the independent variables.
used. Where this occurs, the relationships between the other variables and the regolith may have been affected.

In cases where there is no relationship between two variables, they should not be used together. For GWR this could be applied using step-wise regression approaches. There are plans for this (M. Charlton, pers. comm., 2001), but they were not implemented at the time of this study.

It is also likely that the errors are in fact over-estimated in the GWR analyses (Lark, 2000). As the GWR t-scores and spatially adjusted ANN $r^2$ values (Appendix 1) have been used as an exploratory tool, and not as a true significance test, overestimation does not affect the conclusions reached here. The determination of more exact significance scores is a challenge for future workers.

### 8.2.4.1. GWR Summary.

The results of the GWR analyses show there is a high degree of localised variation in the relationship between the surface measurable features and the regolith properties at Weipa. However, there remain locations where there are no relationships, or where these relationships are poor. These are inferred to be locations where the landscape is affected by some process not represented by any of the independent variables used. Such effects are discussed in Section 8.3.1.

### 8.2.5. Model Error Summary.

There are many sources of error in the analyses used in this study. Some of these are serious, while others are small and may be dealt with as part of the interpretation of results.

The ANN analyses have been shown to have major biases due to the way they minimise the error. There is still some relationship with the landscape identified by the ANN analyses, and the fact that this has been found is important. However, the spatial diversity of the Weipa landscape, and the spatially implicit approach used, reduces the degree of relationship discerned between the regolith properties and surface measurable features used.

This spatial variability explains the consistent superiority of the GWR analyses, both spatially and in the error matrices. It indicates that local, explicitly spatial,
methods are best used for addressing the research question with multivariate independent data. Implicitly spatial, global analyses such as ANNs are inappropriate to identify local variations in relationships between regolith properties and surface measurable features. The same is implied by the results of the $G_i^*$ analyses when compared with the variogram results. Even though the variograms show some variation, an inspection of the $G_i^*$ results shows that there is a high degree of spatial variability not identified through global analyses.

The local, explicitly spatial analyses, $G_i^*$ and GWR, show a much greater degree of association between the regolith properties and surface measurable features than do the ANNs. As a consequence, they will be used as the basis of subsequent discussions on the implications of the results for the research question.

8.3. The Landscape.

Potential sources of error in the analyses, both numeric and in the models, have been discussed, and the results have been shown to have some limitations. However, not all of the error can be attributed to the models and the data used to derive them. The predictions indicate that there are some definite landscape effects, and these are key to understanding the extent to which the research question has been addressed. The local scale, explicitly spatial analysis results ($G_i^*$ and GWR) indicate that these landscape effects occupy specific positions in the landscape. In many cases they are associated with drainage features, as indicated by the $G_i^*$ analyses, but in other cases different landscape processes appear to be the controlling mechanisms. The scale of the various controlling processes also appears to differ across the landscape, as indicated by the differing size of clusters of good and poor association in all the explicitly spatial analyses.

This section discusses the implications of the model results for interpreting the evolution of the landscape and the development of the regolith at Weipa. It first considers how the models have dealt with prominent landscape features, and inferences about them using the results. Second, it considers the implications the analysis results have for equilibrium of geomorphic and regolith processes in the
Weipa landscape. Equilibrium is an underlying assumption when using surface measurable features to infer regolith maps.

8.3.1. Landscape Features and Processes.
There are several features in the Weipa landscape that have had an evident effect on the analysis results. Some have been identified by the analysis while others have not. This section discusses these features, exploring reasons for identification or non-identification, and the effect others have on the relationship between regolith properties and surface measurable features.

There are six topics discussed in this section. These are the relationships between vegetation and the regolith, the effect of marine incursions, the Andoom redsoil, the arcuate features in northern Andoom, relationships between the parent material and the TiO₂ distributions, and the effect of melon holes in the landscape. Some attempt is made to explain why these features are present in the landscape.

8.3.1.1. Vegetation.

Spectral vegetation response appears to have had limited impact on the analysis results. There appears little evident vegetation pattern in the ANN results, and the clusters of high t-scores in the GWR results were more spatially isolated than for any other variable (Appendix 1). The reason for this is most through disturbance processes affecting the spectral response, but there are other effects.

8.3.1.1.1 Vegetation Disturbance.

The vegetation in the study area is highly disturbed, through both anthropogenic and natural causes (see Chapter 4). This includes mining activities, fire and cyclones.

8.3.1.1.1.1 Mining Activities.

The vegetation in the study area has been heavily disturbed by mining activities, most so by drill roads used for sampling to generate the regolith dataset used in this research. Most of these drill roads are left for vegetation to regrow naturally after drilling has been completed, although some are retained as access roads for
mining operations. There are also roads cleared for drilling operations shortly before the Landsat scene was captured.

The long time period over which the bauxite has been sampled by drilling (from 1955), and the infilling sampling design, has made the vegetation disturbance by access roads inconsistent across the entire study area. Sampling began at 1000 ft intervals along a regular grid, and subsequently at finer intervals of 500, 250 and 150 ft as the spatial density of sampling was increased (Section 4.2.1). In addition, much of the deposit has been redrilled since 1980, and so some parts were very recently disturbed at the time the Landsat scene was captured. Consequently, the vegetation regrowth across the study area is of different ages, and this has reduced the level of possible spectral discrimination. Similar disturbance of geobotanical associations has been found by Cole (1991) when attempting to identify a known geobotanical anomaly in the Charters Towers-Ravenswood mineral province in Queensland, Australia, and so this is a problem for any similar future work.

It is possible to include the date of drilling in the analysis to account for disturbance ages, but such data was not available. In addition, it would be difficult to meaningfully extend any relationships to locations that have not been drilled, as is done in the ANN analyses.

The regrowth of vegetation along drill roads is not the only cause of noise in the dataset, those drill roads cleared at the time the Landsat scene was captured may have a large impact. This is because they have no vegetation, and so the exposed soil will generate a strong response in the infra-red bands. This will introduce another level of uncertainty given two infra-red bands, band four and band seven, have been used here.

Vegetation regrowth was an unavoidable problem and, most likely due to these disturbance effects, only broad scale information was provided by the remotely sensed data. It was mainly used by the analyses to define the break between bauxite and non-bauxite in the presence/absence analysis, with some smaller levels of discrimination of properties within the bauxite.
Possibly methods that can sense through vegetation would prove more useful in similar studies, for example radiometrics and electrical conductivity (see McKenzie and Ryan, 1999). These were not included in this study because they were either unavailable or their sample resolution was too coarse to be combined with the elevation and Landsat data (Section 4.2.3). However, such methods still ignore the vegetation component and, where sampling is not as destructive as in this study, visible and infra-red sensors should prove a useful model component.

8.3.1.1.1.2 Fire.

Fire is another disturbance factor that changes the spectral response of vegetation across the dataset (see Figure 3.2). This will have had an impact on the spectral response of vegetation. As with roads, any disturbance will be through regrowth, although vegetation successions that respond to disturbance by fire are expected to differ from those related to clearing.

The more accurate predictions obtained by the GWR analyses may imply that the local variations in fire disturbance have been accounted for by the local analyses. Such effects are not likely to be discerned by the spatially implicit ANN analyses because there is often no distinct topographic component to the distribution of fire in the Weipa landscape. Other landscapes which have greater topographic variation may show a response in particular parts of the landscape, for example through fire intensity along ridges, but these may still be difficult to identify in an analysis because the ignition location for fire will not normally be consistent in the landscape.

8.3.1.1.1.3 Cyclones and Tree-throw.

Cyclones in the Weipa landscape cause tree-throw, and their impact on the analyses needs to be considered.

Tree-throw causes two small scale disruption features, but have also been found to cause major changes in some soil properties (Meyers and McSweeney, 1995). In Meyers and McSweeney’s study the pit was generally wetter than the surrounding knoll, bulk densities were less in knolls than cradles and particle size distribution was also changed.
There were extensive tree-throws in the Weipa area after the 1995/1996 wet season, which experienced one cyclone. However, there was little disturbance of the bauxite itself by root systems of thrown trees. In most cases the tap root had broken near the top of the bauxite layer. The lateral roots tend to grow in the surface soil layer, or A horizon, and so most of the disturbance was in that layer (Figure 3.6).

The changes measured by Meyers and McSweeney (1995) only impact on short term regolith mapping. The long term effects of tree-throw will be spatially averaged. Given the observed effects at Weipa, tree throw appears to have had little discernible effect in this study, particularly given the resolution of the topographic information available for this study (Section 4.2.2.1).

However, while the effects of tree-throw are averaged over time, there will be some localised disturbance effects on the spectral response of the vegetation where tree-throw has occurred recent to the capture of the Landsat scene. This is most so where a large tree falls, removing the canopy contribution to the spectral response of that pixel. While this is only a part of the total spectral response from the vegetation, it can be an important one. It will also introduce regrowth patterns into the landscape, and these may or may not be associated with the character of the regolith at such locations. It is not possible to determine if such effects have been modelled here, although they are generally smaller than the scale at which any of the analyses in this study have been conducted.

### 8.3.1.1.2 Other Vegetation Effects.

Most variation of vegetation on the bauxite is related to drainage conditions around melon holes. Some concentric features have been observed from aerial photography to radiate around melon holes, but without conforming to the central shape. This is most evident around Willum Swamp in the Weipa Peninsula (see Figure 4.2). Field inspection shows the darker lines around this feature are non-sclerophyll vegetation. These are considered to be related to previous shorelines of the melon holes, and they have become visible through regrowth after fire. These appear not to have been explicitly identified in any of the analyses.
8.3.1.2. **Marine Incursions.**

The effect of marine incursions has been described in Section 3.2.2.4.2. It is likely that much of the regolith at Weipa, particularly in the Andoom Peninsula, has been influenced by mechanical reworking by these incursions and any associated tidal and storm surge effects. The effect of a five metre rise in sea level and associated five metre storm surge is shown in Figure 3.7.

The effect of marine incursions is that the spatial patterns evident in the landscape are expected to be mixed to some degree, most likely locally. This will then have some control over the relationship between topography and regolith properties.

East Andoom appears unaffected by marine reworking, as its elevation is too high and it is sheltered from direct effects of storm surges by the Andoom Peninsula. Those areas of the Weipa Peninsula that would be expected to undergo effects from marine incursions were excluded from the analyses because there was no drill core information. The lower part of the Andoom Peninsula is thus where the greatest effect of marine reworking on these analyses is expected.

The prediction errors in the region closest to the coast in the south of the Andoom Peninsula are consistently high in all ANN and GWR analyses, and consistently show a low degree of modern hydrological control in the $G_{1*}$ analyses. Of all the study area, this part is the most susceptible to coastal processes. In particular, it would be most often subjected to reworking by marine incursions and storm surges. Its low elevation means that it will be covered by even moderate incursions. Also, a greater frequency of storms of varying intensity will have an effect on this location.

Despite the obvious potential effect of marine incursions and storm surges, and evidence for their recent occurrence high in the landscape ($870+/−60$ a BP; Foster, 1996; Section 3.2.2.4.2), there are still variations in the predictions in those areas. This is for both the spatial association analyses and the multivariate analyses. This indicates that the regolith has adjusted to these effects to some degree. The implications of this are discussed below (Section 8.3.2).
8.3.1.3. Andoom Redsoil.

Another feature of the Weipa landscape that may affect these results, but appears not to have been identified, is the presence of the redsoil in the Andoom Peninsula (see Section 3.2.2.4). This occurs in small zones and has been interpreted by Foster (1996) as resulting from local fluvial reworking of finer material from the surface of the bauxite. It is identified mineralogically by an increase in boehmite and a reduction in the volume of silica present. Similar features are known to exist in the Weipa Peninsula, but have not been mapped. This section discusses the degree to which the redsoil has been identified in the analyses, concluding that the rate of bauxitisation is such that these are very similar in the analyses to the remainder of the study area.

The redsoil features are mapped (Dunster, 1983) as either thin linear features or as circles. This is partly an artifact of the mapping method used, as an orientation to the drill core sampling lines is evident in their spatial distribution. Those areas mapped as long, linear features are expected to be closer to the real distribution, and are used here. It is likely that these underestimate the true distribution of the redsoil, but do provide information on the core areas with greater depths.

A visual inspection shows there are no close associations between the mapped redsoil features and the spatial distributions of mineral variables as mapped by the \( G_1^* \) analyses (Figure 8.1). There are some locations where the redsoil is mapped around features that are low in \( \text{SiO}_2 \), but nothing closer.

The lack of relationship between the landscape and the redsoil is not surprising, as the redsoil is usually deposited as a layer over the original bauxite layer. The mineral values in the dataset are for the entire profile, and not only the redsoil layer. Many of the unique values in the redsoil are thus expected to be subdued by aggregation during sampling. Those locations where there is a relationship with \( \text{SiO}_2 \) are inferred to be where the redsoil mineralogy dominates the profile. Why they are found around the zones of low \( \text{SiO}_2 \) is not known, but may be to do with the mapping inference process.
Figure 8.1  Redsoil distribution in Andoom plotted against the G. C. results. There is a weak relationships with SiO₂, but little else.
The lack of relationship between the redsoil and surface hydrology is explained by the redsoil being deposited in hollows (Foster, 1996). This then changes the surface morphology so the locations of preferential deposition no longer exist in the landscape. This is one of the key factors controlling the relationship between surface topography and sub-surface regolith properties.

Another reason for the lack of relationship between the redsoil and the regolith properties, as shown by the G\text{*} analyses, may be due to the rate at which controlling processes change the regolith in the Weipa landscape. The modern hydrological spatial association results imply that the mineralogy of the bauxite layer at Weipa is under modern hydrological control up to a distance of 120 m around most locations. An inspection of the width of the redsoil zones shows that they are most often less than this. It is therefore likely that the bauxitic redsoil has been affected by pisolith formation processes, and that these are recent. This is supported by radiocarbon dates in the redsoil of 8080+/-400 a BP and 11,770+/-200 a BP (Foster, 1996). Their position in the redsoil indicates they are redeposited and so they are likely to be maximum ages.

It therefore appears likely that, if much of the redsoil was deposited since the last Glacial Maximum (21 ka BP), and at least the last interglacial (approximately 105 ka BP), then pisolith formation of bauxitic material is extremely rapid in the Weipa environment. (This rapidity is in relation to the postulated age of up to 54 million years; see Table 3.1). As with the effect of the marine incursions, this has implications for the time scale of the equilibrium processes in this landscape (Section 8.3.2.3).

### 8.3.1.4. Arcuate Features in Andoom.

One location where all of the analysis predictions show a distinctly different response to the remainder of the study area is in the north of the Andoom Peninsula. In this location there are three arcuate features aligned approximately north-south. These are convex eastwards, and appear to be associated with ridges. There is also a fourth, possibly associated, feature to the east across Pine Creek. The arcuate features are visible in the different spatial analyses as high values of each variable in the G\text{*} and GWR results, and have been noted as areas of high error in ANN analyses of Al\textsubscript{2}O\textsubscript{3} in this dataset by Laffan (1999).
A closer inspection of the $G_i^*$ results shows the clusters do not strongly overlap between variables (Figure 7.2). There is a clustering of high values of $\text{Al}_2\text{O}_3$ along the crests of the ridges, with lower or average values of $\text{Fe}_2\text{O}_3$, $\text{SiO}_2$, and $\text{TiO}_2$. Depth to Ironstone is also lower on the ridges. These other variables are higher below the ridges, indicating drainage controls are removing minerals downslope. A comparison of clustering in the remainder of the Andoom Peninsula shows that there is a similar response in the central ridge east of the Botchett Swamp melon hole. This area is not included in the ANN and GWR analyses because it had already been mined by the time the Landsat scene was captured, and so was excluded from analysis. Consequently, there may be a common cause.

These arcuate ridges, and the central ridge, in the Andoom Peninsula occupy the highest parts of the Andoom landscape (see Figure 4.2). They have the greatest local relief, and differ from the remainder of the landscape. This appears to be the reason for the inadequate predictions in the ANN analyses, as these features differ too much from the remainder of the training set. This problem is reinforced by the ANN bias to the modal response, or dependent variable value, but indicates there may also be a bias to the modal landscape form, or independent variable values, in this case.

The abundance of $\text{Al}_2\text{O}_3$ is always higher on ridges because $\text{Fe}_2\text{O}_3$ and $\text{SiO}_2$ are removed by the action of drainage enhanced by steeper slopes, and so the values of $\text{Al}_2\text{O}_3$ are relatively enriched. The average $\text{SiO}_2$ value on broader ridge crests is explained by the flatter slopes on these crests changing the drainage controls.

**8.3.1.5. Parent Material.**

The landscape features discussed above all have some easily identified surface measurable component. However, parent material does not.

Parent material is one of the major controls over regolith properties, and is considered as one of Jenny's (1941) five state factors of soil formation. Normally this would be applied using geological units, such as is inferred for the bimodal distribution of $\text{Fe}_2\text{O}_3$ between the Andoom and Weipa Peninsulae, but this does not enable an understanding of within-unit variation and its effect and so was not used in this study.
The environment in which the parent material is deposited is expected to have some effect on the distribution of the mineral properties in the landscape. For example, the Weipa Peninsula is underlain by high energy fluvial sediments, and some of this structure may be retained in the spatial distribution of the regolith properties. This may therefore be used to explain some of the patterns seen today.

TiO$_2$ is often used to infer weathering rates through ratios of mineral abundances between parent material and weathered regolith because it has a low solutional mobility (see for example Eggleton and Taylor, 1999; Taylor and Eggleton, 2001). Much of the spatial structure of TiO$_2$ from the original parent material is therefore expected to be preserved in the weathered regolith component and will thus be visible in the G$_i^*$ results.

This section discusses possible controls by parent material on the spatial distribution of regolith properties at Weipa, in this case TiO$_2$. It first considers the extent to which this approach may be used, and then the inferences made from the G$_i^*$ analyses. This approach should allow some understanding of the extent to which the parent material controls regolith properties in the study area.

### 8.3.1.5.1 Using TiO$_2$ to Infer Variations in Parent Material.

The concentration factor of TiO$_2$ from the original parent rock to present bauxite implies a twelve metre lowering of elevation in both the Andoom and Weipa Peninsulas through the process of weathering (Eggleton and Taylor, 1999). The calculation of this figure assumes there is limited lateral reworking. It is also based on drill core samples from only four locations, although there is a total of approximately sixty sub-samples down these drill cores (see for example Figure 3.5). The 12 m lowering figure is more tenuous for the Weipa Peninsula than for the Andoom Peninsula due to limits of sampling.

TiO$_2$ has also been shown to be mobile in tropical latitudes (Cornu et al., 1999). The effect of such mobilisation and reworking processes may only be to "blur" the spatial distribution of TiO$_2$, but it remains a point of uncertainty.
8.3.1.5.2 Inferences.

This section discusses the implications that the spatial distribution of TiO₂ has for previous interpretations of depositional environments for the Weipa and Andoom Peninsulæ parent material.

The Weipa Peninsula is inferred to overlie high energy sediments (Le Gleuher et al, 1994; Zambelli, 1991), while the Andoom Peninsula is purported to be shallow marine and deltaic (Smart, 1977). A high energy or deltaic environment would ideally leave preferential deposition of heavier minerals along channels, while a shallow marine environment might have a broader spread of such minerals. The exact distribution would be affected by channel migration processes, but much of the distribution would be preserved during lithification and remain in the profile after weathering.

The G_i* results show that the clustering of TiO₂ is much smaller in spatial extent than the other indices in the Weipa Peninsula (Figure 7.2). This is negative clustering, and thus lower than the mean. While it is possible that it is through the deposition of the Bulimba Formation, these zones may also be the result of exposure of bedding through the warping process that created the Weipa Peninsula. Given these clusters are aligned along the axis of the peninsula, warping appears a likely explanation. This also allows for broader deposition of TiO₂ without the need for it to be retained in distinct channels. Even if it is deposited in channels, it is likely that there will be some broader distribution through point bar and channel deposition in laterally migrating fluvial systems.

The mapped channels in the Weipa Peninsula are aligned along the axis of the ridge. It is likely that the ridge is present because of this deposition. There are, however, no obvious relationships between mapped distribution of clay content and unit depth in this region. As a further caveat, the mapped distributions are in the kaolin and aquifer zones, and not the bauxite zone from which the TiO₂ data are obtained.

The Andoom Peninsula is formed on the Rolling Downs Group, which contains sediment of shallow marine origin with some deltaic components. The G_i* response for TiO₂ shows a large area of uniform positive spatial clustering over a
large spatial extent in the south-east of the peninsula (Figure 7.2). This area extends 5.5 km east to west and 8.5 km north to south. There are also smaller north-south cluster lineations in the north. If the TiO₂ distribution does represent parent material deposition, then this implies a marine origin for the southern portion, with possibly a deltaic environment in the north where many channels control the spatial distribution of minerals. Warping may also have some effect here, particularly in the north where the G_i* clustering alternates between positive and negative.

It is also possible that the reason for the large positive cluster of TiO₂ in the south-east of the Andoom Peninsula is reworking by marine incursions. However, the size of this cluster, and the lack of such a feature on the western, seaward side of the Andoom Peninsula, is evidence against this. This large cluster of TiO₂ may also have some implication for the cause of the melon holes, as there are none in this section of the Andoom Peninsula.

An alternate interpretation of the TiO₂ patterns is that they relate to more recent additions from parent material to the regolith profile as the weathering front and surface landscape are lowered. Given the complexity of the Weipa landscape, and the very different mobilities of the four oxides studied, it is likely that a combination of remnant and recent spatial patterns of TiO₂ are present. Further clarification of this question should be the subject of future work.

It is thus difficult at this stage to accept or refute either possibility, of depositional or of structural control, of TiO₂ distributions and thus parent material controls on regolith property distributions. It is likely that both processes occur, each of which has implications for the present day distribution of regolith properties. These are through the effects of drainage in the study area, most so through the melon holes.

8.3.1.6. Melon Holes.

Some of the most prominent features in the Weipa landscape are the melon holes. The results indicate these are strongly related to the distribution of regolith properties in the landscape. This is through their control over modern hydrological conditions and over longer landscape evolution processes. There have been no attempts to date the melon holes, but they must be older than the present day
landscape for them to exert such a degree of hydrological control over adjacent regolith mineralogy. They are considered to be pseudo-karst features, and this section discusses them in more detail after first discussing the controls they have over the distribution of regolith properties today.

8.3.1.6.1 Present Day Control of the Regolith.

Melon holes and their connecting drainage lines form localised low points in the landscape. As a result there is an apparent localised modern hydrological control over the regolith around these features, most apparent with Depth to Ironstone and SiO$_2$. This is because these melon holes are a major control over the redox front, which defines Depth to Ironstone, through their regulation of the water table. Subsequent controls of the lateral movement of saturated groundwater by a blocking effect will cause SiO$_2$ in solution to precipitate.

Concentric vegetation patterns around several melon holes (see also Section 8.3.1.1) are interpreted as receding shorelines from wetter periods. These are made visible by recent fires providing a contrast between the differing mid-storey vegetation. The age of these shorelines is unknown and no topographic expression was observed in the field. The colour of the topsoil around the melon holes changes laterally from grey to yellow with distance. This colour change is thought to be due to the melon holes controlling the oxidation environment, with drainage improving away from them. Other colour changes, related to the humic content immediately adjacent to melon holes, are made evident by a darker A-horizon. This may be expected if the melon holes have experienced higher water levels in the past.

While there are distinct controls by the melon holes over present day hydrology and regolith, it remains to be explained why they exist in the landscape in the first place. It also remains to be explained why some are permanently full of water, and why some are only seasonally inundated. The next section attempts to provide some possible explanations.
8.3.1.6.2 Formation Mechanisms of Melon Holes.

The locations of melon holes and patterns of larger drainage lines in the study area are intertwined, and it is probable that they have similar causes. This is particularly so if the melon holes are, as expected, pseudo-karst sinkhole features resulting from collapsed subsurface drainage. This section describes one method of such pseudo-karst collapse.

Higgins and Schoner (1997) found sinkholes formed in a compound alluvial fan under flood irrigation. The identified causes of the sinkholes were:

1. A gently sloping surface with subsurface buried sand and gravel channels.
2. Sediments that consist of dispersible silty soil or alluvium with sufficient clay to form and retain shrinkage cracks.
3. A lowered water table.
4. Deep dewatering of the sediments to produce desiccation cracks that can reach from the surface to a buried channel.
5. A strong inflow by surface water into the dessication cracks long enough to enlarge the opening and form sinkholes.

The melon holes at Weipa conform to some of the above conditions. The slope conditions are similar to those of a low angle alluvial fan, and the fluvio-marine origin of the Rolling Downs Group and the Bulimba Formation provide antecedent drainage channels for piping within the weathered sediments. Such pipes, up to one metre in diameter, have been identified in Andoom during field work, although they may not be related to antecedent drainage conditions. These pipes appear to flow parallel to the ground surface and occur beneath the ironstone layer in the kaolin and mottled zones (Figure 8.2). They occur within regions of other voids and macropores, up to 1-2 cm in diameter, which appear laterally elongated. These have also been identified elsewhere in the study area by Zambelli (1991), who noted the presence of sub-vertical, interconnected tubular voids. These were generally 1-2 cm in diameter, but some were as large as 50 cm.

The third condition of Higgins and Schoner (1997) is met by the end of every dry season when the water table recedes to a depth of more than 10 m across most of the study area (Figure 3.3). This is into the clay rich mottled and kaolin zones within which the pipes, voids and macropores occur. There is also termite activity
visible in pit faces several metres below the ground surface. Termites tend to follow open paths in the cohesive clays of those zones, and so are assumed not to have developed the system themselves. These cracks and voids satisfy condition number four. The fifth condition is expected to occur seasonally with the influx of meteoric water from monsoonal rains.

The melon holes at Weipa are considered to have formed through collapsed piping. In such a case Higgins and Schoner's fourth and fifth conditions are not necessary. The roof of a pipe will collapse if solutional erosion by preferential flow through the piping removes too much regolith material. If the pipe is close enough to the ground surface then a surface depression will result. The low gradient in Weipa indicates that such blockages would not cause channelised flow, they would instead result in the shallow depressions that are the melon holes, most probably where several nearby pipes collapse.

Figure 8.2. Pipes and macropores below the bauxite layer, Andoom, through which groundwater flows preferentially. The pipes appear aligned with the melon holes and may therefore be related to their development. The helmet is placed in one such pipe.

Some evidence for palaeochannel collapse is shown where there appears to be a linear pattern between melon holes roughly following the north-south aligned
drainage patterns in the Andoom Peninsula (Figures 3.1 and 3.2). These are linked by vegetation patterns shown in a vegetation map produced for Comalco (not available for reproduction due to commercial confidentiality). These lineations are not strongly evident in the vegetation spectral response. This weak relationship may be through vegetation disturbance effects discussed above, but may also be because the variation is spectrally indistinguishable. The piping described above also appears to follow this north-south orientation, based on observations on two sides of a 5 m wide water access trench dug between the Pine River and Botchett melon holes. These two melon holes have the most obvious alignment of all those in the study area.

Other evidence for palaeochannel origins is shown immediately to the north-west of the Andoom Peninsula where there are numerous closely spaced melon holes with a linear pattern evident from the elongation of the Melon Holes (Figure 3.2). In this case they are aligned east-west. The frequency of the melon holes in this region might be explained by it overlying a different parent material. The lower elevation and flatter topography of this area could also cause poorer drainage conditions. Consequently, any collapse features would be more difficult to clear or bypass, resulting in a greater frequency of melon holes.

The absence of melon holes in East Andoom may be the result of greater relief allowing better drainage. Consequently, any blockages through collapsed piping or macro-pores will not have a permanent effect as the water will have sufficient energy to find or create new drainage paths. Alternately, the blockages would cause an increase in saturated overland flow through the build up of moisture in the soil. This would then increase surface erosion, which in turn would increase the drainage capacity of the regolith through channelisation. Such a mechanism is not inconceivable given the long time period over which the landscape at Weipa has been evolving (Section 3.2.2.4.4).

No melon holes are visible in the breakaway country. This may mean either that prior melon holes have been removed with the erosion of the breakaway country, or that collapse occurs only within the upper part of the regolith profile.

The reason why some of the melon holes are permanently full of water, while others are seasonally inundated is unclear. Neither type occupies consistent
modern topographic positions. The permanently full melon holes appear to be deeper, allowing the retention of more water. Those seasonally inundated melon holes tend to be shallower, and so cannot retain water above the ground surface. However, this still does not explain why the permanently inundated melon holes are deeper. This remains a topic for future research.

8.3.1.6.3 Palaeo-drainage Controls.

It appears most likely that these melon holes are pseudo-karst features. It now needs to be considered in more detail what layer enabled such piping to exist for collapse to occur. Palaeo-drainage controls over sub-surface water flow appears a likely cause, as it can predispose the regolith to piping or macropores over such long distances and on such low slopes. Understanding the cause of the palaeo-drainage, regardless of whether it was at any stage surficial, may then allow a better understanding of what sort of relationships might exist in the regolith.

There are three, non-exclusive, possibilities for the cause of the palaeo-drainage. These are antecedent drainage from the parent rock, localised faulting along which groundwater will flow, or features relict from some previous phase of the development of the bauxite. The last option is rejected on the basis of the piping observed in Andoom and the magnitude of chemical changes in the bauxite layer itself.

8.3.1.6.3.1 Antecedent Drainage.

It is possible that the distribution of the melon holes and primary drainage channels reflect antecedent drainage conditions inherited from the parent rock. Such antecedent drainage, as well as superimposed drainage, has been noted for larger channels in the Cape York Peninsula (Pain et al, 1999). The distribution of structures in the kaolin zone has also been noted to follow palaeo-drainage lines in the parent material (Zambelli, 1991).

The parent materials on the Weipa Peninsula are fluvial sediments, while the Andoom Peninsula has shallow marine and deltaic sediments. The spatial analyses of the TiO₂ distributions have suggested that the deltaic patterns in Andoom may be channelised in the north of the peninsula and a shallow marine basin in the south. Their presence would be associated with channel deposits
within the parent material which could provide the macropores for piping to occur. Inspection of these distributions against the melon holes shows they relate to the distribution and orientation of melon holes in the Andoom Peninsula. There are no melon holes in the south-east within the large, structureless mass of high TiO$_2$ values. This is further support for the hypothesis of prior drainage, provided it is related to depositional conditions of the parent material.

The distribution of melon holes on the Weipa Peninsula may also be related to drainage controls within the parent material, but their size and frequency are both lower than on the Andoom Peninsula. This may be related to the better drainage conditions on the Weipa Peninsula related to its higher relief. The same applies for East Andoom, which has no melon holes but is highly dissected and has a high relief relative to both the Andoom and Weipa Peninsulæ.

It is also possible that the Miocene (6.3-24 ma) Wyaaba Beds have an impact on the melon holes in Weipa. These unconformably overlie the Weipa Beds, and would therefore be expected to exert some control over the subsurface drainage in Weipa.

8.3.1.6.3.2 Faulting.

The major drainage features in the region, the Mission and Embley Rivers, appear related to the major geological structures of the area. These features include the laterally offset arcuate coastline of the west coast of Cape York Peninsula. The offsets have been inferred by Bourke et al (1988) to be caused by transverse faults associated with extensional rifting, and the arcuate component caused by subsequent wrench faulting. These features are most visible in the area where Duyfken Point is the southern end of one arcuate fault while, to the south, Urquhart Point is the northern extent of another fault.

The general pattern of the medium sized drainage features, such as Pine Creek and Andoom Creek, may be the result of local faulting or other non-regional structural elements such as boundaries between geological units. Their degree of incision is much greater than the smaller drainage features across the study site.
There are geomorphic differences either side of these features, for example the Andoom Peninsula and East Andoom. These are probably the result of a combination of faulting and lithological differences, where vertical movement along the fault exposes different sections of the geological profile after planation processes.

It is therefore possible that the lineations evident in the drainage and melon holes could be the result of faulting and fracturing, probably in addition to antecedent drainage effects. It must be considered that such faulting appears to have a limited effect on the local drainage features across the bauxite deposit compared with the larger drainage features. Therefore, is faulting is the cause there must be deep controls on drainage being expressed at the surface.

However, observation of the piping in Andoom showed no vertical faulting. Instead, there was an extensive horizontal cracking above the level of the pipes. This therefore precludes faulting as a major cause of, and control over the distribution of, the melon holes.

Antecedent drainage conditions inherited from the parent rock are therefore considered to be the major control over the distribution of the melon holes. It must be considered that any relationship between regolith properties and parent materials will be observed through secondary effects on surface measurable features. This may obscure many of these relationships, making them difficult to discern analytically.

8.3.1.7. Landscape Features Summary.

The landscape at Weipa is complex, with a range of geomorphic, geobotanical and other processes operating to shape the landscape, in this case its regolith, topographic and vegetation variations. These operate over a variety of temporal and spatial scales, and so it is therefore not surprising that the analyses have found very localised relationships between regolith properties and surface measurable features. Indeed, the fact that any relationship has been found at all is useful.

The next section discusses the results in the context of landscape equilibrium processes. This will allow a clearer understanding of the reasons for the
relationships observed in the results, and also allows a more confident extension of the results beyond the Weipa study area.

8.3.2. Landscape Equilibrium.

Equilibrium is one of the underlying concepts upon which this study rests (Section 1.2.2), and this section discusses the implications these results have for regolith-landscape equilibrium processes in the Weipa study area.

It may be considered that the regolith is in, or near to, some form of quasi-equilibrium with the landscape where the multivariate models used show a low error and where the spatial association results are stronger for the watershed sampling. In the case of the variogram and G_i* analyses this will be in locations where there is modern hydrological control of the regolith, as modelled using surface watersheds. For the ANN and GWR analyses, those locations that exhibit a low prediction error are considered in, or near, quasi-equilibrium. Locations with a high prediction error that is not explained by known model limitations and error are considered out of phase with present day landscape processes. Possible reasons for this have been discussed above (Section 8.3.1).

This section discusses the implications of the analysis results for equilibrium processes in the Weipa landscape. It first considers the response times of the regolith properties investigated to external changes and the different spatial extents over which these processes occur. It then discusses indications of equilibrium processes. Finally, it discusses the time scales required for the Weipa bauxite to approach quasi-equilibrium.

8.3.2.1. Mineral Mobility and Exposure to Weathering Processes.

The key factors affecting equilibrium relationships between regolith properties and the landscape in which it rests are the solutional mobility of the mineral properties and their degree of exposure to weathering processes. This applies to the mineral properties directly, while the control of the landscape over the redox front regulates the precipitation of iron in the regolith profile, and thus Depth to Ironstone.
The time required for the spatial distribution of a regolith mineral property to come into equilibrium with the landscape is proportional to its mobility and to the duration, frequency and intensity of weathering processes. If the rate of mineral mobility is slower than the rate at which the landscape is evolving, or the regolith is less often exposed to weathering processes, then equilibrium will not be reached. Consequently, the relationship between regolith properties and surface measurable features is reduced, or even erased.

Indicative solutional mobilities of the four mineral properties analysed in this study are shown in Figure 8.3. This is directly related to the pH of groundwater, which at Weipa is normally 4.5 (Eggleton and Taylor, 1999), but varies seasonally due largely to meteoric inputs during the wet season (Evans, 1965). SiO$_2$ is more mobile than Figure 8.3 suggests because it is contained in the clays, which are more mobile than Al$_2$O$_3$ and Fe$_2$O$_3$.

![Figure 8.3. Weipa pH and element mobilities (after Summerfield, 1991). SiO$_2$ is much more mobile in the study area than the diagram suggests because it is contained in the clays. These contain neither quartz nor amorphous silica. TiO$_2$ has an extremely low mobility.](image)

That Depth to Ironstone has such a high degree of association with modern hydrology indicates that the redox front is more readily adjusted to the controls of
the surface landscape than are the minerals within the bauxite pisoliths. This is entirely in the lower elevations of the study area, and is near constant for all distances tested in the $G_i^*$ analyses. This is also where the greatest degree of control of the water table and its annual fluctuations by surface conditions would be expected.

The effect of seasonal variations in the water table has been shown by Evans (1965) to control when the different minerals are mobilised and precipitated. $\text{SiO}_2$ is mobilised into solution during the water table rise at the beginning of the wet season, and deposited during the fall of the water table at the end of the wet season. The reverse applies for $\text{Al}_2\text{O}_3$ and $\text{Fe}_2\text{O}_3$. This confirms that $\text{SiO}_2$ is most mobile in the present landscape, although the spatial extent of this relationship cannot be inferred from Evan's work because the sample locations are not known.

The timing of the uptake and precipitation of $\text{SiO}_2$ can be related to its spatial distribution of modern hydrological control. The greatest degree of modern hydrological control of $\text{SiO}_2$ in the bauxite in the Andoom Peninsula occurs near the edge of the deposit, which is in the lowest elevations. It is through these locations that groundwater flows during wet season inundations, and therefore where the most precipitation will occur when the water table falls at the end of the wet season, or where the slope lowers the velocity of the groundwater to cause greater rates of precipitation. A similar, but less obvious, relationship is seen in the Weipa Peninsula. This is inferred to be due to its form, as it is more elongate than the Andoom Peninsula. Groundwater has a shorter distance to drain across the axis of the peninsula and so mobilises less $\text{SiO}_2$ as it passes through the regolith.

The distribution of $\text{SiO}_2$ appears therefore to be a local expression of a regional process. This reiterates the point that equilibrium processes and relationships operate at different scales simultaneously (see Section 1.2.2).

The relationship of water table fluctuations with the mobilisation and precipitation of $\text{Al}_2\text{O}_3$ and $\text{Fe}_2\text{O}_3$ is less clear. Evans (1965) interpreted his data as meaning precipitation during high water tables and uptake into solution during the dry season. Possibly this is actually a dilution effect, and the rate of mobilisation remains near constant while the volume of water increases.
It should also be considered that the controls of pisolith geochemistry are slower than those for the matrix in which they rest, but it has already been discussed that there is a linear association between the composition of the pisoliths and the matrix (M. Morgan, pers. comm., 1996; Section 3.2.2.4). Pisoliths are also commonly cracked, allowing water to pass through them. This will enable some change in their mineral content, most so for hydration (eg boehmite to gibbsite) and for the more mobile components, or of those components that have a greater surface area for chemical weathering processes to act on.

The seasonal relationships between mineralogy and water table rises and falls may therefore be because more of the Al$_2$O$_3$ and Fe$_2$O$_3$ is locked into the pisoliths, while there is a greater volume of SiO$_2$ available to weathering processes because it is contained in the clays. These clays occur as skins on the surface of, and in cracks within, the pisoliths. The Al$_2$O$_3$ and Fe$_2$O$_3$ more often make up the pisolith rings themselves, and so there is less surface area available for weathering processes to act upon them. This relationship is then expressed through the degree of modern hydrological control.

An additional consideration is the hydrous content of pisoliths, which is expected to vary closely with changing modern hydrological conditions. This has been noted in an alternation between goethite and haematite depending on whether conditions are wet or dry (L. Foster, pers. comm., 2001). Data on the hydrous content would be useful in any further work on the deposit.

### 8.3.2.2. Spatial Patterns of Equilibrium Relationships.

One of the advantages of the $G_{i*}$ and GWR analyses used in this study is that they allow an exploration of the spatial distribution of the relationships between the regolith properties and the surface measurable features. This is most useful when identifying the scale and spatial extent of equilibrium relationships in the landscape.

The spatial extent of equilibrium relationships is broad for watershed hydrology at scales of less than 210 m around each location, but is very limited for scales greater than 210 m. This is also evident in the relationships between the regolith properties and the multi-variate surface measurable features. The spatial extent
of absolute t-scores greater than two in the GWR analyses is very limited (see Appendix 1 for spatial distributions of individual variables). A t-score of two used in the exploratory case indicates that the relationship is strong. Normally clusters of these more extreme t-scores are of the order 1-2 km diameter. However, these clusters are generally isolated from each other, and co-located strong relationships with more than two individual variables are uncommon (Figure 8.4).

Overall, less than 50% of drill core sample locations in the seven cell analyses, and 40% in the ten cell analyses, have a strong relationship with the surface measurable features tested. Added to this, less than 15% of the sample locations in the drill core dataset have strong relationships in the seven cell analyses with two or more surface measurable features, and 20% for the ten cell analyses. Those locations with two or more strong relationships tend to be clustered together, which does indicate that pockets where equilibrium relationships exist are not randomly distributed in the landscape.

The spatial extent of co-located strong t-scores from the GWR analyses indicates that the spatial extent of multi-variate equilibrium processes in the landscape is variable. This is generally in response to changes in the controlling processes.

**8.3.2.2.1 Scale of Modern Hydrological Control.**

The spatial extent of the equilibrium clusters may allow some inference over which processes are controlling the spatial distribution of regolith properties at Weipa. This is most due to hydrology, but hydrology operates over many different scales and has differing expressions. The effect of hydrology on the regolith properties at Weipa is by interactions between surface hydrology, melon holes and streams on regional and local groundwater movement. These scales have been dealt with to some extent in the analyses, but the relationship is more complex. There are definite cases where the zones of modern hydrological control are local expressions of regional processes.
Figure 8.4  Count of GWR t-scores exceeding than +/-2. Locations with more than two such scores are limited.
Periodicity in the Weipa landscape has been described by Morgan (no date; see also Section 3.2.2.4.1). A period of 1,000 m is inferred to be caused by minor creeks and affects several factors, those most relevant to this study being the degree of bauxitisation, iron mobility, thickness of the bauxite, and the degree of reworking of the deposit. The variograms agree quite closely with Morgan's interpretations, as they imply average distances of association around 500 m to 1,200 m, with a decreasing rate of change beyond these distances (Section 7.2.1). This lends further support to the view that hydrology is a major control over the landscape.

The $G_i^*$ and GWR results show that the scale of equilibrium processes identified in this study tends to be short-range. Generally this is of the order of 120 m for watersheds around most locations, and these are sometimes grouped into elongate zones. In addition, the best global GWR results were for the seven cell analyses (210 m), which implies the scale of the multivariate relationships tend to be of the order 210 m. Smaller radii were not tested, and so the multivariate scale may be smaller still. Conversely, the best t-scores were obtained for the ten cell analyses, indicating there is still some degree of spatial variation in the regolith-landscape relationships.

The hydrological spatial association analyses show the mineral distributions are under modern hydrological control, or approaching hydrological quasi-equilibrium with surface drainage, at a lateral scale of less than 120 m. There are also distinct zones where this extends to 300 m. The modern hydrological control over Depth to Ironstone is fairly constant for all scales tested but may decrease when greater distances are assessed.

The zones of modern hydrological control of Depth to Ironstone are also restricted to the lower part of the deposit, and appear restricted to those areas where bauxite depth is shallow and thus so is the redox front. This, and the spatial extent of the zone of hydrological control of Depth to Ironstone in the Andoom Peninsula, indicates that it is controlled by regional groundwater movement. The zone of modern hydrological control inferred through the $G_i^*$ analyses is therefore a localised expression of this regional pattern. It may also be the case in some
locations that Depth to Ironstone controls the distribution of surface hydrology by being an impermeable barrier to flow.

The zones of \( \text{SiO}_2 \) under control of surface hydrology are also explained by regional groundwater processes, with precipitation under localised control. This is best shown at the base of the Andoom Peninsula, but also around other depocentres, for example near melon holes. This is supported by the global modern hydrological control of \( \text{SiO}_2 \) indicated by the variogram analyses. The localised expression also confirms that the melon holes act as regional controls of groundwater movement.

It must also be considered that hydrological processes in the regolith profile have a vertical component. There is a concentration of \( \text{SiO}_2 \) at the top of the profile, possibly through uptake by vegetation with subsequent deposition as phytoliths, and also through deposition of aeolian dust. This means there would possibly be a stronger relationship with surface hydrology as it will have most relationship with the upper part of the regolith profile. In addition, the removal of \( \text{Fe}_2\text{O}_3 \) to the ironstone layer, at the redox front, appears in many cases to be vertical. This is inferred from the scale of modern hydrological control over \( \text{Fe}_2\text{O}_3 \), which is smaller than for the other mineral variables. That the redox front shows such a strong surface hydrological control is due to localised controls over the groundwater surface.

That the \( G_i^* \) results calculated using the watershed sample are consistently higher than those calculated using the directional samples indicates that there may actually be localised hydrological control within broader hotspots. This needs to be the subject of future work, as comparison with four sample directions is not conclusive.

8.3.2.2.2 Non-Hydrological Factors.

One factor to consider with equilibrium is the differing response for each of the regolith properties. Much of this appears to be due to solutional mobility, and so hydrology is considered to be the dominant controlling factor for the evolution of the Weipa bauxite. That the \( G_i^* \) analyses showed this to be in most cases a distance of between 120 m and 300 m for the mineral properties indicates that
these processes are occurring slowly, and are greatly affected by the other mechanical factors such as marine incursions, storm surge, aeolian, and other palaeodrainage agencies (Section 3.2.2.4.2). Many of these processes mean it is probable that any reworking by mechanical erosion will alter the landscape such that present day watersheds do not represent the conditions as they were at precipitation.

Such mechanical processes might also confound equilibria between regolith and landscape where surficial reworking has redistributed the regolith such that the values in the regolith property dataset would be an average of two distinct layers in the bauxite. An example of this might be associated with the cemented layer identified by Foster (1996) as a boundary between an earlier bauxite surface and the results of reworking by surface erosion. Differing patterns of spatial association may be found where these layers are analysed separately. Appropriate measurements have been done at Weipa since bench mining was introduced but were not made available for this study.

There are also palaeo-climatic factors to be considered, and these have varied greatly over the life of the deposit. With vegetation and parent material variations, Weipa is truly an example of all of Jenny’s state variables for soil formation (see Section 1.2.2.1).

8.3.2.3. How Long Does It Take to Reach Quasi-Equilibrium?

The results of this study allow statements to be made about the spatial distribution of quasi-equilibrium relationships in the Weipa landscape. It is also useful to attempt to understand the length of time the regolith has taken to achieve this state. The time taken for the regolith to come into equilibrium with its controlling processes will vary with many factors. For this study these factors are most related to the rapidity with which each regolith property can adjust to the changing conditions of landscape, and the rate at which the landscape is changing.

There are many processes operating in the Weipa landscape. Thus, the degree to which the regolith is controlled by, and sometimes controls, the landscape changes greatly with location. Nevertheless, there are identifiable features and
zones that appear to be in quasi-equilibrium. The simplest of these is the degree to which the regolith is related to surface hydrology.

Eggleton and Taylor (1999) consider the bauxite in Weipa to be "more or less in equilibrium with the present climate". This is based on the close conformation of the components of the bauxite profile with the current water table fluctuations, and that the groundwater is in equilibrium with its mineralogy. The presence of ferrihydrite in water bodies is evidence that iron is "active" in the present landscape.

Tilley et al (1994, 1998) interpreted the micro-structure of bauxite nodules as representing three phases of bauxitisation, where kaolinisation and ferruginisation were the dominant processes leading to mottle and nodule formation. The time period of this bauxitisation is not stated by Tilley, and it is difficult to determine without quantitative dating control on the bauxite itself (see Section 3.2.2.4.4). These phases of bauxitisation may be spaced over the entire period of bauxite development, or may only represent three recent phases of increased bauxitisation.

The results for redsoil locations (Section 8.3.1.3) indicate that the landscape appears to have been most recently changed by landscape evolution processes since the onset of the Pleistocene glaciations and their controls over climate and sea levels. It appears that the bauxitisation processes occur over much shorter time periods than this.

Marine incursions provide the broadest scale reworking process in the Weipa study area. There is also the extensive surficial reworking inferred by Foster (1996). These processes are expected to change the landsurface topography to the extent that it would destroy, or at least partially reduce, any relationship between local hydrology and the regolith properties. Any association between regolith properties and local surface watersheds in these locations have therefore evolved since these reworking events occurred. A partial reduction of the relationships may be more common than total destruction, as the \( G_i^* \) surfaces indicate the distributions of each of the mineral properties have not been extensively "blurred".
The timing of the most recent marine incursions is likely to be during the last interglacial, around 120 ka BP. That there are evident locations of modern hydrological control in those areas considered to be inundated (compare Figures 3.7 and 7.4) indicates that the time taken for the regolith to approach equilibrium with surface hydrological processes is less than 120,000 years, at least for a local spatial extent of 120 m, and in some cases further than 300 m. This has significant implications for the time taken to reach equilibrium between regolith properties and topography in this landscape.

At shorter time scales, the redsoil in Andoom has been dated as more recent than the Last Glacial Maximum (21 ka BP) and is indistinct from the present day topography. Its differences are largely chemical, and it is likely that the redsoil is merely the location of greater deposition of reworked material. This, together with likely post-depositional pisolith formation, indicates that pisolith forming processes operate in the Weipa landscape over relatively short time-scales. These are of the order tens of thousands of years, and not hundreds of thousands and greater. While the rate of these processes varies with the intensity of the controlling processes and the degree of external disturbance, it is still an ongoing process. The spatial variation of these relationships also indicate that the intensity of bauxitisation varies spatially.

There is also the possibility that some of those locations identified as approaching, or being in, quasi-equilibrium represent relationships preserved from previous landscapes, or represent continued evolution of such relationships. An example of this is the north-south aligned zone showing modern hydrological control of Fe₂O₃ in the Andoom Peninsula evident at the 300 m scale Gᵣ⁺ surfaces (Figure 7.34. This is also evident in the Al₂O₃ Gᵣ⁺ surface. This zone shows a generally low clustering of Gᵣ⁺ values of Fe₂O₃ between -0.4 and 0, and moderately high Gᵣ⁺ values for Al₂O₃ between 2.5 and 3.5. It is not consistently co-located with any present day feature, as it is aligned across both a low ridge and drainage features. It may therefore be a palaeo-feature preserved from previous landscapes. Its location may have reduced the amount of physical reworking by storm surges and their blurring effect.
Such reactivation, or continued activation, of equilibrium relationships appears to agree with Tilley's multiple phases of bauxitisation. It also indicates that the timing and intensity of these are spatially variable in the landscape. There may actually be more than three phases of enhanced bauxitisation in some parts of the landscape, and fewer in others.

8.3.2.4. Landscape Equilibrium Summary.

The use of ANNs and other spatially global models assumes the regolith is in equilibrium with topography and vegetation across the study area. The GWR results clearly show this is not the case, and that localised equilibrium conditions exist, most often only as partial equilibria. This is supported by the $G^*_i$ results for the mineralogical variables. Many of these equilibrium relationships are local expressions of regional processes, with a spatial extent of less than 120 m, although some extend beyond 300 m. Depth to Ironstone, which is under more direct control by mechanical landscape evolution processes, shows a greater degree of association with modern hydrology in the lower parts of the study area.

These local equilibrium relationships are the result of landscape evolution processes occurring over many time scales, from years to millenia and beyond. For some locations the time taken to approach quasi-equilibrium between the regolith properties and local hydrology in the present day landscape must be less than 120,000 years, and is likely to often be less than 10,000 years. Conversely, the rate at which regolith reaches quasi-equilibrium with other controlling processes appears to vary greatly. Such spatio-temporal variability has significant implications for the results of other studies addressing similar research questions.

The analyses using the Weipa dataset have enabled a greater understanding of the relationships between regolith properties and surface measurable features in the Weipa study area. It now remains to extend the implications of these results beyond the study area.
8.4. Broader Implications.

It is important that the results of this study be compared with previous results, and that their implications for other areas and regolith properties be considered. This is done in this section. First, the results of this study are compared with those of previous studies. Second, the testing of the research question to other properties and landscapes is considered. Finally, avenues for future research methods are described.

8.4.1. Comparison with Previous Work.

This section compares the results obtained in this study with other studies addressing similar research questions.

The only study which may be directly compared to the analyses using watershed sampling is that of Pickup and Marks (2001), who used models of sediment entrainment related to flow accumulation and slope indices using radiometrics data. It is probable that their analyses will benefit from the spatial association approach used in this study because they are applied locally rather than globally.

For the multivariate analyses, there has been a great deal of work addressing the research question in other landscapes around the world, using a variety of methods and geomorphometric indices (see Sections 1.2.1 and 2.3.2). This variety makes it difficult to directly compare many of these previous results with those obtained here, and so instead generalised comparisons are made with those most similar. The $r^2$ is used for these comparisons (Table 7.4), as it is the most commonly cited assessment measure.

The results of Moore et al (1993) showed relationships with between 41% and 64% explanation ($r^2$) of regolith properties using implicitly spatial analyses with geomorphometric indices. Park et al (2001) found relationships between wetness, profile and plan curvature and soil depth variables of between 27% and 52%, with the best results for thickness of loess horizons. McKenzie and Ryan (1999) found relationships of 42%, 78% and 54% respectively for predicting soil profile depth, total phosphorus and total carbon.
Comparison of results from the above studies with those of this study (Table 7.4) shows similar $r^2$ responses for the ANN predictions, and higher for the GWR results. Moore et al. (1993) also expected that the maximum relationship would be approximately 70%, and the GWR prediction $r^2$ results in this study are clearly higher than this. These results are thus further support for the use of local, explicitly spatial analyses to address this research question. McKenzie and Ryan's (1999) phosphorus predictions also exceed the proposed 70% limit of Moore et al. (1993), however use was made of radiometrics which are expected to provide a direct measure of the regolith. Radiometrics are a potentially useful datasource that should be used in future studies (see below).

However, one problem with using the $r^2$ in this context is that it is a global statistic. Local variations in the correlation are ignored, even if a local model is assessed at the global scale. In addition, like for the error tolerance figures, the $r^2$ values for the local means in this study (Table 7.4) are higher than the results of Moore et al. (1993). This is further evidence that global indices will fail to identify a large part of the variation present in a landscape.

Much of this previous work has used spatially global analyses because temporal and fiscal limitations make it difficult to sample thousands of regolith locations as part of a research project. This means that many of these previous results have been based on samples of fewer than one hundred, and sometimes as few as thirty, locations. The results of this study indicate that there are serious limitations with analyses using spatially sparse datasets. Using the accuracy figures of the multivariate analyses, any of these previous results may be missing up to 45% of the variation in terms of absolute accuracies, and up to 22% of the variation in terms of the accuracy against the local mean of the sample. Spatial association analyses will also miss much of the variability present in a study area.

The sparsity of sample data is possibly the major problem faced by studies of this type, but must be surmounted if truly usable results are to be obtained. High density mineral exploration data is actually uncommon, and so remotely sensed indices that directly measure regolith properties may need to be used, for example radiometrics. While remotely sensed indices will normally be a proxy for the actual variable of interest, they may at least have a sufficient spatial resolution and
density with which to conduct analyses. Although radiometrics only measure the gamma ray response from 30-45 cm depth, they can provide good information about sediment mobilisation patterns (eg. Pickup and Marks, 2001). This is important when investigating regolith properties that are physically mobile.

8.4.2. Other Landscapes and Properties.

The results of this study are for one location and for five regolith properties. While there is a high degree of spatial variation present in the Weipa landscape, a more complete answer to the research question will only be obtained when more studies like this are undertaken in a variety of landscapes and for a variety of regolith properties. This section discusses the application of the methods used in this study to other landscape and regolith properties.

The Weipa landscape has an extremely low relief, which means that many processes observed in the landscape have a limited relationship with the geomorphometric indices used. This is because much of the variation is due to regional scale processes with small areas of local scale expression. There were attempts to model less local effects using the multi-scale geomorphometric variables, but the ANN analyses in which they were applied were unable to properly use them.

In areas with greater relief it is expected that there will be a greater degree of association between regolith properties and geomorphometric indices. This is because the velocity of water will be increased, and so there will be greater opportunity for chemical weathering reactions and mechanical adjustment to topographic conditions, provided climatic conditions allow it.

It must also be considered that the low relief of the Weipa landscape is common on the Australian continent, and so many analyses in other regions will suffer from topographic limitations (eg. Pickup and Marks, 2001).

Vegetation is important for the analysis of presence/absence of bauxite, as there are distinct differences in vegetation communities on and off the bauxite (Specht et al., 1977; Section 3.2.3). These differences imply there is some possibility of predicting distinctly different regolith properties in other landscapes, for example where there is a distinct mineralogical change due to drainage controls.
Vegetation change has been used for many years to define class boundaries in soil and regolith maps (Section 2.3.1.2), and the presence/absence results are further support for this process. However, the division of the landscape into soil classes remains spurious. It would be better to identify breaks in the landscape associated with known mineralogical or physical changes, and then predict them on the basis of vegetation and topographic associations. This approach is obviously for cases where the analysis of the distribution of regolith properties proves infeasible and the spatially averaged response represented by classification is of use.

Landscape history also has a major effect on the relationships between the regolith properties and surface measurable features, particularly vegetation response. Fire is extremely common in the Australian landscape, as is disturbance through anthropogenic agencies. The effect of agricultural activities needs to be considered, as many of the applications of mapping regolith properties are agricultural.

The choice of regolith property to analyse will have a significant control over any expected outcomes, as the rate at which it responds to landscape changes regulates any subsequent relationships. Those previous analyses that showed a strong relationship between regolith properties and topography tended to use indices such as soil moisture content (Bell et al., 1992; Bell et al., 1994; Lindsey et al., 1992; Thompson et al., 1997). These properties are expected to show a stronger relationship with surface measurable features as they will be closer to an equilibrium state due to their greater mobility. Other relatively mobile properties like soil carbon or A-horizon depth are also expected to adjust to changing conditions at a rate faster than the topography is changing. In such cases, disturbance effects on the vegetation response are far more important than changes in landscape morphology.

Ryan et al. (2000) assert that the causal processes controlling regolith formation may not have clear surface expression in ancient landscapes, and that the use of geomorphometric measures is limited. Ryan et al.'s assertion is unfounded because these landscapes remain affected by modern causal processes. It is only that these modern processes are the most recent of a series of superimposed
processes, and so are not expected to wholly control the regolith-surface relationships. The problem thus rests more with the spatial scale of the analysis.

The equilibrium relationships in old landscapes like Weipa are very localised, and so the global models used in similar studies miss much of the variation. The GWR results in this study show that between 12% and 22% of the dataset does have some relationship between the regolith and the surface measurable features, depending on which regolith property is assessed. This may even be improved by using other analysis methods.

8.4.3. Future Research Methods.

This study has provided an important step in the analysis of regolith properties and surface measurable features. However, there are some definite limitations with the analyses. While these do not affect the conclusions, it is useful to consider some of the methods by which these analyses could be improved. This may allow the research question to be addressed from different angles and therefore may provide further useful results.

For the spatial analyses it would be useful to assess the statistical significance of both the watershed and geometric sampling methods, for example using Monte Carlo methods. This was not necessary in this study due to the geomorphic plausibility of the results, but may be needed in other studies. For the watershed sampling the DEM could also be perturbed by adding a random component to the DEM and resampling the data (cf. Fisher, 1991, 1992). This would allow some understanding of the uncertainty introduced to those analyses by the DEM.

The explicitly spatial analyses may also benefit from using non-binary spatial weights matrices. With optimisation procedures this would allow the calculation of maximal distances of spatial association, and therefore more information about the spatial extent of quasi-equilibrium relationships could be extracted from the dataset. Alternate non-binary spatial weighting schemes could also be calculated using stream-tube type flow path weighting schemes (Costa-Cabral and Burges, 1994), most so in landscapes with sufficient relief for the assumptions of the stream-tube method to hold.
For ANNs and other implicitly spatial methods, boosting (De Fries and Chan, 2000; Friedman et al, 2000; Schwenk and Bengio, 2000) may provide a means of maximising the overall accuracy and reducing the bias to the modal response. Boosting is a method whereby hundreds or thousands of classifiers are trained, each of which gives greater weighting to those patterns poorly predicted in previous training iterations. This may enable better predictions where sample datasets are sparse and geographically local analysis methods are not feasible.

The GWR analyses would benefit from the implementation of step-wise regression, by which those independent variables that provide little extra explanation of dependent variable are excluded form the analysis. Other forms of explicitly spatial implementations of analysis tools may also provide insights, for example analysing each independent variable at its most appropriate scale within the model.

8.5. Chapter Summary.

The landscape at Weipa, even though it has low topographic expression, is one of high variability. There are numerous relationships between the landscape and the regolith, many of which cannot be explicitly dealt with by the analyses.

There are many different processes operating in the Weipa landscape. Some of the larger scale landscape features have regional controls over the spatial distribution of regolith properties, but there are many local scale hydrological responses superimposed on them. The analyses have generally identified the local scale effects, most because of the spatial scale of the indices used. Where larger scale indices, such as the distance variables, were used there were definite interaction effects from local scale processes.

While large scale landscape features are easy to identify by eye, it is difficult to quantify their relationships with regolith properties using surface measurable features. This is because topography is only a moderate predictor of subsurface conditions, particularly where the landscape is flat. The relationship with vegetation spectral response is similarly subtle, due largely to disturbance effects.

The GWR analyses also showed that 10-22% of the samples have some relationship between the regolith properties and surface measurable features.
This is based on the improvement over using the mean of the local sample as a predictor. The extent to which the regolith is related to surface measurable features is therefore between 10-22%. However, the total accuracy of these predictions is between 75-90% for the mineral variables, and 60-65% for Depth to Ironstone. The spatial association statistics also showed that the local analyses gave a much more detailed indication of the degree of modern hydrological control in the landscape. Given this, geographically local analysis methods have great utility in any further studies.

For future analyses, local, explicitly spatial analyses should therefore be used where possible. The $G_i^*$ results were far more informative than were the semivariograms, and the GWR analyses consistently outperformed the ANNs. The GWR results imply that global analyses applied to a dataset with a low sampling density may incur up to a 45% error before the analysis is even begun, simply by ignoring spatially local variations. While this may be partly addressed by rectifying the limitations of the ANN model, it remains a major consideration for any future analysis.
Chapter 9. Conclusions.

The degree to which regolith may be inferred using surface measurable features, in this case geomorphometric indices and Landsat TM spectral response, is highly spatially variable at a local scale. The main conclusion from this result is that previous analyses addressing similar research questions may have missed a large part of the regolith-landform relationships, and that any future studies must be structured to take this effect into account to avoid misleading results. Modelling with the assumption of quasi-equilibrium between causal processes and the regolith property investigated is fraught with error, and will result in significant economic costs in some cases.

The results of the spatial association analyses show that much of the regolith at Weipa is under modern hydrological control for distances up to 120 m, and some areas further than 300 m. The reduction of the area under modern hydrological control appears to be into spatially contiguous, and geomorphically plausible, regions. These regions are often the local expression of regional processes.

The multivariate analysis results are supported by the spatial association analyses. These show that, when using a geographically local sample, regolith properties are predictable to within a precision of half a standard deviation of the distribution for 65%-90% of sample locations, depending on the mobility of the property assessed. When the results are compared with the expected response (local mean) there is an improvement in 12% of test locations for the mineral properties, and 22% for Depth to Ironstone. These improvements are also in spatially contiguous locations, which implies that inferrable relationships are not randomly distributed in the landscape.

The multi-scale geomorphometric indices also provide little extra information about the regolith at Weipa. This is attributed partly to the limitations of the ANN method, but also implies the relationship with surrounding topography is limited in its spatial extent, something supported by the spatial analysis results.

The implication of these results for other studies is that the spatial scale of quasi-equilibrium in the landscape is spatially variable over short distances, often in
relation to processes operating at other scales. This is partly a consequence of
the slow rates of regolith and landscape evolution in much of Australia, due to arid
climates and low relief, but still limits the rate at which the regolith will respond to
causal topographic and vegetation changes. As such, it is expected that the cause
and effect relationship between topography, vegetation and regolith will normally
be out of phase for much of the landscape. This makes inferences about regolith
properties based on present day landform conditions more difficult. How this
spatial variation of equilibrium conditions is dealt with in future work is an important
issue.

Any study using an implicitly spatial analysis method, for example ANNs or global
regression, will therefore be missing a large part of the variability present in the
landscape. Further, this implies that most previous studies addressing similar
research questions have actually under-predicted the relationships between
regolith and surface measurable features because they have used such spatially
global analysis methods. The aggregation effects of such methods can obscure
up to 45% of the overall accuracy of any predictions. While some of this may be
addressed by correcting the models themselves, the effect of such localised
variations must be considered.

The effect of the regolith and topography being out of phase at the broader scale
is that, where mineral exploitation is the objective, a high degree of association
should not be expected. However, it might be expected that there will be localised
clusters where the regolith and landscape are in equilibrium, and so some form of
correlation analysis might be attempted. Identifying methods to locate these
clusters without intensive drilling programs is the subject of other research, but
might use remote sensing as a proxy for regolith properties.

Where an investigation is for agricultural purposes it will often be expected that
mineral variables will be more mobile than in this study, for example carbon and
nitrogen. In such cases there should be a greater degree of association with the
surface measurable features. In addition, the depth to which such minerals will be
of interest is shallow (rooting depth), and so it is expected that they will have a
stronger relationship with features at the land surface. However, where the
agricultural process needs to identify relationships between surface measurable
features and less mobile regolith properties such as clay contents, the same issues as with mineral exploitation will apply. The low topographic variation where much cropping agriculture is undertaken must also be considered.

In summary, many issues remain to be addressed before regolith properties may be reliably inferred using surface measurable features. Much of this is because the inter-relationships between surface measurable features and regolith properties are strongly scale dependent. Analysis methods and sample data appropriate to this scale dependence are needed for future work.
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Appendix 1. Digital Data.

See attached CD.
Due to file space constraints the whole appendix could not be included, but is available on the CD in the deposit copy in the ANU Library. Following are the index pages of Appendix 1. Digital Data for information.

Appendix 1. Digital Data.
Linked files are in Adobe Portable Document Format (PDF).

Variograms
SiO$_2$ shows the most modern hydrological control at the global scale, while Al$_2$O$_3$ shows a limited relationship. The other properties appear weakly related at best. A greater spread of the directional variograms around the omnidirectional indicates there is some directional relationship, although it may not be related to the watersheds.

$G_i^*$
Patterns differ between regolith properties, and the shorter spatial lags identify the same clusters as the longer lags. The different sampling methods also identify similar clusters at each spatial lag, although the wedge sampling more often shows a lower degree of clustering than the omnidirectional and watershed sampling.

Al$_2$O$_3$, Fe$_2$O$_3$, SiO$_2$, TiO$_2$, Depth to Ironstone

$G_i^*$ Comparison Surfaces
The zones where watershed sampling returns stronger $G_i^*$ clustering than omnidirectional sampling show consistent patterns in the landscape that differ for each regolith property assessed. For the mineral properties this reduces from covering most of the landscape at the 120 m sampling distance into spatially contiguous zones by 300 m. SiO$_2$ shows the most control of these properties, most often around the base of the bauxite and local low points. This pattern is inferred to be through a local topographic control over regional groundwater processes. Depth to Ironstone shows a near constant pattern in the lower parts of the landscape for all spatial lags used.

Comparisons with wedge samples are similar to the inverse of the patterns shown in the figures.

Al$_2$O$_3$, Fe$_2$O$_3$, SiO$_2$, TiO$_2$, Depth to Ironstone
Multi-scale Elevation Statistics

This multi-scale approach allows an understanding of the geomorphometric variation in the landscape as it changes with distance within the local watersheds. For example, the jumpdowns at the edge of the bauxite plateau are clearly visible, as are the extremely flat areas in the centre of the Weipa Peninsula. Their response as the spatial lag changes provides potentially useful information for analyses.

Binary ANN Analyses

Both sets of predictions show a clear separation of bauxite from non-bauxite across much of the study area, but there is a large part along the boundary where there is high confusion between the two classes.

The network structures show that not all of the hidden nodes are required, but also that this should have a limited impact on the predictions.

Interval ANN Analyses

The predictions show a clear bias to the modal value for both the conventional and multi-scale indices. This is due most to limitations of the ANN model, but also to the use of spatially global models which will suppress much of the variation present.

The network structures show a situation where not all the hidden nodes are used. As with the binary predictions, these are expected to have a limited impact on the quality of the predictions.

GWR

The GWR predictions show much greater spatial variation than the ANN predictions. This illustrates the local scale of the relationship between regolith properties and surface measurable features, as indicated by the Gi* results.

The GWR regression slopes and t-scores allow an investigation of where each surface measurable feature is related to each regolith property. These results indicate that the scale of such relationships is often very local, and differs for each surface measurable feature.

Seven cell (rotate 90° clockwise to view): Al₂O₃, Fe₂O₃, SiO₂, TiO₂, Depth to Ironstone
Ten cell (rotate 90° clockwise to view): Al₂O₃, Fe₂O₃, SiO₂, TiO₂, Depth to Ironstone

The frequency with which GWR t-scores exceed 2 shows that there are few locations where more than three surface measurable features have a strong relationship with the regolith properties, although these do tend to be clustered. Future analyses should consider this and the effects of varying scale.

Spatially Adjusted Interval ANNS

The spatially adjusted ANN predictions have a similar degree of spatial variability as the GWR predictions, and also have a greater spatial extent due to the lower degrees of freedom requirements. However, the r² values indicate that there are few locations where confidence may be had in these predictions.