The regolith – a view from within

by Tony Eggleton

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I became a regolither thanks to my colleague, co-author and friend Graham Taylor. After much insistence, round about 1970, he managed to persuade me to *look* at the world around me rather than grind it up and put it in an X-ray machine. He was abetted in this at one point by Keith Crook, who had been teaching the subject under the label "paleopedology" for most of the years I had been buried in hard rocks. Eventually I became sufficiently curious to sit in on that course. By 1973 I had concluded that this weathered stuff had some scientific potential, so in order to really get inside the regolith I set out to learn electron microscopy, and also, with the help of Geoff Hope, to learn about landscape. For even at that young age I could see the portents that from some day, still far off I hope, I would spend the rest of eternity looking at regolith from within.

I am going to offer three very different perspectives on the view from within:

- 1) From within the crystals that comprise the regolith how I see the science
- 2) As a regolith geologist who has taught for 30 years teaching in the new millennium
- 3) As one who had a close view from within LEME wither LEME2?

I am a mineralogist, and there is quite a good understanding of the minerals of the regolith, of their physical and chemical properties. We have *some* idea of how they interact with each other and perhaps rather less about how they interact with the surrounding regolith solutions - but more of that later. There is a part of regolith about which we had very little idea 20 years ago, and that part was the actively changing interface between a fresh mineral and its weathered offspring. We didn't know what existed in between, and certainly not any of its properties. It was in order to try to find out about the way minerals weathered that I embarked on a program of transmission electron microscope research, and on the way discovered the important interface material.

While many of the projects were done by a team of graduate students - Jill Banfield, Wang Qi-Ming, David Tilley, Mehrooz Aspandiar and Ma Chi:- it all actually started in Giralang here in the ACT because Graham asked me if I had noticed an apple-green clay in a road cut there. I had, and I had put some in the car for my then young daughters to play with. But it was I who ended up playing with it, and the ramifications continue today. The clay was nontronite, formed from the weathering of the Fepyroxene hedenbergite in a skarn. To summarize in a single image about 10 years of research, here is a picture of another pyroxene, enstatite, weathering to another clay mineral, talc. The processes are the same for both except the oxidation of iron rather complicates the hedenbergite process.



Figure 1: TEM image of enstatite altering to talc, viewed in projection down the pyroxene z-axis

I will return later to one of the clues that led to this result, but for now I want to concentrate on the interface between the parent enstatite and the product talc.

You can see from Figure 1 that there is a band of complex structure made up of double chains and triple chains between the fresh enstatite (on the right and largely out of picture, though there are two strips of enstatite in the image - single chain) and the product talc. (For more information see Eggleton, R. A. and Boland, J. N. (1982) The weathering of enstatite to talc through a series of transitional phases: Clays and Clay Minerals 28, 173-178.) Parallel to the pyroxene chains there are molecular sized tunnels along which fluids and ions can diffuse. In these tunnels large cations (which

don't normally belong in enstatite or talc) can be trapped - things like NH^{4^+} , K^+ , Ca^{++} and so on. You won't be able to see this stuff by X-ray diffraction or scanning electron microscopy. But its presence surely changes the reactive character of the weathering mineral.

As a second example, and one of a more common mineral than enstatite, look at the interface between K-feldspar and its weathering product smectite.



Figure 2: K-feldspar altering to smectite via an iron-rich labile amorphous phase (photo Jill Banfield)

Here is an unexpectedly Fe-rich amorphous interface – the Fe:Si ratio is about 1:1. There is no iron in the feldspar, so the amorphous material must be soaking it up from regolith solutions. As the smectite crystallizes from it, the iron must be lost, since the smectite is iron poor. (For more detail see Banfield, J.F. and Eggleton, R.A. (1990) Clays and Clay Minerals 38, 77-89). But all over the surfaces of weathering feldspars there is such a reactive adsorbing metastable phase, and its influence on the behaviour of regolith solutions and process is most profound.

Another common reaction - olivine to clay, shows (Figure 3) minute channels filled with clay, again, an unexpected labile and adsorbing phase that exists at the weathering face of the olivine. (For more information see Eggleton, R. A. (1984) The formation of iddingsite rims on olivine: a TEM study: Clays and Clay Minerals, 32 1-11)



Figure 3: Dissolution channels in weathering olivine with smectite infills.

In these three examples you see there are labile, or metastable phases within the altering primary mineral.

There is another, much more common transient regolith mineral - ferrihydrite. This mineral forms wherever ferruginous ground-waters oxidize or undergo pH change toward neutral or where certain bacteria thrive or when ferruginous water simply evaporates. It stays around for a year or two and then either redissolves or recrystallizes into goethite or hematite. As you can see from the TEM image, Figure 4, the crystals of ferrihydrite are very very small, and their surface area is correspondingly very large.



Figure 5: Ferrihydrite crystals (Eggleton, R.A. and Fitzpatrick, R. W. (1988) New data and a revised structure model for ferrihydrite. Clays and Clay Minerals 36, 111-124.)

Ferrihydrite has phenomenal adsorption ability, and can suck up many cations and anions, such as Cu, Au, phosphate or arsenate. When it redissolves, so do its adsorbed elements; when it recrystallizes, many of those elements become held in the stable goethite or hematite. Depending on the local regolith-water chemistry, ferrihydrite can be a sink or a source, it can hold cations or anions. I think that if you want to understand laterite, or pathfinder element distribution, or regolith biota, understanding ferrihydrite is probably quite useful.

A common regolith mineral about which we know little because of its small grain size is anatase - TiO_2 . Figure 6 shows one of David Tilley's SEM photographs, anatase associated with smectite, both the product of weathering titanite (sphene). Though the crystals are much bigger than those of ferrihydrite, they are still only about one micron, and their trace element chemistry is little known. Here is a ubiquitous regolith mineral; it forms early in weathering then survives through to the end and beyond. Probably it carries historical information in its make-up, as trace elements, as crystallographic character, or in its morphology...Feldspars tell us about igneous rocks; what might anatase tell us about regolith?



Figure 6: SEM image of anatase crystals (euhedral, pillow-shaped), about one micron in size with "corn-flake" smectite, alteration product of titanite. Photo D.B.Tilley.

Part 2 - Teaching

I understand that children who have been raised for their first 3 or 4 years without any conversation, never acquire good speech. Apparently we need to learn language from other people. In fact we don't seem to have much in the way of instinctive skills – few of us can even swim without lessons, though ducklings can. I will hazard the guess that in our early years we learn to learn by the example of others.

Until the invention of the printing press, learning was restricted to a very few; no more than the available teachers could teach, using a very limited supply of hand-written texts – texts too precious to let into the hands of a student. The spectacular increase in knowledge from Gutenberg to 1970 can be attributed very largely to access to information via books.

But putting knowledge in a book doesn't ensure that it can be learned. At the age of 40 I tried skiing for the first time. I wasn't brave enough to try down-hill, so I strapped on a pair of X-country skis, opened the book and started down the slope. To stop, I read, put your skis in the position of a V. Good, clear advice – if you are skiing backwards. After surgery to sew my legs back together, I realized that the author had been looking at the matter from the wrong perspective. How much more use would that book be with the help of a person as a teacher?

About 1970, books were supplemented by easily accessible movies in the form of video tapes. Here there seemed was another revolution in teaching. Eliminate the teacher, put it all on video. I remember reading a critique of David Attenborough's

classic series "Life on Earth" In essence it said, "great images, but what do you remember after it is over?" That comment revealed a lot about the critic's understanding of learning. Video is a great medium for showing new concepts – it preconditions you for learning. I used it regularly to teach mineral optics. I can draw sketches and write words till I am chalk white in the face, but simply running a video shows the phenomenon. Once you have a visual image of what I am talking about, I can explain its theory quite easily (I think). First books, then videos, widened the net of who could learn. Students learned as always, from a mentor, but the detailed information, the opportunity for the repetition that leads to recall came from those media.

This Century has started with PCs, Macs and the internet. Obviously there is a progression here in opportunity to learn, Easier access to knowledge through books, then video, then the internet. Faster information retrieval: books from their index, and though videos never really achieved this we now have spectacular search engines.

But there is an important aspect to information that we mustn't forget – it is the authority of the informer. I often think, as I switch from JJJ to ABC FM, "What makes a piece of music a classic?" I think the answer lies in the authority behind its presentation. First the composer has to write it. Then a conductor, one of the most knowledgeable people in this field, has to decide to try it out. Next there are 70 professional musicians who have to be convinced it is worth their while learning it, and that playing it in public won't irretrievably destroy their credibility. Finally some hardnosed business has to be willing to risk capital to produce a record. When you finally hear it, you know it has passed a series of tests, and if you don't like it there is probably something wrong with your musical taste, not with the music.

This kind of quality control also works with academic books –a bookseller has to be confident that the author knows the subject, then assessors have to okay the outline, and an editor exercises some control on the output.

The internet browser has no such protection. Anyone can put up a website and it can be full of lies, deceit, bias or whimsy. And even sites that are provided as resources in good faith may be wrong. I copied and distributed some stuff about the structure of steel to a second-year class once that happened to have an experienced structural engineer in it. He told me the facts were all wrong!

I heard a frightening thing about the internet on Wednesday. Suppose you are a young parent looking for information about the safety and desirability of having your child

vaccinated. Rather than go to the Doctor, you go to the internet and type " infant vaccination" into Google. Many of the first ten sites it delivers are sites devoted to dissuading you from choosing vaccination. They are pseudo-science, using anecdotal stories as evidence. Evidently the web is just as wonderful a way to disseminate lies as it is to share truth.

But let's assume that teaching regolith is being done by people who know their subject and are smart enough to either build their own web-site or select among those available for accuracy. How well can the internet replace a person in leading a student along the path of learning?

Whether that path is directed reading, open lecturing, field demonstration or web-site sequencing doesn't matter. What does matter is that the students' minds are opened, their curiosity aroused and their presumptions challenged. And their questions replied to, including the questions that have never occurred to the teacher.

In 1972, in my sixth year of teaching first year mineralogy, a student asked why pyroxene cleaved along the $\{110\}$ planes when the structure model I drew made $\{100\}$ cleavage so much more likely.



Figure 7: Diagram of the pyroxene structure viewed down the z-axis (as in Figure 1). Tetrahedral chains are shown as triangles, larger circles are Ca, smaller circles MgFe. {110} cleavage is shown passing between the chains as explained in 1970

I had never asked this question, nor ever heard the point raised. Had I been writing a book on mineralogy, or constructing a web-site, I might have explained why {110}; I wouldn't have explained why not {100}. Answering that question was integral in leading me to the career in electron microscopy that I have outlined earlier in this talk. (You can see the "weak", electron empty, regions as white dots in Figure 1 through which the cleavage passes)



Figure 8. Explanation of pyroxene {110} cleavage 2002 version. The silica tetrahedra-Mg octahedra unit is strong, and the cleavage does not split it. Description of pyroxenes, amphiboles and micas in terms of such TOT units is now standard.

When a computer can answer such unexpected questions that require a new perspective, use it as a teacher. Until then, use a person.

There's probably a lot of advice I would give to a young teacher, but it has all been given before. I will restrict myself to three points. Two come from one of the few, and famous, women teachers, *Hypatia*, Head of the University of Alexandria, around 400 AD.

She said:

"Reserve your right to think, for even to think wrongly is better than not to think at all."

So do not teach didactically; do not preach. Your students must know that you want them to think for themselves. My least favourite question, of the many I have been asked in class in response to a lab exercise is: "What do they want". My answer is - who cares what THEY want! What do YOU want to get out of this exercise?

She also said: "To teach superstitions as truth is a most terrible thing".

In our science a superstition is anything that you believe without knowing why. How many of us "know" that laterite is Tertiary (or older?). This is the received wisdom, but it is a superstition based on Jutson and Walther's views of 100 years ago. Last month Juan-Pablo Bernal gave us, in a LEME seminar, what I think is the first radiometric date on a lateritic pisolith, one from Kakadu in the Northern territory.



Figure 9: Pisolith from Kakadu, NT, showing U-series determined ages - courtesy Juan-Pablo Bernal

It was zoned from about 300,000 years in its core to 100,000 on the rim. Not very close to Tertiary. Now by all means discuss the concept of a Tertiary age, present what evidence there is, challenge that evidence. That is teaching. But to teach superstition as truth is indeed a terrible thing.

The third piece of advice comes from me, and applies to both teaching and research: Do not fall in love with your own ideas. Question them as soon as you think them. Test them - don't look for evidence they are right; look for evidence they are wrong! Because if you don't test your ideas thoroughly you can be sure they will one day come and bite you.

3. The future: Whither LEME 2?

Here I stand, bridging LEME1 and LEME2, in a perfect position to pontificate. There are 25 years of regolith experience behind me, and I am now silly enough to talk about what might, or at least should, in my view, happen in the next few years.

First, let me suggest, particularly to those here who are not involved in CRC LEME, that LEME is a *national resource*. There are people, apparatus and skills which are and could and should be shared in the wider research community. What I will say about my ideas for the future of LEME are equally applicable to anyone doing regolith research.

Recently I was re-reading "Dune", and there I came across this:...highly organized research is guaranteed to produce nothing new. (Frank Herbert 1965. Dune. New English Library.) A very sobering thought when you are part of a highly organized research group. But what does it mean?

It has been said that scientific advance is like building a road. It is not. Though you might know where you are starting from, you don't know where you are going until, quite by accident, you arrive.

Look at explorers like Columbus going to India but finding America, or Sturt, looking for an inland sea, led by a dream, by a conviction - and finding something quite different. Or Marie Curie, puzzled by excessive radiation in pitchblende and discovering radium, or Newton collecting apples and being hit by gravity. Careful, organized experimental work, such as allowed Charles Butt and Mel Lintern to establish a Ca-Au relationship does allow the pattern to emerge, but you still have to have the time and insight to see it, and of course you can't even *plan* to go to a place you have never heard of.

Nor can you discover things because a director tells you to. Just consider a few important discoveries, and see if you can find the hand of the research organizer directing any of them. Did someone tell Galvani to discover electricity? Darwin's

"director" would have been the Captain of the Beagle, I suppose. William Smith was directed by whoever wanted a canal dug, and he certainly wasn't instructed to discover stratigraphy.

The point I want to make is that it is impossible to organize creativity externally. The closest a science manager can come to this is to recognize ability and provide a nutritious environment. That is how I see a CRC: a group of able scientists working, sometimes together, sometimes alone, with a common goal – to understand their bit of the universe while sharing knowledge, sharing understanding, but being trusted to be doing this science even when it appears they are asleep with their feet on the desk.

But this is only half the story. Sadly, but realistically, not every scientist is a genius, and some of us work away all our lives without making that discovery that changes the world view. After the explorer, after the lucky break, then science does become a bit more like the engineer building a road. Now there is a goal, and the rest of us come along, and fill in the gaps, extend the network, lay a mile of bitumen here or put in a drain there. And here there is a crucial role for the science manager, for the research leader and a highly organized research group. So maybe this group won't discover anything new, but they might be able to turn potential into product.

Now let me look into the Palantir of Regolith - where are we headed?

I find it a bit interesting, when I consider one of the definitions of regolith, *the intersection of the lithosphere, atmosphere, hydrosphere and biosphere*, how little more than one quarter of it has been approached by LEME.

The lithosphere got a lot of attention in LEME. We mapped it, we chemically and mineralogically analysed lots of bits of it. We dated some of it. We drilled and sampled and scrutinized little bags of it.

The hydrosphere. Patrice and his group, and Leah at UC got us going in this part, and there is some watery activity in Adelaide I believe. Riding on the salt's back, this conference has shown that LEME is making a real effort to investigate the regolith hydrosphere

The atmosphere. We contributed a lot of CO_2 to it, but that's about all.

The biosphere. If you think about it, it is curious that this topic hasn't been at the forefront of regolith research for a hundred years. All life on the land lives in the

regolith. So of course regolith scientists ignore it. Soil scientists don't, but the rest do. Of course I know we have made a beginning. Lea Hill made geobotany her PhD topic, and Frank Reith is looking at microbiota. Katie Dowell found bacteria in opal, and Honours students at UC working at Broken Hill routinely describe the interrelationships between plant communities and regolith, and use plants in geochemical studies such as we heard in the talks by Anthony Senior, Karen Earl and Matilda Thomas. But we need to go further, to appoint bright young scientists and say: "You have a free hand to think about regolith biota. Don't just improve or apply the relationships we know. See if you can make it work for us". Are there trees that can pump nutrients from bedrock to replenish depauperate soils? Is there a butterfly that concentrates copper like oysters do? It is a gamble, it is casting your bread upon the water, it is jumping off a cliff with an umbrella and hoping the wind will blow in the right direction. But you won't find a new concept by writing quarterly reports of progress, achieving prescribed goals, or passing milestones. These belong in the developmental phase, after the discovery is made.

Now what is it about the regolith that really matters to us? I scratched my head as I wrote that question, feeling I had the answer but that it was too simple. But I couldn't get past that simple answer – what matters is how the regolith behaves - process, as Graham said in his opening Plenary Lecture.

Is it going to shift suddenly and bring down our houses? Is it going to dry out, kill the vegetation and blow away? Is it going to leak radio-active elements from Ranger into Kakadu? Is it going to release copious quantities of salt into the near-surface ground water? Is it going to conduct gold tracers to our exploration sampling site? Is it going to breed microbes that impact on all or any of the above?

Then I started to think of the regolith as a system. Systems only work if one part of the system is in communication with the others. The Mac I am using has an operating system that relies on constant electronic communication among all its bits, and it crashes when that communication fails. Your family is another system that stops functioning when it stops communicating. And so does the regolith.

For a system to communicate there needs to be a medium of communication. Electrons for my Mac. Shouts and whispers for the family. And for the regolith the medium is water. Water operates on the surfaces of the regolith minerals. Water supports and transports clays, bacteria, molecules, chelating compounds and ions. There are two essentials in the changing evolving regolith - time and water. It is those

other three spheres - *atmosphere, hydrosphere and biosphere* that carry the water to the lithosphere. This is a direction for the future. I feel that if regolith research doesn't move with energy into the field of water-air-biota-regolith interaction, the science will pass us by.

LEME2 has the mix of people to attack these unknowns. You know who they are; some have spoken at this conference. But what happens at the end of LEME? Who will carry on regolith science? Presumably only those who have convinced the population, the politicians, the Directors of CSIRO, the Vice-chancellors, the Survey Chiefs that regolith science is important science. Did you know that one of Australia's pre-eminent regolith research labs will close on December 31? It is the Section at CSIRO Land and Water in Adelaide that was formerly under the direction of Keith Norrish and from whence came copious fundamental publications about Australian soil mineralogy. But they couldn't convince their paymasters that they mattered, and now they are history. And we know what UC thinks of the only regolith-centric teaching Department in Australia. You have another five years to secure the future of this vital earth science, and if you think it will survive simply because it should, think again. Perhaps the best work any of you could do in LEME 2 would be to get regolith into the public consciousness. In this time of salinity and drought, just possibly water will be the aspect that will turn the tide. Even if you feel you are not good at selling, recognize its importance and cooperate. For a CRC is a cooperative research centre, and if you don't all agree on what's important and then act in concert, there is no future.

This working together bit is hard. It also depends, as does the operation of the Mac, the family and the regolith, on the medium of communication. So what is the medium of communication for LEME? Is it perhaps e-mail? Is it conferences like this? Is it field trips together? Is it workshopping ideas in small groups? All of these might be useful, but they are not the medium of communication. The medium is "Trust". For as David Boon said: "The key is knowing who your best players are and then putting a little trust in them".