14. Weathering and Regolith

The regolith consists of the zone at the Earth's surface between fresh rock and the interface with the air. In Australia, regolith profiles can be up to several hundred metres thick as a result of a very long history of weathering on ancient landscapes that may have been exposed for hundreds of millions of years (Pillans, 2008). Since unweathered and slightly weathered rocky exposures cover less than 15 per cent of the 7.7 million km² of the Australian landmass, the nature of the regolith in areas of cover is of major importance.

Regolith materials range from thin soils over slightly weathered bedrock to situations where weathering has reached more than 100 m beneath the surface. A range of important geological and biochemical cycles operate with the regolith zone: these include the passage of groundwater and nutrient cycles involving carbon, nitrogen, oxygen, phosphorus and sulphur. Bioturbation can mix materials in the near-surface, and geochemical processes can also transport traces of deep-seated mineral systems into the surface zone.

In the upper part of the regolith—the pedolith—the original bedrock structure has been destroyed by the weathering of the original minerals and the redistribution of secondary materials such as clays and oxides. Often the pedolith develops in situ but can also constitute transported materials. In the saprolith beneath the pedolith, the bedrock fabric is weathered but the original bedrock structures can be still recognised. Within the pedolith and saprolith there can also be secondary induration with, e.g. cementing by silica, iron, aluminium and carbonate. Such layers, such as calcrete, can play an important role in shaping the landscape and the properties of the regolith across Australia.

Intensely weathered regolith is likely to arise from the interaction of a number of factors:
- landscapes where the rate of erosion is low compared with rates of accumulation and with a long time span for weathering;
- bedrock that contains highly weatherable materials; and
- environmental conditions that promote rapid weathering through the action of water, temperature and biological action.

Provided there is sufficient time to weather the bedrock, and denudation rates are low, high weathering rates are not required to produce deep weathering. Thus ancient landscapes with low relief and low slope angles can be highly weathered, and can also be affected by more recent processes.

14.1 Weathering Intensity Index

The extent to which the regolith is weathered is linked to the factors that lead to the formation of soils, including the nature of the substrate, topography, climate, biological activity and time. As the weathering intensity increases, there are progressive changes in the physical and geochemical characteristics of regolith materials. With weak weathering, there is little change from the parent materials. But with intense weathering and leaching of the regolith, almost all traits of the original unweathered rock are overprinted or completely lost.

Weathering intensity has a strong influence on the extent to which the mineralogy of the original bedrock is converted into secondary minerals such as clays and oxides. With similar parent materials and climatic conditions, increasing weathering intensity leads to a change in the nature and proportions of the secondary minerals, so that more stable clays are produced and the regolith has more distinct zones.

With increased weathering, soluble elements such as potassium, sodium and calcium are lost into solution, while the more stable oxides and minerals such as quartz and zircon are retained in the regolith. This enables a measure of weathering intensity to be derived from geochemical indices based on the relative proportions of the stable elements compared with their more mobile counterparts. Measurements need to be taken from sample points through a weathering profile, and cannot be easily extrapolated across the landscape from the specific sample points.

With calibration at a broad range of sample points with different classes of regolith, a weathering intensity index can be developed exploiting radiometric information and terrain attributes from a digital elevation model (Wilford, 2012). The field sites were assessed using a six-level classification scheme. Level 1 describes largely unweathered landscapes with a high proportion of fresh bedrock exposed at the surface. Level 6 is assigned to areas where bedrock is completely weathered to secondary materials such as clays and oxides. The intermediate levels are based on the level of preservation of bedrock structures and fabrics, the relative proportion of clay and the degree of mottling and iron staining.
As discussed in Chapter 3, airborne gamma-ray spectroscopy provides a measure of the flux emitted from the major radioelements in soils and bedrock to a depth of about 40 cm. For a 100 m flying height, about 80 per cent of the recorded gamma rays will originate from about 600 m radius around the flight position. Hence estimates of element concentration and total flux (dose) provide averages over a significant footprint. The full continental coverage of radiometric results across Australia means that these results can be exploited to provide proxies for weathering intensity in conjunction with information on relief.

The concentration of potassium (K) generally decreases with increase in weathering because its compounds are soluble, and given sufficient time leach from the weathering profile. In contrast, thorium (Th) is less soluble, and by association with clays, oxides and weathering resistant minerals is retained in preference to the more soluble K. Very highly weathered materials such as iron-rich duricrust and bauxitic soils typically exhibit high-Th responses.

Some rock types contain few or no gamma-emitting radioactive elements, e.g. highly siliceous sandstones or ultramafic rock. Where the gamma-ray dose is very low, it is necessary to exploit the relief derived from digital elevation models on the assumption that landscapes with high relief are likely to maintain thin soil and slightly weathered bedrock.

Where the total dose is high (about 90 per cent of the continent) a broader range of environmental variables are brought into consideration for a weathering intensity model, exploiting, in order of importance, K concentration, relief, the Th/K ratio and the total dose.

*Figure 14.1*: Weathering intensity index with superposition of geological provinces.
These two classes of model for relating weathering intensity to aspects of the surface and sub-surface have been trained by comparison with weathering results from around 300 sites in southeastern Australia to develop regression models for the weathering intensity index (Wilford, 2012). For intermediate gamma-ray dose, a linear combination of the two models is employed to remove any abrupt boundary effects on the final grid. This composite model has then been further refined using machine learning techniques.

By this means, the combination of the radiometric results from Chapter 3 and digital elevation data for the whole continent can be brought together to provide a continent-wide measure of a relative weathering intensity index (Figure 14.1). As might be expected, this index shows a strong correlation with geological province boundaries, but also notable variation within provinces. Strong weathering is commonly associated with major areas of sedimentary basins, but there are many instances of strong weathering without sedimentary cover, e.g. in the North Australian Craton and the southeastern Yilgarn Craton.

When examined in detail, the weathering index has a good correlation with prior regolith-landform maps, with sharp boundaries in index behaviour often corresponding to erosional scarps (Wilford, 2012). There is also reasonable correlation with geochemical indices for weathering based on ratios of mobile and immobile elements.

Weathering intensity reflects changes in the geochemical, physical and hydrological aspects of the regolith as the bedrock breakdown under weathering and leaching. Understanding the nature of weathering through the weathering intensity index can help with understanding the pattern of pathfinder signals used in geochemical exploration for mineral signatures, and potentially mapping of paleo-landscape features.

Many upland areas of Australia show the impact of recent erosional processes superimposed on much older features as a result of tectonic processes, e.g. tilt and regional scale warping (Sandiford, 2007), changes in the base level of basins and climate. The weathering intensity index allows assessment of the interplay of such changes across a wide range of spatial scales.

**14.2 Regolith Thickness**

In addition to the radiometric estimates of the K, Th and U concentrations in the near-surface, a number of other geophysical fields contain a signature from shallow contrasts. Thus the Bouguer gravity anomaly (Figure 5.7) is sensitive to the density contrast between the lower density regolith and the bedrock. Gradients of the gravity field can also highlight contrasts in density. The local magnetic anomaly (Figure 4.9) also provides information on bedrock structure. Estimates of the depth to magnetic source based on the gradient properties of the magnetic anomalies help to discriminate between magnetic and non-magnetic components of the regolith and bedrock.

Wilford et al. (2016) have used the full range of such geophysical and geological constraints in conjunction with multi-scale attributes from digital topography to develop a model for regolith thickness across the whole continent. They use a database of depth to bedrock derived from drillhole data as the training dataset.

The drillhole information has been extracted from the National Groundwater Information System database. There is a broad spread of sites across the continent, but uneven coverage and notable gaps, e.g. in arid areas. Automated procedures were used to extract an estimate of the depth to fresh bedrock, from the descriptions of the logging parameters. This was a complex procedure because there had been no standard protocol for recording the drillhole information. The datasets were winnowed to remove records that were inconsistent with neighbouring drillhole estimates and landscape setting. The weathering intensity index was also used to define areas with relatively fresh bedrock.

This procedure yielded around 128,000 sites across the continent for which there was an estimate of the depth to the base of the regolith. The statistical distribution of these depth estimates is strongly skewed with a very long tail. to limit the impact of possible spurious values, Wilford et al. (2016) restricted the maximum depth to 200 m. This means that that regolith thickness will be underestimated in regions of thick cover such as depositional basins.

The suite of drillhole estimates was then used to develop a multivariate model for regolith thickness that could be used across the whole continent. The model fitting was carried out using the logarithm of the drillhole depths, which ensures that regolith thickness estimates remain positive.
The fitting procedure employing a large suite of continental-scale datasets is based on a complex decision tree approach, employing multiple linear regression models at the terminal nodes of the tree. Uncertainty estimates based on the difference between the 5th and 95th percentiles were generated using a bootstrap procedure and stabilised after 100 iterations.

The resulting model (Figure 14.2) has reasonable predictive power in matching the drillhole information, and extends coverage to the whole continent in a consistent framework. There is a tendency for some bias towards shallower depth for the base of the regolith, arising from the processes that were used to reduce the variability of the drillhole dataset. For example, where regolith thickness is greater than 200 m, bedrock may well not be reached in sedimentary basins, particularly those with unconsolidated sediments of Cenozoic origin.

The most useful covariates for the regolith prediction include the nature of the local geo-logy, the distance from outcrop, the depth to magnetic source, the characteristics of the terrain, radiometrics and the weathering intensity index, and soil clay characteristics. Many of the factors considered depend strongly on surface and near-surface character and processes, so that the principal controls at depth come from the geophysical information.

The uncertainty in the model estimates increases steadily with regolith thickness, but the relative uncertainty remains roughly constant and of the order of the thickness estimate itself. Thus the model provides a useful framework for assessing regolith thickness that can now be supplemented by area specific information.

Figure 14.2: Estimate for the thickness of the regolith based on geophysical information, with geological provinces superimposed.