Geological Society of South Africa

geobulletin

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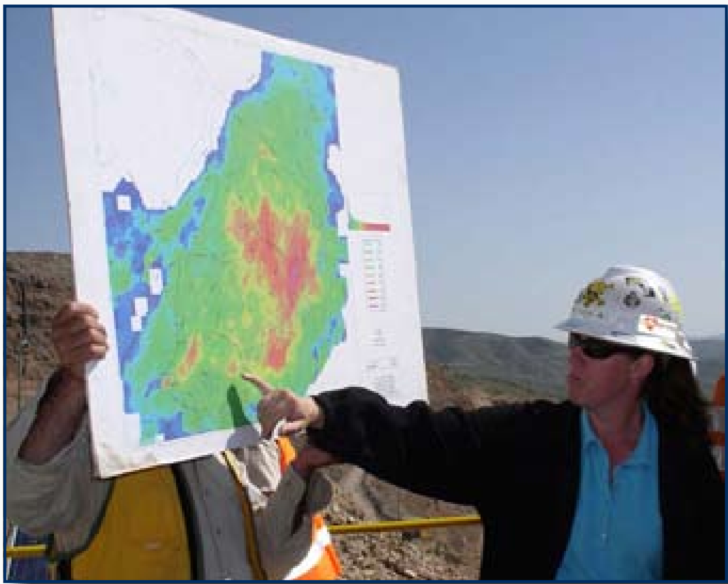

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Maggie Newman's: Annotated version of "Aftermath of the End-Permian in mass extinction in the Karoo Basin"

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Maggie Newman's depiction of "Aftermath of the End-Permian in mass extinction in the Karoo Basin"

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from the editor's desk

Chris Hatton

The jackal-proof fence is one of the challenges of Karoo geology. Ideally one has the permission of the farmer so the only challenges are those directly associated with the actual negotiation of the fence. All too often however the fence marks the boundary of a farm for which one has not yet obtained permission. Then the challenge is convincing a newly-acquainted farmer that you are only following an outcrop and that your bakkie is not being used for the unlawful acquisition of sheep. A further challenge has now arisen; convincing the farmer that your interests are purely geological and that you are not part of the impending army intent on extracting the gas buried deep below his precious farm. In contrast to the USA, where landowners receive something for the gas below them, current South African legislation gives the farmer little incentive to allow, let alone encourage, exploration on his land. Many Karoo farmers regard themselves as custodians, rather than owners of the land, and are genuinely concerned about the damage indiscriminate exploitation may inflict.

Like the resident farmers, the resident jackals are often the best protector of their environment. Like the farmer, the jackal is very wary of strangers. Irresponsible adolescents are not tolerated. Given that jackals will include the occasional sheep in their diet, not all Karoo farmers treat the resident jackal as their ally, resorting instead to shooting them. Of all the mysteries of farmer-jackal interaction, the only clear conclusion that has emerged is that the real troubles start when the shooting starts. Freed from the restraining influence of their elders, marauding adolescent jackals rampage across the Karoo, recklessly preying on whatever is available and taking a heavier toll on the sheep than the resident jackals ever did. The jackal-proof fence and the gun have not rid the Karoo of the jackal. Even in a full-scale war against nature the jackals would probably be among the few survivors. Clearly it is time for a truce, and to indulge the natural South African instinct to appreciate nature, beginning of course, with the rocks.

Whether or not shale gas is ever extracted from the Karoo, exploration drilling will inevitably lead to ever more detailed understanding of Karoo stratigraphy. Currently these strata can be reasonably resolved at a million year scale, but as ever more sophisticated technology is brought to bear, there is realistic possibility that one day some Karoo farmers will be able to display dinosaur bones with a resolution comparable to that of the belemnite guard illustrated on p. 39 of this issue.

The figure displaying the temperature during three winters and four winters in the life of a belemnite is in Jan Kramer's review of the age of earth, originally prepared as a tribute to Hugh Allsopp. Tebogo Makhubela contributed a condensed version of this article to Quest, a popular science magazine from the Academy of South African Science. Because Jan's original article never appeared in print, this unusually long, by Geobulletin standards, article is preserved for posterity in this issue.

Another unusually long contribution is Ian McLachlan's obituary on pp. 56-62. Here the reason for the extension is the intertwining of Ian's life with the early days of petroleum exploration in this issue. Separating the two became difficult, and with the revival of hydrocarbon exploration, this time for gas (see pp. 33-34), a combination of history and obituary seemed appropriate. In the other obituary Roelof van de Merwe is especially remembered because he devoted his later life to birds. Given the endless variety and lessons to be learnt from close observation of these feathered dinosaurs, such devotion marks a worthwhile life.

The 35th IGC is close now, and two IGC field trips are featured. The first is an excursion through Zambia, taking in some of the rich history of that country along the way. The second trip is to Kilimanjaro, also covered by our peripatetic Geotraveller. In addition though, the ascent to the peak will be preceded by a descent to the deepest point in Africa allowing the unique opportunity to complete a vertical traverse exceeding the height of Everest. Having the IGC in Africa is a unique, once-in-a-lifetime experience, justifying the not inconsiderable expense of participation in this event. At the opposite end of the spectrum is the shoestring experience that is the IMSG (pp. 13-17). For this, participants gathered in an unventilated shed in the high summer heat of the West Coast, but for the quality of the contributions and at the price, no complaints were recorded. A point that Steve Prevec noted is that the South African community has increasing access to indigenous instrumentation, and the results of this are feeding into the science. The news from UCT of the relaunch of the Radiogenic Isotope Facility is therefore especially encouraging. No doubt South Africa is currently going through dire straits, but Nenegate has closed and we still have a useable currency. Things can only get better.

executive managers corner

Craig Smith

The 35th International Geological Congress is definitely on! By the time this issue of Geobulletin goes to print, the February 29 deadline for abstracts will be closed. But I can report that by end January, the technical committee had fielded over 3000 abstracts from varied parts of the globe. Get onto the website at http://www.35igc.org/ and check regularly; updates will occur frequently from here on.

The main event of the first quarter of the year was Mining Indaba in Cape Town, and as would be expected, attendance by both delegates and exhibitors was down considerably this year due to the major slow-down in the resource sector. While no official figures have been released as of the time of writing, I would not be surprised if attendance was off by as much as thirty per cent. In my opinion, this made the meeting a bit less frenzied than in previous years. The interaction with people was less hectic and a bit higher quality than in prior years. Deal making was still happening, and I have the impression that the 'fringe crowd' (those who hang around the hotels looking for contracts without actually attending) thought it was a relatively successful event. Good projects are still being funded and work is still being done.

Without question, the main theme pervading the event was the very severe downturn in the resource industry – in both commodity demand and prices. It will turn – but it will not turn quickly, and 2016 at least is going to be a painful year for countries such as South Africa that are highly dependent on resource exports. Why has it happened? Everyone likes to blame the slowdown in Chinese growth, and specifically the shift in the Chinese economy from large scale infrastructure investment to consumer led consumptive growth. Both types of growth reflect as high GDP growth – but the resource industry is much more dependent on infrastructure investment. The Chinese slowdown is most certainly not the only cause, however. Other factors include over-investment in marginal projects during the good times. Many (most!?) of our mining leaders as well as investors are seriously guilty of viewing the world through rose tinted spectacles and investing in marginal projects sustainable only in a protracted boom at historically high metal prices. In some countries (such as South Africa) regulatory uncertainty is seriously unattractive for any inward investment. In other countries (such as South Africa!) labour cost and unreliability is also a serious impediment to investment. As highlighted in various ways in several presentations I saw, a long term three way linkage between industry, government and labour has to happen. If it does not, expect to fall behind the countries that get it right. South Africans live in the most resource-rich country in the world – but that no longer matters in an overproducing world. The winners will be those countries that get this relationship right, and these are not necessarily those with the richest resource base.

Another theme was a focus on innovation, because the future is very possibly not predictable based on the past. Innovation means a lot more than in the technical space, and includes processes and strategy. Are there new ways of funding projects? Canada is a leader in crowd-funding and it could be a developing trend in the resource industry, from exploration through to mining. Are there new ways of operating mines, using technology solutions? It is a given that the labour force of the future is going to look nothing like the relatively unskilled labour now used. Better entrepreneurial skills are clearly needed; do our universities produce the right calibre of people to fill that role? When have we seen an Honours level graduate who has been exposed to financial strategy? I would love to see some debate between industry and academia about the type of graduates coming out! We will publish letters to the editor in coming issues if you would like to engage on the topic.

As could be predicted from last year's meeting, social contract issues – the relationship between miners and the communities in which they operate - was a central and repeated theme. It does not matter how good the ore body is or how many investors are backing you or how good your technical expertise is, if the social contract is not 'solid', there is disaster ahead. This is not just an issue at the mining end of the value chain; it can apply at greenfields exploration. Very possibly we need sociologists who have a deep understanding of geology and mining engineering. Or geologists with sociology courses in the curriculum. Dare I suggest one less course in igneous petrology and adding one in the sociology of mining communities……..? Effective communication to all stakeholders is also an issue. Maybe an additional requirement for an honours degree – in addition to a technical thesis – would be to prepare a two paragraph summary of the work that could be published in a newspaper and be understandable to the non-geological wider public (particularly politicians).

Most of us hold the view that the African continent is the world's best source of commodities that the world needs for the next couple of generations. One presentation I saw put that into a rather more sober context. Africa has actually seriously fallen behind the rest of world as a commodity supplier in the past ten years. There are a number of reasons. There is not enough exploration spend in Africa. Capital productivity is poor. Regulatory environments are not favourable to investment. Labour productivity is poor. Infrastructure is not being developed rapidly enough. And there is a poor supplier base. These issues and others all require innovative thinking and leadership to resolve. And as I heard in one presentation, the role of leadership is not to solve all of the problems but rather to set the context in which the problems can be addressed. Are we setting the context – and creating an enabling environment for investment and development – or are we stuck on the small stuff? We cannot count on future commodity booms or weakening currencies to save the day.

Mining Indaba is an interesting meeting, and is 'over-the-top' in many ways, not least of which is the cost of participation. As of the time of penning this article, I have seen several items in the popular and business press lamenting the expected demise of Indaba. But I'm not clear that's true; the meeting does serve as an important gathering for African exploration and mining; it is an important networking event. The challenges going forward for Indaba are to keep the pricing down for both delegates and exhibitors, and to better integrate the exhibitioners with the delegate profile.

Craig Smith

president's column

Jeannette McGill

What an interesting quarter this has been! The end of the 2015 calendar year seemed like it would never arrive as the sector pressure just did not recede. Eventually the annual South African vacation season did begin and with it the time to reflect on the past year and set goals and objectives for the year ahead. The 2016 year has begun with continued depressed levels of the global commodities market and resultant intense global restructuring of the sector.

This backdrop continues to add pressure on the operating environment of the Geological Society of South Africa. The needs of our membership base are shifting to supporting a headstrong shelter for the turbulent times ahead. Society revenue is impacted through membership deferment due to affordability, as well as reduced numbers in attending our continuing development programs. We as Manco and Council take this responsibility seriously and continue to support the membership in terms of a learned and professional society. We encourage members to support the Society and the International Geological Congress to maintain important professional networks and linkages.

I was invited to participate in the first Unearthed Hackathon to take place offshore from the Australian base this company has created. A hackathon is an innovation platform where developers, programmers and technical specialists are presented various challenges, closeted away for effectively 54 hours and then given an opportunity to present their outcomes. This hackathon focused on problems impacting operators within the minerals sector. The stunning Waterfront venue in Cape Town saw interrogation of data-sets, lateral thinking and problem solving. The impact a short run opportunity can make was profound. Each problem was highly relevant and the level of engagement high. A team that contributed at a particular high level contained geologists and the value of clearly understanding the core resource problem was critical to the team's solid performance.

This engagement once again supported the three important R's that remain my continued Presidential theme for this year. Firstly, all the assignments were highly relevant to the operations who had contributed them. Second, the teams acknowledged their responsibility to the task and the opportunity that was at hand. Finally, staying committed to a problem solving tasks for the duration of the event for extended hours demonstrated the resilience of the participants - Once again all traits that we should be supporting also within the Society.

In our internal push to drive change within the organization we too are looking at problems differently and assessing how we maintain our relevance going forward. Some exciting offerings from our meetings portfolio will be revealed soon, and we remain excited about developments in providing the CPD platform. We held engaging discussion with the new management of SACNASP and acknowledge the significant gravitas and importance of the Society within the South African scientist landscape. We are relevant and we are ensuring resilience through this portion of the commodity cycle.

Thank you for your support and contribution to the geological community.

Dr. Jeannette E. McGill

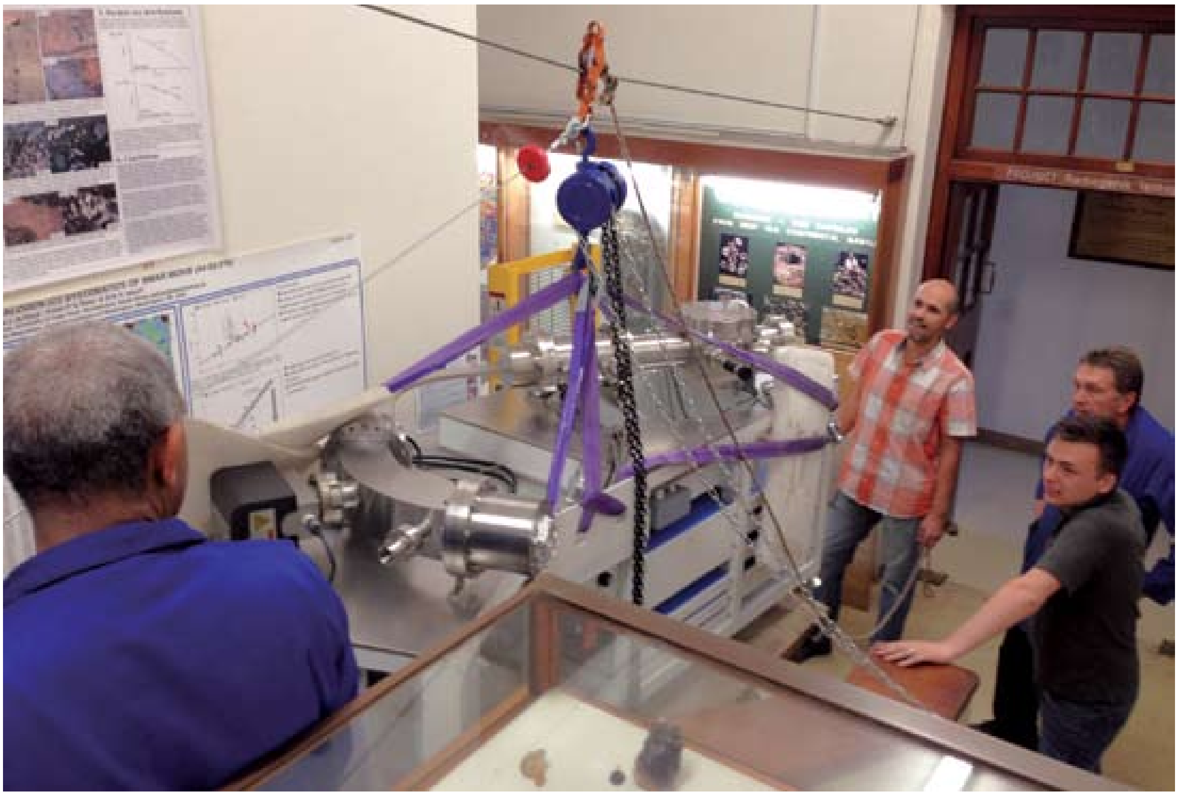
all the news fit to print

UCT

New staff:

We are happy to welcome a new staff member to the Department – Dr Robyn Pickering officially took up her new role as a lecturer in January 2016. Part of Robyn's research plan is setting up a new U-series (U-Th and U-Pb) lab in the existing and newly renovated clean lab. Robyn is excited about her return to South Africa after a decade away and is looking forward to the challenges of setting up a lab and research program. She recently received a prestigious P rating from the NRF in recognition of her work on dating carbonates associated with early human fossils.

Dr Robyn Pickering



Relocation of disassembled MC-ICP-MS instruments using an improvised 2-tonne zip-line. Everyone looking relaxed.

Renovations and re-opening of MC-ICP-MS lab:

After extensive renovations to the Radiogenic Isotope Facility that was first established 26 years ago, UCT re-launched its multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) laboratory in early December 2015. This facility builds on UCT's reputation in geochemistry, and combines a renovated instrument laboratory housing two plasma mass spectrometer instruments with a renovated 60m^2 metal-free clean chemistry laboratory. This combined laboratory suite is the only facility of its kind on the African continent. The multi-collector inductively-coupled plasma mass spectrometer instruments and renovated metal-free clean chemistry laboratory is vital to the work of geochemists and archaeologists.

The entire facility operates under new ultra-clean air supply equipment and acid-resistant air extraction systems, with 12 metres of new, non-metal laminar flow exhaust hoods for improved ultra-clean sample preparation. As can be seen from the photographic evidence, this was at times a nerve-racking exercise especially when the two MC-ICP-MS instruments were relocated using an improvised in-house 2-tonne zip-line. Instrument relocation was critically overseen by Nu Instrument engineers, and both MC-ICP-MS instruments passed the original installation specification after being re-assembled and given a mid-life check-up in their new home.

Since January 2016 the facility is again operating at full capacity, providing routine Sr, Nd and Pb isotope ratio

A panorama view of the MC-ICP-MS instruments looking happy in their new home.

One of the new metal-free exhausted laminar flow hoods.

Bob du Toit with the 4 medals

analysis by solution MC-ICP-MS analysis and Sr and Pb isotope ratio analysis by laser ablation MC-ICP-MS on appropriate materials. Future development for 2016 is focussed on making our in-house Hf isotope ratio analysis by solution MC-ICP-MS routine, establishing a method for Mg isotope ratio analysis by solution MC-ICP-MS, and also a novel method for B and Li isotope ratio analysis by laser ablation MC-ICP-MS of whole-rock samples.

As always, visitors are welcome to come and experience for themselves the wonders of samples preparation and isotope analysis by MC-ICP-MS. We especially encourage visits by post-graduate students to gain vital experience in analytical geochemistry, and to obtain a full understanding of the analytical process behind their isotope data.

This generational infrastructure project, funded by the UCT Faculty of Science, ensures the continued successful operation of this 8-year old facility. We look forward to continued support and association of our many users as we build on our proud history of consistent delivery of world-class radiogenic isotope data to the South African and international scientific community.

Alex du Toit's medals donated to UCT:

Robert (Bob) du Toit very kindly donated his grandfather Alex du Toit's scientific medals to UCT. The four medals include the Draper Medal of the GSSA, and the Murchison Medal of the Geological Society of London awarded in 1933. The medals will be displayed in the library or common room spaces in the Department.

Bob tells the story that he once took a train journey from Johannesburg to Cape Town with his grandfather, SH Haughton and TW Gevers for company. He, however, spent his career as an engineer rather than a geologist!

Johann Diener

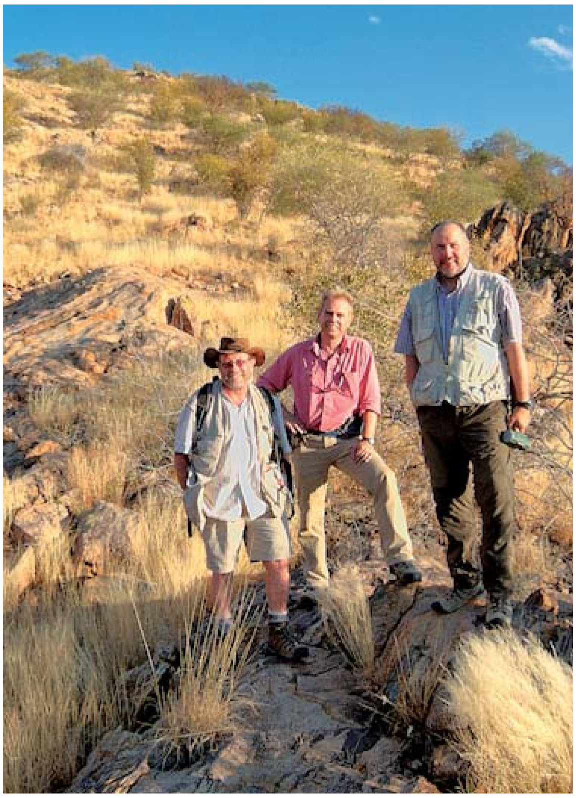
University of Stellenbosch

Like all other departments, Stellenbosch is plunging into the business of another promising teaching year. We didn't really report on these things last time, so here is the research news.

Profs John Clemens, Alex Kisters and Ian Buick, with two students, are embarking on their final NRF-funded year of investigating the giant Donkerhuk batholith in Namibia. Great progress has been made in understanding the conditions under which the magmas were formed and their mode of emplacement only slightly higher in the crust. What remains to be worked out is how this extremely heterogeneous and long-lived plutonism fits into the overall tectonic setting of the Damara Belt during Early Cambrian times.

Prof Buick (for scale) on an pavement outcrop of Donkerhuk granite, nicely illustrating the highly heterogeneous, sheeted nature of the batholith

Following up on an NRF CSIR-grant on "Precambrian Dykes across the Greater Congo Craton", Dr Martin Klausen and MSc-student (Wean Welgemoed) managed in July to sample sections of the Kasai River (along the DRC-Angolan border) by boat. This was logistically feasible through collaborations with Prof Louis Kipata (Head of the Geological Department at Lubumbashi University), who also contributed with an MSc-student (Philip Mukonki) working on the felsic host rocks. Thus, a basic petrological and geochronological study has been initiated on the under-investigated Kasai Craton, including an older, migmatised, TTG gneiss terrane with granite plutons, cross-cutting mafic dykes and metamorphosed dykes associated with an older metagabbroic complex.



Profs Kisters and Buick on a Donkerhuk outcrop, with collaborator Prof Jung from Hamburg

Prof. Ian Buick continued his collaboration with Prof. Cristiano Lana (Federal University of Ouro Preto, Brazil) on the development of accessory-phase U-Pb and Nd/O-Hf reference materials for LA-ICP-MS/SIMS instruments, funded through the "Science Without Borders" program of the CNPq (Brazil). Potential monazite reference materials for U-Pb and Nd-isotopes have recently been described (Gonçalves et al., 2016; Chemical Geology); development of other monazite (U-Pb, Nd, O) and a zircon (U-Pb, Hf) reference materials are in the manuscript pipeline. Work in 2016 will focus on assessment of potential columbite-tantalite U-Pb reference materials.

Zandri Rademan (honours student) examining plant-like fossils preserved within the Lembombo lavas in Kruger National Park

Over the past two years, our palaeontologist/sedimentologist, Ryan Tucker, has developed key projects with collaborators at Wits (Zubair Jinnah and Bruce Rubidge) and UCT (Anusuya Chinsamy-Turan and Emese Bordy), supporting honours and masters student projects. One such project focuses on Triassic-Jurassic Boundary Karoo sediments (Elliot and Clarens formations) of Lesotho (in collaboration with UCT's Emese Bordy and Lara Sciscio). The fluvio-lacustrine and aeolian rocks of the Triassic-Jurassic Elliot and Clarens formations preserve a broad suite of vertebrate body and a plethora of trace fossils (photo on p.8). These ancient life remains and their mode of preservation in the host sediments can be used to decode messages about the dynamics of a ~ 200 Myr old palaeoecological system in southern Africa (Stellenbosch honours students Jani van Gend and Marisca Beyers). The second of these projects focuses on a unique deposit in the Lebombo Group lavas, exposed in Kruger National Park. This study seeks to uncover the sedimentological and palaeoecological context for "recently discovered" floral assemblage. This fossil record is particularly intriguing because of its age, which preserves a thriving and diversifying assemblage, and because the Karoo large igneous province (LIP) coincided temporally with a minor global extinction event (15% of genera). Furthermore, this 'in-situ' assemblage seemed to have thrived in the middle of this LIP during highly active volcanism; a rare occurrence (photo above). Despite these important factors, much of the contextual details surrounding this assemblage remain unresolved. This will provide crucial understanding of how South Africa's Jurassic terrestrial flora thrived not only in a hostile environment, but also during a minor global extinction event (Stellenbosch honours student Zandri Rademan and collaborator Martin Klausen).

On the recent conference front, Profs Gary Stevens and Alex Kisters both delivered well-received keynote lectures at the recent Granulites conference held in Windhoek. Staying with that meeting there was a 5-day, post-conference field trip with 30 participants from academia and industry, which was led by Alex Kisters and Dr Johan Diener (UCT). This concentrated on the high-grade parts of the Damara belt, looking at aspects of crustal melt migration

Well preserved dinosaur footprint in the lowermost Upper Elliot Formation

and emplacement. Dr Jodie Miller and Prof. John Clemens also attended and presented papers at the Goldschmidt conference in Prague.

On the more local front, the annual IMSG (Igneous and Metamorphic Studies Group) meeting has turned into a convivial venue for the presentation world-class science carried out in South African departments. This year, it was organised by UCT, with an associated two-leg field trip led mainly by Profs Chris Harris (UCT) and Gary Stevens (Stellenbosch). As usual, Stellenbosch had a significant presence at the meeting. Indeed, itl transpires that the president (John Clemens) is one of only 3 people who have attended and presented at all 8 of the meetings, sharing this distinction with Chris Harris of UCT and James Roberts of Pretoria. A full report on the meeting can be found on p. xx-xx of this issue.

Finally, Stellenbosch has acquired some significant new equipment capabilities. For example, the CAF Electron Microbeam Unit has acquired a new Carl Zeiss MERLIN high resolution field emission SEM with nano-scale image and micro- and cryo-EDS analytical capabilities. The MERLIN combines ultra-fast analytics and high resolution imaging. The system is fitted with a number of detectors for imaging including: in-lens and chamber secondary (SE) detectors, an in-column energy-selective backscattered electron detector, a retractable diode backscattered electron detector a cathodoluminescence detector and a Scanning Transmission Electron Microscopy detector with a resolution of 0.6nm. Analytical capability is provided by an Oxford Instruments XMax 150mm2 detector for obtaining high resolution spectra and high spatial resolution maps. Furthermore, the instrument has a Quorum cryostage for cryo-micro-quantitative analysis of beam sensitive samples and a facility for local charge compensation for the analysis of insulating samples. Fancy stuff that will have numerous applications in Earth Sciences research.

J Clemens

IMSG conference

8th Annual Igneous & Metamorphic Studies Group (IMSG) conference

The 8th annual instalment of the IMSG national meeting was hosted by the Department of Geological Sciences of the University of Cape Town, from January 17-20, 2016. The meeting has a history of combining research talks with relevant field visits, but this year's event was novel inasmuch as it consisted of two days of talks sandwiched between two days of field excursions, and the conference was held away from campus, out amongst the rocks, creating a proper field conference. The conference venue was Windstone Farm, a "backpacker's lodge / adventure centre" near Langebaan, about 130 km north from Cape Town.

The meeting commenced in the field on Sunday, January 17, with the bulk of the participants, led by Chris Harris, Johann Diener and Dave Reid, leaving from UCT and heading to the migmatites at Sea Point contact, a national heritage site, where the Cape Granites intrude Malmesbury meta-sedimentary rocks, showing well-developed injection migmatites produced by the granite emplacement, as well as hornfels. The trip proceeded up the coast to the Bloubergstrand, where intermediate lavas are intercalated with clastic sediments. From there, after extricating the vehicles from having been inadvertently laagered-in by kerk-goers, the travelling circus headed north to Yzerfontein to examine intermediate intrusive rocks (mostly quartz monzonites) of the Cape Granite Suite.

By this point, the tour had reached almost its full size, having been joined, over the course of the morning, by latecomers, just in time for lunch on picturesque granitoids at the sea side, with added shear-hosted copper mineralisation for colour (mostly green). After lunch, the tour proceeded north to see hydrothermally altered diorites at Die Eiland, before heading to the final stop at the SAS Saldanha naval base grounds, where the trip was joined by the final two participants/leaders, Profs John Clemens and Gary Stevens from Stellies. Here we were treated to a short safety and environmental awareness talk by Able Seaman Steenkamp, followed by a bracing post-prandial stroll across the Hoedjiespunt Granite, with temperatures in the mid-30s. Although we were guaranteed that we would encounter ticks, as far as I know we escaped

Locally Cu-mineralised (not shown) granitic dykes in diorite, chock full of host rock xenoliths, south of Yzerfontein.

Modal layering in G3 Granite; the granite people and the Bushveld people share a moment.

incident, with the closest encounter with injury being the risk of rupture in push-starting Prof. Frei's Mercedes after every stop. Controversies of the day centred on outcrops of the Saldanha quartz porphyry near Bomgat. They included "recrystallised ignimbrite versus hypabyssal granitoid", and a related debate on the origins of possible xenoliths (or alternatively intrusive contacts) therein.

The field trip arrived at Windstone in late afternoon, quickly depleted the bar of beer, and cleaned up for dinner, while other delegates who had chosen not to partake of the field also filtered in. Dinner consisted of spit-braai with accessories, which appeared to be to most everyone's tastes and satisfaction. The accommodation setup was convenient for a conference, including shared convivial accommodations ("luxury" accommodation got you access to a shared kitchenette and lounge), dining halls, and the presentation venue all within one complex, which promoted both socialising and interaction as well as lots of more private spaces for smaller groups to connect, indoors and out. And speaking of outdoors, a number of the participants chose to camp in tents, rather than share housing, and an even larger number of us chose to haul our mattresses outside every night and sleep under the stars, in spite of the mosquitoes, as an alternative to the pervasive heat, which option turned out to be very pleasant indeed. The night sounds were ripe with the crowing of roosters and the heavy snoring of geochemists, giving an overall effect of some kind of special summer camp for poultry with sleep-apnia.

Conferences breed collaboration: Dirk Frei gets a jump start from Bjorn von der Heyden.

On Monday morning the serious science began, our appetites having been whetted by granitoids and heatstroke. The IMSG President, Prof. John Clemens (Stellenbosch) bustled in just in time to deliver the opening address for the meeting, and with a few words on behalf of the organising committee from Prof. Chris Harris, the sessions commenced. Without going into too much detail, the session themes included felsic igneous rocks (featuring source and emplacement processes), anorthosites and the Bushveld Complex, mantle magmatism (with a strong emphasis on alkaline magmas and metasomatism), and more on mafic igneous rocks to finish for the day (at about 6:30 PM; a long but stimulating day). The celebrity highlight of Monday was the arrival in mid-morning of Dr Craig Smith, representing our GSSA sponsor and himself a staunch supporter of the IMSG since its inception. Tuesday proceded in a similar fashion, with sessions on geochronology and analytical methods, metamorphism both with strong deformation themes, a short session on slightly exotic economic geology, and finally a session on extraterrestrial and planetary geology.

Although the two day format resulted in long days in a stuffy venue, afternoon breezes blew up each day and were dependably refreshing, and the quality and breadth of the talks was high and suitably challenging to promote questions and discussion throughout. Nobody fainted away in the mid-afternoon après-dejeuner heat (or if they did, they did it discretely). While there was a general emphasis on topics linked to southern African geology, there was a broad international spectrum of topics touched on, from Central and North Africa to the Alps, and India (so far, all technically Gondwanan Africa), but also a Canadian impact melt, Greenland and the Antarctic, and Shergottite meteorites, which, as we know, come from Mars, which is further still. There was a strong postgraduate student contingent, as always at the IMSG, but there was a distinct shift away from Honours talks (of which there were only one or two) to almost entirely MSc and PhD talks, with quite a few post-docs presenting as well. This represents, to my perception, a noticeable and commendable shift from the distribution at the early meetings; while there are no drawbacks with having lots of Honours talks, it suggests that the level of postgraduate research activity nationally has increased, which is a good thing. The recipients of the R1000 prizes for best student talks this year were Matthew Mayne (Stellenbosch) who presented the application of a new P-T-X modelling tool (Rcrust) to the study of melt sources, P-T-X paths and the effects of melt loss in partially molten systems, and Elizaveta Kovaleva (UFS), who gave a fascinating talk about zircon grains with evidence of crystal-plastic deformation.

One of the conference highlights was the opportunity to participate in the development of a petrographic teaching tool, facilitated by Matthew Huber of the University of the Free State, which tracked eye movement of "expert petrologists" to see how they really conduct diagnostic optical petrography. The cream of South African petrography was given the opportunity to identify simply "igneous, metamorphic, or sedimentary" rocks based on colour photomicrographs (through crossed Nicols); the winner of a six-pack of beer and indefinite bragging rights as a God of Petrography was Jean-François Moyen (visiting from St Etienne, France) for getting all 30 out of 30 correct; next best were several people with 27/30, and most of the participants were demonstrably competent (correct more than 60% of the time, comfortably). The other notable feature for me was the prominence (featuring in various presentations) of U-Pb geochronology from the Stellenbosch LA-ICP-MS lab of Dirk Frei, and of electron microprobe data from various domestic sources (including Wits, Rhodes, UCT, and UJ). These appeared to me to represent areas of growth compared to a few years ago, where a lot of the quantitative data appeared to be sourced from overseas.

Dinner on Tuesday night was a feast by the Atlantic Ocean at the Boesmanland Plaaskombuis, next door to Club Mykonos in Langebaan. The buffet dinner was excellent, as was the unlimited supply of cold beverages, and most of the conference participants took the opportunity to get their feet, at least, into the sea. The celebrity highlight of Tuesday was the impromptu performance of John Gurney's classic kimberlite conference anthem "Garnet Nodules" by Dave Reid, on a borrowed guitar (see also https://www.youtube.com/watch?v=NwXekxsSzLg for the 'original' music and video, unlikely to be covered by Adele any time soon, but well worth a look), which was much appreciated by the geological audience, but not by the owner of the guitar.

On Wednesday, the participants piled into the more off-roadworthy of the vehicles for a tour of the geology in the Saldanha area, beginning with the Saldanha volcanics, featuring somewhat more compelling (less recrystallised) ignimbrites. We then drove through scenic Paternoster to the Columbine Nature Reserve, where coastal granites in light mist were the setting for lunch, followed by a 2 km walk, which featured fairly spectacular xenoliths of 'granite in granite' (no really; it was impressive; a highlight was the spirited discussion on the nature of the xenolith contact between Gary Stevens and Martin Klausen, both of Stellenbosch,

Little Mermaid in the foreground, Saldanha iron ore terminal on the horizon, and geologists in the water, from the stoep on the Boesmanland Plaaskombuis.

who eventually 'agreed to agree that the other was mistaken'), as well as an impressive cormorant migration episode. The final stop of the tour, and of the conference, featured impressively high-contrast black amphibolite dykes cutting granites, which themselves featured actual modal layering, with unconformities and everything. It felt like just the right stop to end the tour with, and after half an hour of good-byes, most everyone headed back to Windstone and parts South, or East, in time for dinner and/or flights home.

The conference featured about 72 registered participants, which is consistent with the higher turnout since 2014, and retained the breadth of representation that allows this to function as a genuine national meeting. It has in fact been noted by the regular attendees of big international events (such as EGU or CAG) that the science presented at IMSG is at least on a par with that at such international meetings, and at a fraction (perhaps 10%!) of the cost. I believe UKZN was not represented this year; Jürgen Reinhardt, who has been attending regularly from UKZN, was back again as a member of the University of the Western Cape, who were first-time participants, with Russell Baillie present as well; welcome to UWC!; but UKZN were not forgotten (every year, we remember to be thankful that we're not meeting in Durban in January, although it's only a matter of time). It was announced

Gneissic, deformed granite within later, 'happy' granites. Humans for scale.

that next year's meeting will be hosted by the University of Johannesburg, and the year after (2018), by the University of the Western Cape.

The IMSG would like to thank the owners and operators of Windstone Farm for their tolerance and hospitality, the organisers (Chris and Johann in particular) from UCT, and the GSSA for its continued funding support, and particularly Craig Smith, as noted earlier. Jodie Miller of the Western Cape Branch of the GSSA generously allowed the IMSG to use the WCB bank account and helped out when cash flow became an issue. We look forward to future such meetings with keen anticipation.

Contributed by Steve Prevec (of the University currently known as Rhodes) with Chris Harris and John Clemens

IGC 35 Irumide field trip

Tectonic evolution of the SE margin of the Congo Craton:- a traverse of the Irumide Belt of Northern Zambia.

The Irumide field trip will develop a composite cross section across this fold and thrust belt that defines a part of the SE margin of the Congo craton. Commencing in Mansa, the trip starts with the volcanics and granites of the Bangweulu block, one of several components of the Paleoproterozoic Congo craton. It will then examine the stratigraphy and structure of the unconformably overlying sediments of the Muva Supergroup. It will trace these sediments into the Late Mesoproterozoic deformation seen in the foreland region of the dramatic, NW vergent, Shiwa Ngandu fold belt. Turning south, it will follow along strike the upright structures and huge late-tectonic granite massifs of the Irumide belt before viewing the SE vergent stuctures of the internal zones exposed east of Mkushi.

Muva orthoquartzite, Chishimba Falls

Several controversies bubble gently around this little studied orogenic belt. Notably the tectonic setting of the Bangweulu Block basement of volcanics and granites; the nature of the Muva cratonic basin, the depositional environment of its quartz rich sediments and its subsidence driving mechanism; the role and implications of the recycled late-orogenic Irumide granite bodies; the geodynamics of the Irumide deformation and metamorphism; and the nature of post-Irumide, cobble conglomerates, and eperogenic deformation. All of which provide room for new contributions to this little studied area.

Syn-tectonic granites

The trip will involve long drives in 4x4 vehicles over the high plateau of Africa. The large distances between key outcrops will allow time for discussion of the evolution of this unique 'rough plateau' and its marginal rifts. Accommodation will be in lodges of variable quality and interest. Historical highlights along the way are the memorial to Paul von Lettow-Vorbeck at the strategic Chambeshi Bridge and the "Africa House" at Shiwa Ngandu. The natural rock formations of the Mutinondo Wilderness camp will also be memorable. The timing of the trip coincides with the unique "early spring" russet colours of the Miombo woodland, characteristic of this high plateau region.

Paul Von Lettow-Vorbeck memorial

Start/end: Lusaka, Zambia: 7 days, Saturday 20th – Friday 26th August 2016

Day 0. Arrive Mansa by Air Lusaka to Mansa scheduled flight
Camp at Mumbuluma Falls about 40km north of Mansa

Day 1: Round trip via Mansa (~250km). Camp @ Mumbuluma.
Bangweulu basement, Muva Supergroup, Luongo Fold belt
Stop @ Musonda Falls (+30km), Johnstone Falls (+30km)
To Mwenda across Luongo Fold (+85km)
Back to Mumbuluma Camp via Mansa (+100km)

Day 2: Stay at Kasama (~350km) hotel or camp
Muva basement contact & Mn mineralization
Drive to Mansa Kiboko mine
Stop @ Chipili for basement/cover contact mylonite zone
Drive to Kasama

Day 3: Stay at Kapisha (~400km)
Irumide deformation front
Stop @ Chisimba Falls; Mbesuma hills; Chimbwe syncline.

Day 4: Stay at Kapisha (~100km)
Irumide Foreland fold belt
Stop @ Bwingi Mfumu range; Danger Hill; Pan African reactivation
Rock paintings; Butterflies

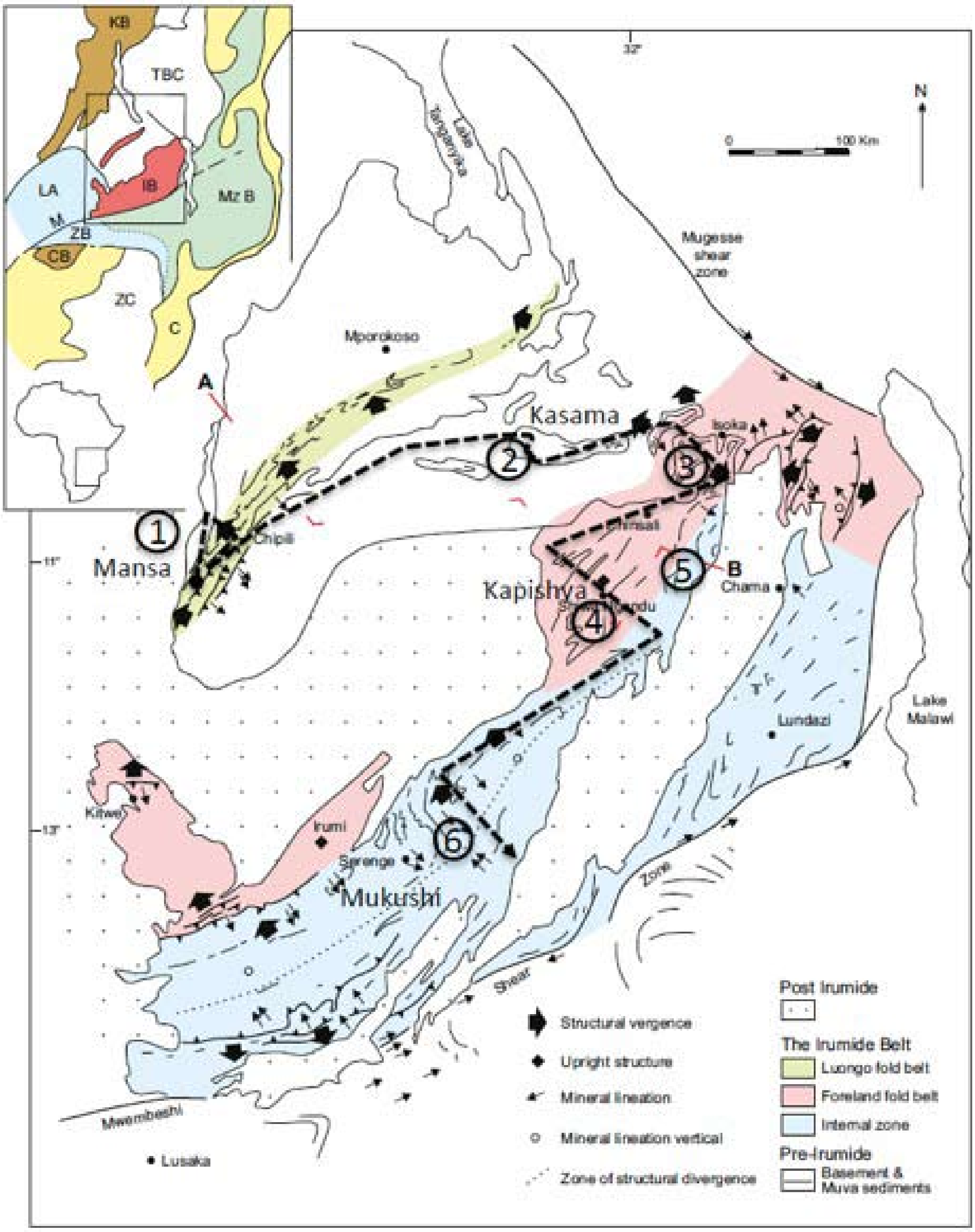
Day 5: Stay at Kapisha (~70km)
Irumide internal zone
Stop @ Rhyolite and new Mn mine; Luswa Granite.
Shiwa Ngandu House visit

Day 6: Stay around Mkushi (~650km)
Irumide internal zone
Cross section east of Serenje, to East verging structures

Day 7: Drive to Lusaka/Kitwe Airport for departures (~500km)

Mike Daly, in collaboration with the Geological Survey Department of Zambia.

Shiwa Ngandu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Lake Malawi
Kitwe
Irumi
Serenje
Mukushi
Zone
Shear
Mwembeshi
Lusaka
Structural vergence
Upright structure
Mineral lineation
Mineral lineation vertical
Zone of structural divergence
Post Irumide
The Irumide Belt
Luongo fold belt
Foreland fold belt
Internal zone
Pre-Irumide
Basement & Muva sediments

35th IGC field trips

The prices published here may be subject to change.

TRIP CODE	TITLE	DAYS	FIELD TRIP LEADER/S	SELLING PRICE	SINGLE SUPPLEMENT
To make reservations for the excursions offered through Grosvenor Tours, please visit the website; http://www.35igc.org/Verso/173/Field-Trips					
PRE2	Cape Granites	2	Gary Stevens and John Clemens	R 3 000	R 980
PRE3	Permo-Triassic Boundary in the Karoo	6	Johann Neveling and Robert Gastaldo	R 17 800	R5 750
PRE4	Karoo Transect	9	Roger Smith and Bruce Rubidge	R 29 000	R5 100
PRE5	Vredefort impact structure	2	Roger Gibson	R 5 900	R1 450
PRE6	Diamonds	5	Mike de Wit	R 21 500	R5 500
PRE7	Eastern Limb of the Bushveld Complex	6	Roger Scoon	R 13 500	R5 850
PRE8	Craton Traverse: A transect through ~2.7Ga of South African history	11	Herman van Niekerk	R 33 000	R7 200
PRE9	Early Cretaceous Basins along the Southern Cape Coast	4	Jonah Choiniere	R 16 000	R2 100
PRE10	Namaqualand Metamorphic Province	7	Alex Kisters and Paul Macey	TBA	TBA
PRE11	Cape Fold Belt	5	Coenie de Beer and Gideon Brunsden	R 15 300	R2 200
PRE12	Seismotectonics and hydrology of fault system in the Western and Southern Cape	7	Chris Hartnady	R 12 000	R2 300
PRE13	Western Kaapvaal Craton	10	Wlady Altermann and Vusani V Mathada	R 30 000	R5 500
PRE14	Orange River geology by canoe	7	Dave Reid	R 17 000	R 175
PRE15	1 Ga of crustal reworking, Northern margin Kaapvaal craton: Murchison Belt to Limpopo Central Zone	6	Jean-Francois Moyen	R 21 936	R2 240
PRE16	Geology of the Barberton Greenstone Belt: Processes on the early Earth	6	Gary Byerly, Christoph Heubeck, Don Lowe	R 28 000	R6 300
PRE17	Africa rising on the African Superplume	3	Rodney Maud	R 13 800	R2 500
PRE18	Karoo magmatism and continental breakup	8	Mike Watkeys	R 28 750	R4 799
POST2	Eastern Bushveld, Mpumalanga Drakensberg Escarpment and Kruger National Park	7	Morris Viljoen	R 18 500	R4 150
POST3	Big 5 & Big 5: Mineral commodities and animals			being reviewed	

TRIP CODE	TITLE	DAYS	FIELD TRIP LEADER/S	SELLING PRICE	SINGLE SUPPLEMENT
POST 4	Eastern Bushveld and Nkomati	5	Christopher Gauert	R 14 600	R1 500
POST5	Mountain Geomorphology of the Drakensberg	3	Jasper Knight and Stefan Grab	R 8 000	R1 300
POST6	Archean Stromatolites and their depositional environments	8	Wlady Altermann and Vusani V Mathada	R27 000	R3 200
POST7	Geology of the Barberton Greenstone Belt: Processes on the early Earth	7	Christoph Heubeck, Eugene Grosch	R 23 000	R6 300
POST8	The Pongola Supergroup: Earth's earliest stable continental margin	7	Allan Wilson	R 20 000	R2 800
POST9	Western Cape Wine Tour	3	Genevieve Pearson	R 6 700	R1 150
POST10	Meandering in the Main Karoo Basin, Eastern Cape province	6	Emese Bordy and Goonie Marsh	R 22 500	R3 300
POST11	Southern Cape Geology: Evolution of a rifted margin	5	Jean Malan, Jurie Viljoen	R 14 700	R2 245
OD PRE1	Cape West Coast: Langebaan and West Coast Fossil Park	1	West Coast Fossil Park	R 1 100	
OD PRE2	Witwatersrand: geology, historic mining and environment	1	Morris Viljoen	R 1 300	
OD PRE3	Magaliesberg Cable Car	1	Morris Viljoen	R 1 200	
OD PRE4	Cradle of Humankind Hominin Sites	1	Francis Thackeray	R 1 750	
OD PRE5	Geological walking tour of Robben Island	1	John Rogers	R 850	
OD PRE6	Cape Peninsula	1	John Compton	R 1 400	
OD PRE7	Cape Town Geology	1	John Compton	R 1 400	
OD PRE8	Cape Town Building Stones	1	Doug Cole	R 250	
OD POST1	Cape Town Building Stones	1	Doug Cole	R 250	
OD PRE9	Table Mountain Hike	1	Taufeeq Dhansay	R 1 100	
OD PRE10	Table Mountain Hike	1	Taufeeq Dhansay	R 1 100	
OD POST2	Table Mountain Hike	1	Taufeeq Dhansay	R 1 100	
OD PRE11	On the trail of Charles Darwin and John Herschel: The Cape in the 1830's	1	INHIGEO; Gregory Good, Brian Warner, Barry Cooper, John Compton	R 1 250	
OD POST3	Tulbagh-Ceres and SW Cape seismicity	1	Coenie de Beer and Nicky Flint	R 2 200	
OD POST4	Zevenwacht Wine Farm and Tin Mine	1	Doug Cole	R 1 650	
OD Dur1	Mantle Room	1	John Gurney, Steve Richardson, Philip Janney, Rory Moore	R1000 students R500	

TRIP CODE	TITLE	DAYS	FIELD TRIP LEADER/S	SELLING PRICE	SINGLE SUPPLEMENT
	Reservations for Africa's Geological Summits; http://www.adventuredynamics.co.za/Africas-Double-Summits-Expedition-Kilimanjaro-Expedition.php				
PRE1	Africa's Geological Summits: The deepest and highest points of the African continent (US$) Tanzania, East African Rift System; active volcanoes and game (US$)	7	Jeannette McGill	$2 875	
	Reservations for Tanzania excursion; http://www.wildfrontiers.com/?q=con,214,Tanzania+Safaris				
ExSA POST 2	Tanzania,East African Rift System; active volcanoes and game	11	Roger Scoon	$4 951	
	Reservations for Namibia excursions http://www.natural-destinations.com/index.php/en/our-tours-en/special-interest-tours-en/35th-igc-en				
ExSA PRE2	Nama Group geology and Ediacaran fossils	5	Pat Vickers-Rich, Guy Narbonne	R 17 353	
ExSA PRE3	Otavi Mountain Land	6	Arno Gunzel, Volker Petzel	R 16 799	
ExSA-PRE4	Namibia Mineral Deposits	6	Anna Nguno, Kombada Mhopjeni, Keith Webb	R 19 969	
ExSA-PRE5	Namib Desert	6	Mary Seely, John Ward, Roger Swart	being reviewed	
ExSA POST3	Damara Orogen traverse, "Snowball Earth"	6	Roy Miller	R 22 000	
ExSA POST4	Namibian Diamonds		Jurgen Jacobs, Gabi Schneider	R 31 609	
ExSA POST5	Granites and Uranium Deposits		Judith Kinnaird, Paul Nex, Vicky Da Cabo	R 15 610	
ExSA PRE6	Zambia Copper Belt (US$)		Murray Hitzman, Imasiku Nyambe	$2 475	
ExSA PRE7	The Bangweulu block and Irumide Belt: A traverse across the SE margin of the Congo Craton, Zambia (US$)		Michael Daly	$6 200	
ExSA PRE8	Okavango Delta, Botswana		Piotr Wolski	R 15 400	R 7 720
ExSA POST 6	Southern Angola - from the Humpata Plateau to the Namib Desert		Isabel Duarte and Antonio Gonçalves	being reviewed	
ExSA POST 7	Tectonic and metamorphic evolution of the Paleoproterozoic Eburnean orogeny, west African Craton, NW Ghana		Sylvain Block	being reviewed	
EXSA POST 8	Gold in Ghana		AngloGoldAshanti, GoldFields, Newmont Mining	TBA	
ExSA POST 9	Gold deposits of Loulo-Gounkoto, Mali		Randgold Resources	TBA	

africa's geological summits

Deepest and Highest points of the African continent

The 35th IGC together with AngloGold Ashanti and the Geological Society of South Africa present the geological excursion for the adventure seeker! The trip starts by descending to the deepest point on the African continent: the Mponeng Gold Mine (-4200m) in the heart of the Witwatersrand Gold deposit then transfer to Moshi, Tanzania where we ascend, via the highly successful Rongai route, to the very highest point of the African continent: Kilimanjaro (5895m) at the edge of the African Rift Valley. By completing this "greater than Everest ascent" you will become part of a very select group having been to the highest and lowest points on the African continent: each a geological superlative in their own right. We will record a special summit message to be used during the opening ceremony of the 35th IGC. Each participant will receive a special edition plaque and branded sweatshirt in recognition of this unique adventure and double geological summit!

Adventure Dynamics International

Adventure Dynamics International (ADI) has been leading and guiding trips up Kilimanjaro for over 15 years and their knowledge, expertise and professional staff make their expeditions a truly great experience. They guide to mountains around the world and thrive on the fact that they are professional climbers. This gives them the opportunity to impart the knowledge and service necessary to make this an unforgettable expedition.

Kilimanjaro is more than just climbing the highest mountain in Africa. It's about an adventure with a group of people to achieve a common goal and dream. It's about pushing your mind and body to new limits in a strange and exciting place. ADI offers all routes on Kilimanjaro and the 35th IGC organizers have chosen the Rongai route for this expedition, for its scenic beauty and high summit success, due to increased acclimatization. We are especially fortunate to have global mountaineer and double 7 Summiteer – Sean Disney - as the climb leader.

Climb Leader: Sean Disney

- CEO and Owner of Adventure Dynamics International
- 23 years experience of mountaineering & guiding
- 2 times Everest summiteer
- 2 times 7-Summits summiteer
- 20 times Kilimanjaro summiteer
- First South African to complete GRAND SLAM with Vaughan De La Harpe, includes skiing to North and South Pole
- Author of the book "Poles Apart with some pointy bits in between"

35th IGC Co-Leader: Dr. Jeannette E. McGill

Jeannette McGill has been to Kilimanjaro twice. She has been to the North Col of Everest and most recently been the 1st South African women on Manaslu, the 8th highest mountain in the world. A seasoned mountaineer, she is also President of the Geological Society of South Africa and Co-President of the 35th IGC. She is passionate about sharing mountain adventures with others having lead groups on the Drakensburg escarpment previously for the Mountain Club of South Africa. Coupled with her geological and mining acumen she is well placed to co-lead this exciting trip together with Sean Disney.

DAY BY DAY ITINERARY

10 Day Itinerary

DAY 0: Sunday 14 August 2016:
Optional early day to check into excursion hotel and do any last minute shopping at nearby Sandton City. Overnight at excursion hotel: The Capital Empire, Sandton. Note: Cost is additional.

DAY 1: Monday 15 August 2016:
Deepest point on African continent.
Altitude: 3,900m below surface.

Full group convenes - depart excursion hotel at 07:00 - group transport to the Anglogold Ashanti Mponeng mine site - Mine induction and safety briefing - proceed underground to the deepest point on the African continent - Overview of the geological superlative: Witwatersrand Basin - transfer back to excursion hotel: The Capital Empire and overnight, dinner at an award winning steak house is included. For individuals electing not to overnight at the hotel the expectation is that you still join the group for dinner as this is important for team dynamics and information sharing purposes.

DAY 2: Tuesday 16 August 2016:
Travel to Tanzania.
Early breakfast at Sandton hotel - transfer to ORT - depart South Africa for Tanzania arriving at Kilimanjaro International Airport (JRO) in Arusha - overnight at the Protea Hotel Moshi.

DAY 3: Wednesday 17 August 2016:
Rongai Gate to 1st Caves Camp
Altitude: 1,950m to 2,600m.

Breakfast at hotel then drive and register at Kilimanjaro National Park Gate and transfer (approximately two and a half hours) to the Rongai trailhead. Begin hiking from the village of Nale Moru. The small winding path crosses maize fields before entering pine forest, then climbs gently through a forest sheltering a variety of wildlife, including the Kilimanjaro Colobus monkey. Our campsite is on the edge of the moorland zone with expansive views of the Kenyan plains.

Day 4: Thursday 18 August 2016:
1st Caves Camp to Kikelewa Caves.
Altitude: 2,600m to 3,450m.

Challenging ascent to the "Second Cave" where you will relax and have lunch with superb views of Kibo and the ice fields on the crater rim. After lunch proceed towards the jagged peaks of Mawenzi, where we camp in a sheltered valley near Kikelewa Caves.

DAY 5: Friday 19 August 2016:
Kikelewa Cave to Mawenzi Tarn Camp.
Altitude: 3,450m to 4,335m.
A short but steep climb up grassy slopes offers superb views of this wilderness area. The vegetation zone ends shortly before we reach our next camp at Mawenzi Tarn

spectacularly situated beneath the towering spires of Mawenzi. Spend the afternoon relaxing and acclimatising.

DAY 6: Saturday 20 August 2016:
Rest day at Mawenzi Tarn.
Altitude: 4335m

Active rest day to assist in acclimatization for successful summit – Group overview of the geological superlative: African Rift Valley volcanics

DAY 7: Sunday 21 August 2016:
Mawenzi Tarn Camp - Kibo Hut.
Altitude: 4,335m to 4,750m

We trek across the saddle between Mawenzi and Kibo to reach Kibo Campsite. The remainder of the day is spent resting in preparation for the final ascent with an early night.

DAY 8: Monday 22 August 2016, SUMMIT DAY: Crater Camp - Uhuru Peak - Horombo Hut, ***Altitude: 4,335m to 5,895m*** (Summit) then down to ***3,720m.***

A very early start (midnight) for the final challenge to reach Uhuru Peak (5,895m). Push up further for the short haul up to Uhuru Peak. Remember to take in your day pack, energy bars - biltong is also very good, and munch along the way. Hike slowly on a switchback trail through loose volcanic scree. Rest for a short time to enjoy the spectacular sunrise over Mawenzi. Continue to Uhuru Peak passing close to spectacular glaciers and ice cliffs in the summit area. Team to record a special message via statellite phone and video for 35th IGC conference opening ceremony. Descend to Kibo and a rest then continue down the Marangu Route to Horombo Camp for a well-deserved rest.

DAY 9:Tuesday 23 August 2016: Descent
Altitude: 3720m to 1900m

Descend steadily through the moorland, past Mandara Hut and through a lush rain forest to the Marangu Park Gate where transport will be waiting to drive you back to Moshi. Overnight at the Protea Hotel Moshi, and time for a well-deserved hot shower, dinner and enjoy double summit celebrations.

DAY 10: Wednesday 24 August 2016

Depart Tanzania and arrive in Johannesburg. Excursion ends.

PREMIUM DOUBLE SUMMITS PACKAGE

- Mine Visit and Kilimanjaro Rongai Route 7 days / 6 nights + 2 travelling days.

FULL PACKAGE COST

= indicative USD 3000 (excluding flight prices). Excludes flight Cost @ approx. ZAR7500. See Critical Steps/Dates).

Full Package Includes:

- Fully guided mine visit, lunch, and transfers to and from AngloGold Ashanti Mine.
- Fully guided expedition by expert mountain guide, Sean Disney ex: Johannesburg.
- 2 nights' accommodation Protea Hotel Moshi on a dinner, B&B basis.
- All porters, park fees, camping accommodation and exclusive toilets on the mountain.
- All meals as well as mountain rescue while doing the climb.
- 2 airport transfers in Tanzania.
- Training program designed by Adventure Dynamics International.
- Gear briefing in Johannesburg with optional Skype link for those who are unable to attend in person.
- Optional gear check (if required) on day 0 of the trip.
- Discounts at Drifters retailers in Sandton City for gear purchases.
- Free gear rental of items that you personally do not have, (see what is included under Gear).
- Limited edition fully branded expedition apparel.
- Limited edition expedition plaque sponsored by AngloGold Ashanti.

Excludes:

- Spending money for drinks, curios and extras for the full duration of the excursion.
- Lunches off the mountain, drinks, items of a personal nature.
- Hospitalisation, evacuation or medical costs (ADI can advise, it is strongly suggested that you have).
- Any costs outside the itinerary.
- Any aviation fuel tax surcharge (beyond our control and advised by the Airline at short notice).
- Any unforeseeable increase in Park permit and entrance fees, camping fees and/or any other associated park and government fees.
- Tips for Tanzanian guides (a minimum of USD 180 per participant is required).
- All flights.

FLIGHT COSTS

The best flight and connections from Johannesburg to Kilimanjaro International airport will be communicated to participants in early 2016. Discussions are being held to secure preferential pricing options.

Independent travel arrangements will be considered on a case by case arrangement but are not encouraged.

OPTIONAL EXTRA'S

- Pre-excursion extra night at The Capital Empire Hotel for individuals wanting an extra night in Johannesburg or to complete final gear check and/or shopping at nearby Sandton City.
- 1 night accommodation at The Capital Empire Sandton Hotel (B&B basis).
- Dinner at award winning Local Grill Restaurant, in Parktown North – South Africa's Steakhouse of the Year 2014 and 2015, for the purposes of briefing, group dynamics and communications it is expected that all participants do attend the dinner. Price is for the meal only – drinks are for own account. Transport will be provided return from hotel.
- Airport transfer from the Capital Empire Hotel to ORT on morning of departure to Tanzania.

GEAR

A full breakdown of the gear required for this expedition will be provided upon payment of a deposit and will also be discussed at a gear briefing to be held in Johannesburg and via Skype for overseas participants. As this is a premium package certain gear rental is included free of charge in the expedition cost: Day pack, Sleeping Bag rated -8 degrees, Waterproof / Windproof Jacket, Fleece Jacket, 80 litre duffle bag, windproof gloves, Head Torch (excluding batteries), Snow Gaiters, Sleeping Mat.

(NOTE: Although there will be no charge for the free gear rental included in the package cost, we will need a deposit to cover the replacement cost of any items not returned, or damaged beyond further use)

Training program

On booking you will be sent a training program and gear list designed for success on mountains. This should be started at least 6 weeks before departure. The training program is necessary for several reasons:

- It maximizes your chances of success on Kilimanjaro
- It provides the opportunity for climbers in their respective areas to meet each other.
- It provides time mentally and physically to prepare for the climb ahead.

CRITICAL STEPS / DATES

BY 1 APRIL 2016

- Make a decision on whether you want to be part of the expedition and notify JEANNETTE MCGILL. jeannette.mcgill@gmail.com

BY 20 APRIL 2016

- ADI will send you a detailed gear list and training guide. Gear discount available from DRIFTERS IN SANDTON CITY.

BY 30 APRIL 2016

- JEANNETTE MCGILL will confirm a diary of training dates for each month leading up to departure where interested participants can join her for late afternoon or day out training at various suitable Johannesburg locations.

IN MAY 2016

- A gear briefing by Sean Disney will take place in Johannesburg with Skype facilities available for international participants.

BY 1 JULY 2014

- Balance of fieldtrip payment due.
- Final payment of flight costs due.

EXPEDITION START DAY:
15 AUGUST 2016 (JOHANNESBURG).
EXPEDITION END DAY:
24 AUGUST 2016 (JOHANNESBURG).

35th IGC CONFERENCE BEGINS:
27 AUGUST 2016 (CAPE TOWN).

Media Strategy

To create ongoing awareness of the expedition we will be communicating through various sources of media, leading up to and during the expedition.

RADIO - will be used to create awareness and raise sponsor funds for the 35th IGC conference leading up to the conference opening.
FACEBOOK - will be used to communicate with expedition members, friends and family leading up to and during the expedition.
WEBSITE - we are looking to create a small site for publicity purposes and also as a functional platform to post pictures and video while on the expedition.
Video – Genevieve Pearson (Geoheritage Chair for both LOC & GSSA) will film and photograph the expedition, and a professional editor will ensure the video and summit message is available for the opening ceremony.
SPOT Africa will provide real time tracking with a feed to social media.

Contact Details:

2016 35th IGC – AFRICAN GEOLOGICAL SUMMITS
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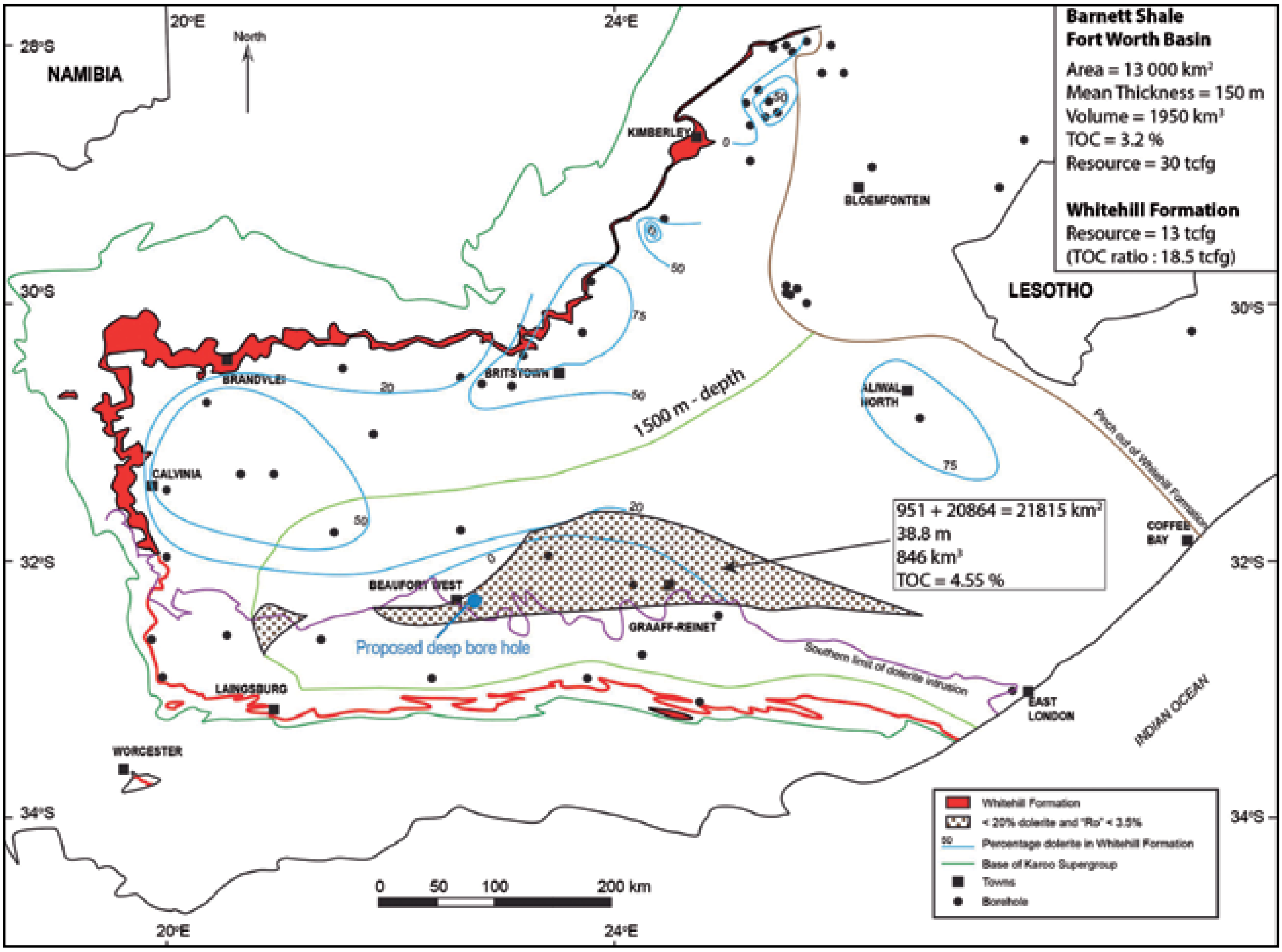
Jeannette McGill (35th IGC Fieldtrip Leader)
Tel: +27 83 2898 722
Email: Jeannette.mcgill@angloamerican.com

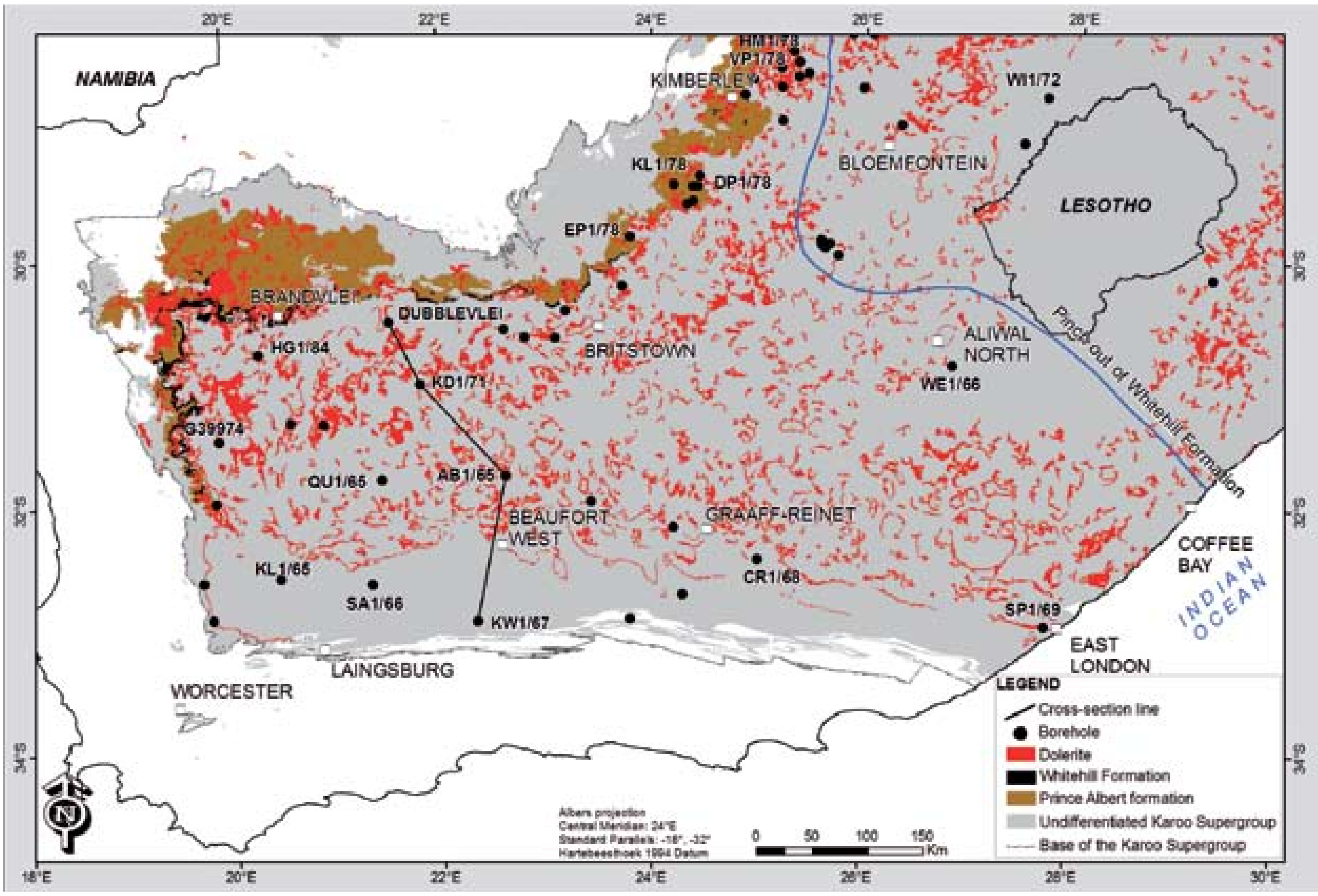
CGS stratigraphic borehole

The Council for Geoscience (CGS) is conducting a three year research programme aimed at undertaking a wide range of geoscientific investigations associated with the drilling of a deep core borehole to better conceptualise the potential impact shale gas activities could have in the western Karoo Basin. With the currently available information, South Africa cannot make quantitative scientifically-based conclusions and recommendations concerning the geo-environmental impacts associated with shale gas exploration and exploitation activities (i.e. deep drilling and subsequent hydraulic fracturing) in the Karoo.

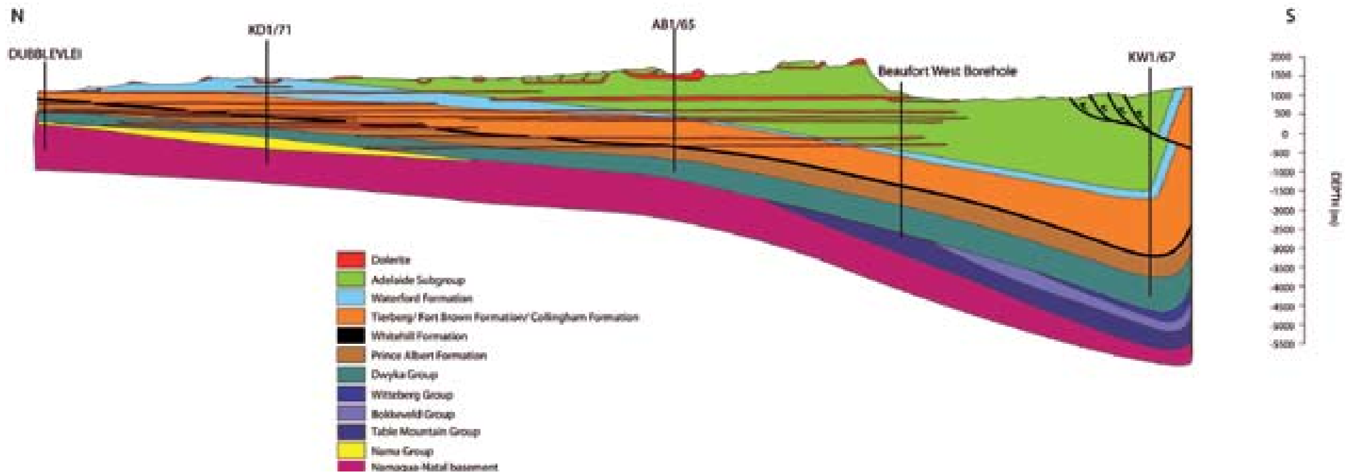
A deep stratigraphic borehole and surface investigations at a selected pilot site, Beaufort West area, will allow the collection of new information on the geology of the Karoo at depth in order to cover various geo-environmental impacts that are of public concern. The objectives of the CGS Shale gas programme are to determine an environmental baseline, assess the amount of recoverable gas, study ground water dynamics and possible contamination and monitor potential seismic interferences. Varying quantities of gas were obtained by desorbed gas analysis undertaken by Soekor on Ecca Group shale samples retrieved from deep borehole cores in the late 1960s (Rowsell and De Swardt, 1976). Only the lower Ecca Group shales within the dry gas window south of latitude 29°S have comparable total organic carbon (TOC) content to those of producing shales elsewhere in the world. The



Karoo sweet spots for shale gas exploration and resource estimation for the Whitehill Formation (Cole, 2014). The proposed drilling site is located just east of Beaufort West.



Regional cross section passing through the proposed Beaufort West drilling site in the transitional zone between the dolerite intrusion domain in the North and the folding domain in the South. The Whitehill Formation is expected to be reached at a depth of around 3500 m.

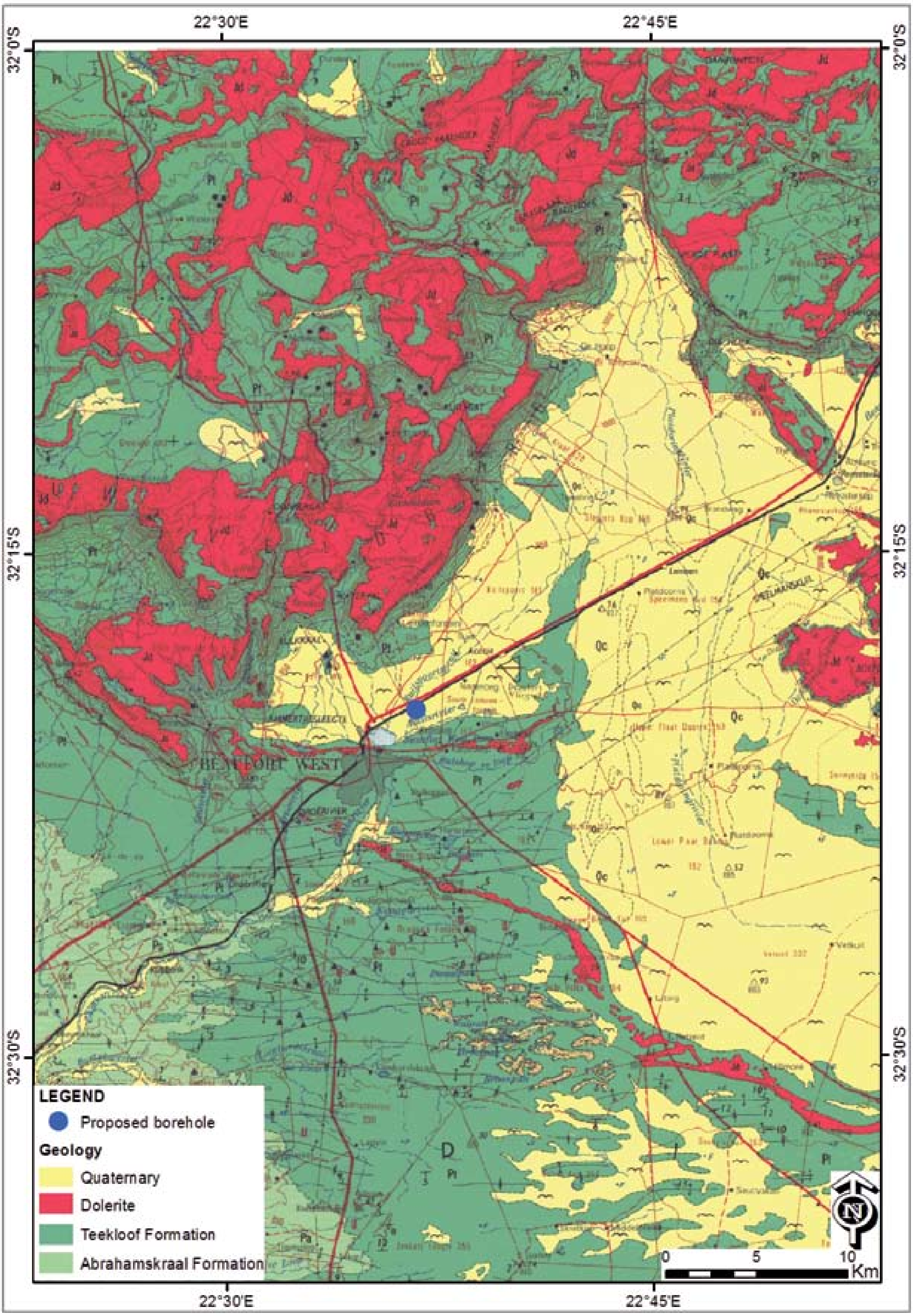


Geology Section Line 2

lower Ecca Group comprises black, organic-rich shale of the Whitehill Formation overlying dark grey shale of the Prince Albert Formation.

The drilling site was selected in the municipal area east of Beaufort West within the "sweet spot", an area defined by Cole (2014) with the highest gas recovery potential from the carbonaceous Whitehill Formation, using a series of restrictive parameters namely formation thickness, relative dolerite thickness, relative total organic carbon content, 1500 m-depth contour and maturity.

The borehole is planned to be drilled in a transitional zone between a domain characterised by dolerite intrusions in the north, comprising dykes and sills, and a domain devoid of dolerite but characterised by shallow folding and listric faulting in the south (Section Line 2 above). The carbonaceous black shale of the Whitehill Formation is expected to be reached at a depth of



Geology of the catchment area around Beaufort West and location of the proposed deep stratigraphic borehole (1: 250 000 geological map from Council for Geoscience).

3500 m. At that depth, the formation is supposed to be free of dolerite intrusions and therefore likely to be unaffected by thermal metamorphism destroying the gas-producing potential.

The geology of the J21A catchment consists of the Teekloof and Abrahamskraal Formations (sandstone, mudstone and shale) of the Adelaide Subgroup, Beaufort Group, intruded by dolerite sills, seep. 28). Two shallow inclined dolerite sheets (dipping 10° North) occur north and south of Beaufort West. The dolerite sheets form part of two shallow saucer-shape dolerite structures that will be intercepted during deep drilling (see Section Line 2). The structure of the sills (dip, contact, offshoot, sediment inclusion) will play a major role in the occurrence of water-bearing fractures at depth and the circulation on such water over long distances.

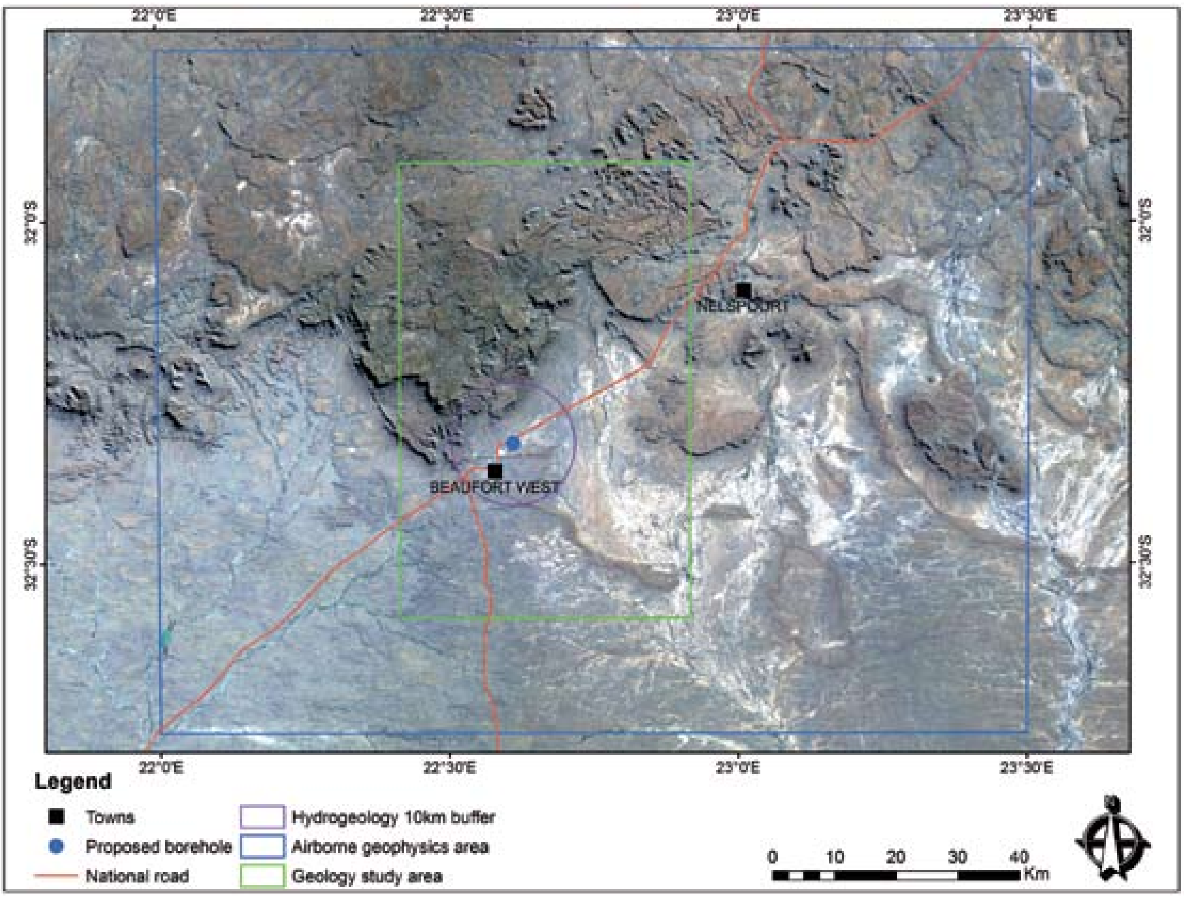
The area is also characterised by 270 boreholes drilled by the Department of Water and Sanitation and the Municipality of Beaufort West for water supply. This precious information (water levels, abstraction, water chemistry) will be used for a hydrogeological baseline study and monitoring programmes.

The following activities (not restricted) will be carried out at regional and local scales around the borehole site (image overleaf):

- High resolution airborne magnetic and radiometric survey over an area larger than the J21A catchment in order to enhance regional structures that do not show at surface (i.e. dolerite, fractures).
- Geological mapping of the catchment area at 1/50 000 scale to ascertain lithology and stratigraphy in the region of the deep borehole at Beaufort West.
- Analysis of existing seismic profiles to better define some of the contacts in 2 D: Whitehill Formation, Dwyka Group, basement.
- Ground geophysics: Time Domain Electromagnetics and Magnetotellurics to better define shallow (<300m) to semi-deep aquifers.
- Groundwater investigations at catchment scale (hydrocensus) for base line record and monitoring programs to identify future changes induced by the deep drilling and the injection.
- Seismological monitoring for base line assessment and changes that might be induced during drilling and injection.
- Surface gas emanations for base line record and monitoring future possible changes after drilling.
- Deep drilling down to 3500 m and groundwater monitoring at nearby shallower holes.
- Injection of pressurised water for enhancing permeability. This is not hydraulic fracturing but standard injection to enhance water bearing fracture and test water circulation at depth.
- Core logging, sedimentological analysis, structures and dolerites.
- Geochemistry analysis of the carbonaceous shales.
- Gas analysis from carbonaceous shales (Whitehill and Prince Albert Formations).
- Down the hole geophysics and camera logging.
- Groundwater sampling of the deep water strikes to characterise the differences, if any, of the shallow and deep aquifers.
- 3D modelling of the drilling site.

One of the concerns in the Karoo is the potential threat of contamination or irreversible damage of its water resources. More specifically the deep drilling should address the problem of deep groundwater (occurrence and quality) and the potential contamination of the drinking water supplies (i.e., the shallow aquifers) as a result of the interaction via pathways created by the deep drilling and/or injection/hydraulic fracturing activities. Another problem would be the decline or water losses in surface water and groundwater resources because of the high water demands needed for multiple drilling activities and production of shale gas.

The pilot site will be open to the scientific community and especially young scientists in order to build a knowledge-based scientific capacity, which can support the transition to long-term exploitation of the unconventional gas resource without detrimentally impacting the environment. This pilot site is anticipated to serve as a platform for the education of scientists in the disciplines of deep groundwater sampling, baseline monitoring for shale gas activities and downhole geophysical logging for characterisation of deep aquifers.



Regional and local mapping programme around the proposed Beaufort West deep borehole.

A technical working group of experts (national and international) for guidance and advising on the scientific approach will be established. This will also aid various international collaborations and build a platform for CGS young scientists to be well trained in various countries that are already exploring and producing shale gas for energy generation.

In 2012, the CGS was a member of the working group tasked by Department of Mineral Resources (DMR) to draft the technical regulations on petroleum exploration and exploitation by means of hydraulic fracturing for the production of shale gas. The CGS contributed in respect to the requirements for the conditions below ground, the submission of geological reports, the requirements for hydrogeological investigations, and the monitoring of micro-seismicity. The draft regulations were gazetted on 15 October 2013 and the regulations for the petroleum exploration and production under section 107 of the Mineral and Petroleum Resources Development Act (MPRD; Act No. 28 of 2002) were published 3 June 2015.

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ARTICLES

the age of the earth

and other stories: : the centennial of isotopes from a geological perspective

J.D. Kramers,
Geology Department, University of Johannesburg.
Dedicated to the memory of Hugh Allsopp, a South African pioneer of geochronology.

1.
Introduction: the beginning and turbulences around the age of the Earth.

In 1905, at McGill University in Montreal, Canada, Ernest Rutherford carried out a set of experiments designed to determine the ratios of mass, charge and velocity of alpha particles emitted by radium[1]. The instrument he devised for this (Figure 1A) was in essence an electrostatic deflection mass spectrometer and his experiment was based on the earlier observation that alpha particles emitted in a specific decay type had uniform energy (and thus velocity). The fundamental conclusion from the work was that the alpha particles should weigh 4 atomic mass units (amu) for an electric charge of +2, which characterized them as helium nuclei.

After the description of the experiment and the result, Rutherford added a section entitled "Age of Radioactive Minerals", opening thus: "I have previously pointed out that the age of radioactive minerals can be calculated from the amount of helium contained in them. The method is based on the assumption that, in a compact mineral, the greater part of the helium is mechanically imprisoned in the mineral and is unable to escape." He then goes on to quote a few examples of previous measurements, yielding apparent U-He ages up to 400 Ma, but also notes that "this is a minimum estimate, for some of the helium has probably escaped from the mineral". The age calculations used the exponential law of radioactive decay[2], which describes the number of atoms of a radioactive species (e.g. N^U), and the accumulation of a stable daughter species (e.g. N^{He}) as a function of time t:

$$N^U_t = N^U_0 e^{(-\lambda t)} \quad \text{and} \quad N^{He}_t = 8N^U_0(1 - e^{(-\lambda t)}) \qquad (1)$$

where λ is the decay constant, i.e. the probability for where nucleus of U to decay in a given time interval (with large numbers of atoms, the probability becomes a constant). The factor 8 stems from the fact that 8 He atoms are produced in the U decay chain. Only one species of U is acknowledged here as isotopes were not yet discovered at the time.

This was the first solid report on geochronological research using the accumulation of the nuclides that are produced in radioactive decay to determine ages. It contained within it both a core assumption that is still critical today in many applications to geological dating, and an implicit reference to a debate that had been raging for centuries, if not thousands of years. The first is the notion that the products of radioactive decay can remain immobilized within minerals, allowing the absolute measurement of times unimaginable to humans, and the second is the Age of the Earth. It is for the second reason that this first solid report of geochronological results and their interpretation had to be hidden in the tail-end of an article with a very arcane title[1]. The age of the Earth was not only controversial between religion and science, but also within science itself.

In 1650 Archbishop James Ussher, after detailed study of the chronologies of the Hebrew Old Testament and making use of Kepler's astronomical tables, had given his best estimate for the start of Creation of Heaven and Earth as Saturday evening, October 22 of the year 4004 BC. In contrast, observers of the rock record later known as geologists, prominent among them James Hutton, stressed that an "unimaginably long time" must have elapsed to produce the stratigraphy and other geological phenomena as we see them today. From Hutton comes the quote[3] that "we find no vestige of a beginning, – no prospect of an end." Efforts (mostly in the 19th century) to estimate the age of the Earth from stratigraphy and the rate of sediment deposition, as well as from the accumulation of salt in the oceans yielded minimum values of several hundred million years. Thus the view that the age of the Earth was at least four orders of magnitude greater than the literal interpretation of the Scriptures suggested was widely accepted in the latter half of the 19th century. However, between 1860 and 1897 William Thomson (later knighted as Lord Kelvin) calculated ages for the Earth based on its rate of cooling from an assumed initial fully molten state, which were consistently revised downwards. His last published estimate[4] was between 20 and 40 million years. Lord Kelvin's authority in the scientific world at that time was immense, and this is probably the reason why Rutherford had to hide his comments on mineral ages in a paper with a different title. At a Royal Society lecture in 1904, where Kelvin was in the audience, Rutherford famously defused the argument by noting that radioactivity also provided the alternative, hitherto unknown, heat source alluded to ("predicted") by Kelvin as a possible reason why his calculations might have underestimated the age of the Earth. Although we now know that radioactive heating would have made very little difference in the approach used by Kelvin (more important was the possibility of solid-state mantle convection[5]), this set geologists and physicists free to pursue various approaches to the measurement of geological time without censure.

It is quite striking that at these early stages of the discipline of geochronology, progress could be made without the knowledge of isotopes. For the case of the decay of natural long-lived uranium (now known to consist of ^{238}U and ^{235}U) and thorium (single ^{232}Th) via a number of intermediate species, the stable end product was identified as lead by Boltwood[6], who noted a correlation of the abundances of lead and uranium in minerals. Following this, Holmes[7] carried out the first chemical analyses of uranium and lead in minerals of a single rock, targeted specifically at determining its age. He separated uranium-rich minerals from a nepheline syenite that could be bracketed as lower Devonian by intrusive and overlying spatial relationships, and determined its age to be about 370 Ma. Today the Devonian is known to run from 416 to 359 Ma, so that Holmes's determination was remarkably close, considering that he measured total lead, and it was not known at the time that uranium consists of two isotopes. In 1913 Holmes published a popular booklet[8] entitled "the Age of the Earth" and a second edition[9] in 1927. This second edition (in the series "Benn's sixpenny library") was reprinted five times in 1927 – 28, showing the very lively popular interest in the subject at that time. Compared to the first edition it had a much larger dataset of chemical U-Th-Pb ages, and contained a geological time scale with constraints for the Phanerozoic eon already close to what we know today, although for the age of the Earth itself only a minimum of about 1600 million years could be given. Further progress became possible through the measurement of isotope abundance ratios.

2.
The discovery of isotopes, mass spectrometry, and new horizons

The discovery of isotopes was closely linked to radioactivity. Already in 1898, Marie and Pierre Curie had identified the radioactive elements polonium and radium[10], which by 1906 had been identified as intermediate links in the radioactive decay chains of U and Th. Further intermediate products had also been found, mostly characterized by the mode and energy of their radioactive decay, and their sequence in the chains determined. They were assigned names such as uranium X1, X2 and II, ionium, thorium 1 and 2, actinium, protactinium, mesothorium, radium (+ A, B and C), and "emanation". Two great puzzles between 1903 and 1913 were that (1) there were too many of these new substances to fit into the given area of the periodic table, and (2) some could not be chemically separated. For instance, "ionium" could not be separated from thorium by any method in the great arsenal of chemistry already in existence in those days, and likewise, the different uraniums could not be isolated. These puzzles were simultaneously and independently solved in 1913 by Kasimir Fajans[11] and Frederick Soddy[12]. They noted that by α-decay, an element moves two places back in the periodic table, whereas β-decay moves it one place forward (the law of displacement) and further, that species with different types of radioactivity and different atomic weights can

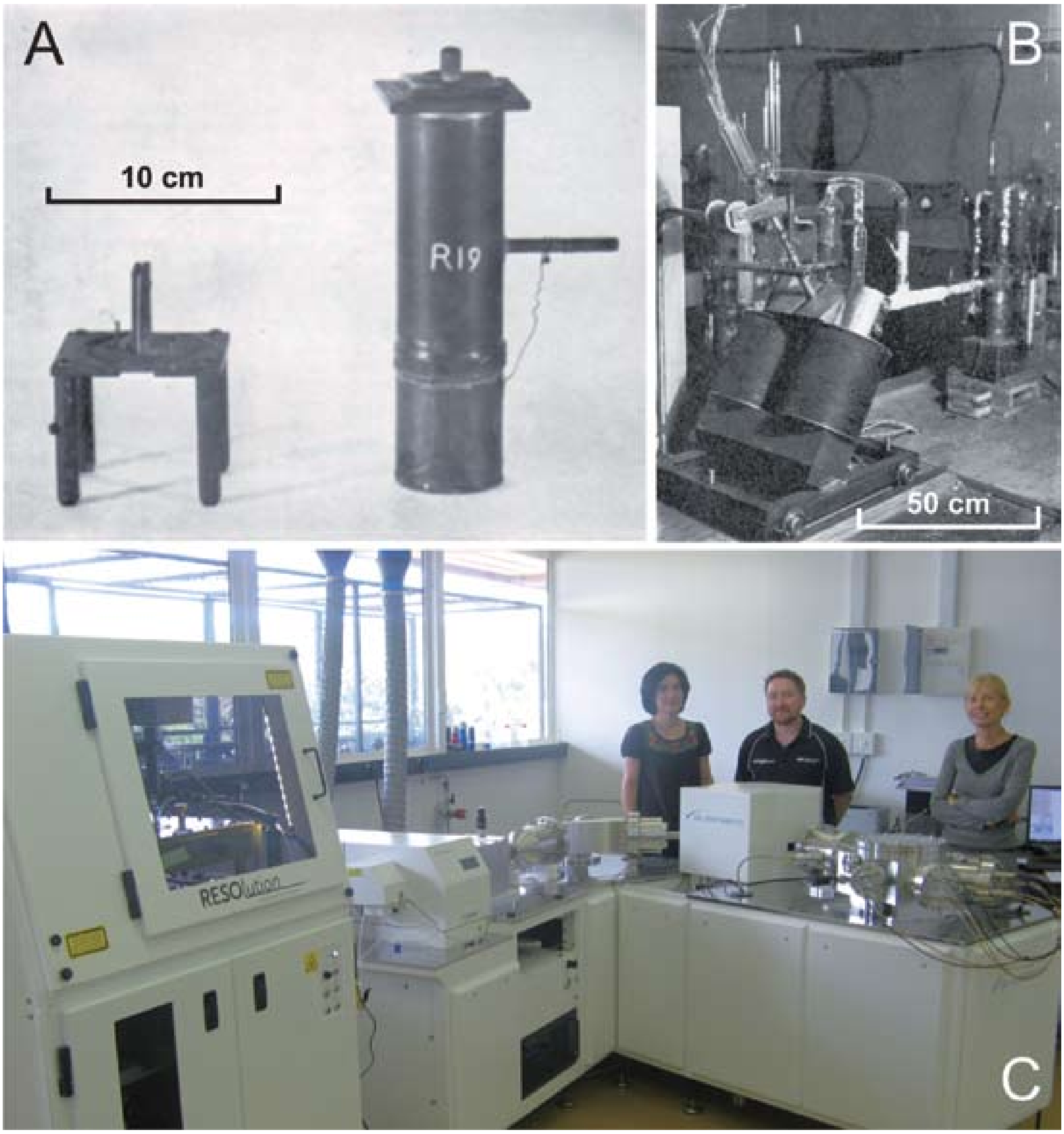

Fig. 1.
Increasing complexity of instruments to detect isotopes and measure isotope abundances
A, device used by Rutherford[1] in 1905.
B, magnet sector mass spectrometer of A. Nier, late 1930's.
C, Cameca 1280 SIMS, operator for scale
(section 6).

occupy the same place in the periodic table, having the same nuclear electric charge - which determines their chemical character. Thus the concept of isotopes (from the Greek, "the same place") was born. The manifold intermediate decay products were different isotopes of only a few elements: U, Th, Pa, Ac, Ra, Rd, Po, Bi and Pb.

In the same year Thomson[13] reported on his experiments with rays of positive ions, which built on earlier experiments of Goldstein[14] and Wien[15] that would ultimately lead to the development of mass spectrometers. Goldstein had observed rays of positively charged particles in low-pressure gas discharge tubes, so identified because they emanated from a hole in the cathode and which he therefore called "Kanalstrahlen" (channel rays). Wien conducted experiments deflecting such rays, produced in hydrogen gas, with magnetic fields, and identified the particles from their charge/mass ratio as H+ ions, or protons. In his Royal Society Baker lecture, Thomson[13] reported, along with neon, "a new gas whose atomic weight is 22". Soon Thomson and his student, F.W. Aston, recognized that this "new gas" was an isotope of neon, ^{22}Ne. Aston went on to develop improved mass spectrographs, and ultimately identified 212 isotopes of the 83 naturally occurring elements[16,17]. Meanwhile, it was not clear for a long time how isotopes could exist, i.e. how different species of nuclides with different atomic weights could be chemically identical. To account for this, Rutherford[18]

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postulated in 1920 the existence of the neutron, defined as an electrically neutral particle with the same mass as the proton, which was finally detected in 1932 by Chadwick[19]. Then everything fell into place: it is the nuclear charge (the number of protons), that determines the electron configuration and therefore the chemical character of an atom (to which element it belongs). Variations in the number of neutrons in the nucleus affect its mass, but not its chemical properties.

The identical chemical character of isotopes of a given element, noted by Soddy[12], makes them into enormously powerful tracers today, with a host of uses in such diverse fields as physiology and medicine, forensic sciences, material sciences, archeology and of course, geology where applications are the subject of this paper. First, while geological events such as melting, crystallization, hydrothermal mineralization and weathering entail strong fractionation of major and trace elements due to their chemical differences, the isotope abundance ratios of elements are inherited by the end products of such processes intact, except for (minor) changes that are related only to their mass differences. Second, if any isotopes of an element accumulate as ("radiogenic") daughter products of a radioactive decay, its isotope abundance ratios preserve a faithful record of this – except, of course, if mixing occurs later. These two points form the basis of stable and radiogenic isotope geology, respectively, about which more is written further below. But the potential of this science could only be realized tens of years later, after sufficiently precise means of measuring isotope ratios had been developed.

The first true mass spectrometer was developed in 1918 by Dempster[20]. This recorded the ion beams not on a photographic plate, but in an electrometer which allowed the direct measurements of ion currents – and the ratio of ion currents related to specific isotopes should be proportional to the abundance ratios of these isotopes. Dempster generated ions not only by gas discharges, but also, following Richardson's[21] experiments, by heating Na and K salts precipitated on filaments, thus initiating thermal ionization mass spectrometry (TIMS). In 1935 Dempster discovered the minor isotope of uranium, ^{235}U, that exhibits neutron-induced fission and fuels atomic bombs as well as nuclear reactors[22].

It was through the efforts of Alfred O. Nier from the early 1930's on, at Minnesota and Harvard, that the use of mass spectrometry in the measurement of geological time as well as in stable isotope geology was initiated. Nier was the archetype of an instrument scientist. A physicist and engineer, he not only designed and improved mass spectrometers (Figure 1B) throughout his 60 year professional career (ion sources of many modern mass spectrometers are still based on his designs), but also inspired their use in various fields. In the early days of isotope measurements, he is credited with the discovery of ^{40}K as the minor isotope responsible for the radioactivity of potassium[23]. During two years (1936-1938) spent as a postdoc in Harvard, Nier met colleagues in the Chemistry Department who were fascinated by U-Pb geochronology, and (also through correspondence with Arthur Holmes), he rapidly realized the advantages that direct isotope ratio measurements would bring to this new field. This prompted him to make precise measurements of the $^{238}U/^{235}U$ isotope ratio[24], as well as the first direct determinations of the lead isotope composition in rock and mineral samples[25]. As shown below, both were indispensible for the proper development of U-Pb dating. Later, he was instrumental in the discovery of variations in the $^{13}C/^{12}C$ abundance ratio, which laid the basis for carbon stable isotope geology[26,27]. Nier's involvement in the Manhattan Project during the Second World War took him away from geochronology, but also led to further improvements in mass spectrometer design, that would benefit the discipline later. After the war, a further major breakthrough in geochronology was laying the foundation for the K-Ar dating method[28]. Alfred Nier continued to work in his laboratory until days before his death in 1994, and the precise isotope compositions of most elements still bear his signature.

3.
The rise of stable isotope geology.

After the existence of multiple isotopes of many elements had been shown by Aston[16,17], small variations in the relative abundances of the two main oxygen isotopes, ^{16}O and ^{18}O, first came to light as variations in the apparent atomic weight of oxygen[29,30]. Following this, the demonstration of variations in the $^{13}C/^{12}C$ ratio[26,27] indirectly demonstrated that such variations were due to isotope abundance ratio differences. The subsequent direct measurement of variations in the isotope abundances of boron and sulphur[31,32] demonstrated that, at least in light elements, such variations are the rule rather than the exception.

Theoretical understanding of these isotope effects had actually preceded their discovery. Although isotopes of a given element are chemically identical, their different masses make them behave somewhat differently. This can be understood as absolute temperature is proportional to the average kinetic energy of molecules or elementary particles, whether in gases, liquids or solids. Since $E_{kin} = ½ mv^2$, the average velocity (whether vibrational, rotational or translational) of a lighter particle is higher than that of a heavier one. Obviously this also applies to lighter and heavier elements, but there the effect is overshadowed by chemical differences.

The early development of stable isotope geology was spearheaded by Harold Urey and his students at the University of Chicago, particularly Samuel Epstein. Urey received the Nobel Prize for his discovery[33] of deuterium (^2H or D), made by exploiting the predicted difference in vapour pressure between H_2O and HDO. Further work in the early 1930's concerned equilibria between molecular species containing the same multi-isotope element (e.g. hydrogen gas and water). It was predicted from theory, and observed, that species with the stronger chemical bond are somewhat enriched in the heavier isotope of a given element, relative to those with weaker bonds[34-36]. The theory, combining the kinetic principle with statistical mechanics at the molecular level and quantum theory, further predicts that this mass-dependent equilibrium isotope fractionation effect should increase with decreasing temperature[37]. This was indeed observed, and in the early 1950's found its first geological application in an effort to determine the temperature of sea water in the upper Cretaceous, using the differences in oxygen isotope ratios between belemnite guards and ocean water[38,39]. This work failed to prove Urey's hypothesis that a cold period was the cause for the extinction of the dinosaurs[40], but revealed a remarkable record of three summers and four winters in the growth rings of a Jurassic belemnite guard[38] (Figure 2). Also in the 1950's in Chicago, Emiliani[41] applied the carbonate/ water oxygen isotope thermometer to foraminifera tests from oceanic sediment drillcores for the first time, and found the cyclical changes in the Pleistocene, with periods of ca. 100'000 years, that correspond to the ice ages.

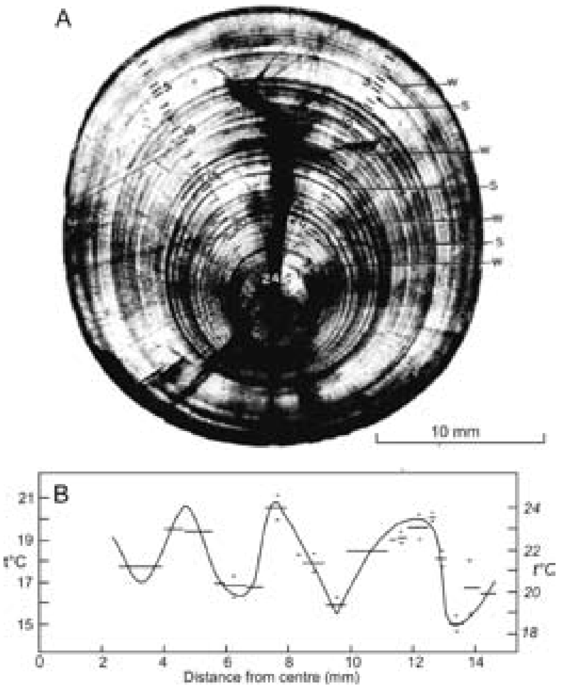


Fig. 2. The first use of oxygen isotope ratios to measure temperature variations of sea water in the geological past[38]. A, cross section of the belemnite guard analyzed, showing growth rings and samples. B, seawater temperatures calculated from oxygen isotopes: Left scale, as calculated by Urey et al.[38] assuming that Jurassic ocean water has the same oxygen isotope composition as today. Right scale, corrected for the ice-free world of the Jurassic (as known today) resulting in lighter sea water oxygen than today and showing more realistic temperatures.

In these papers the convenient delta notation was used for the first time. This relates the isotope ratios measured in samples to that measured on a standard, and has become the universal way of expressing variations in stable isotope abundance ratios:

$\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} -1] \times 1000$
(and analogous for $^{13}C/^{12}C$, $^{34}S/^{32}S$, $^{15}N/^{14}N$, D/H etc.).

The isotope ratios are always arranged in such a way that a positive delta value means enrichment in the heavier isotope relative to the standard, and vice versa.

Samuel Epstein took stable isotope geology to the


M LAMBERT NEWMAN

California Institute of Technology in the mid-fifties. Here, in an explosion of creativity, his group pioneered the detailed research of $\delta^{18}O$ in Pleistocene climate[42], of $\delta^{18}O$ temperature measurements in metamorphic rocks using quartz-iron oxide equilibria[43], and detailed studies of photosynthesis, which showed that strong C isotope fractionation (20-30 ‰ in $\delta^{13}C$) occurred in this process, with the lighter isotope being preferentially incorporated in the organic matter produced. It could be shown that this is a kinetic fractionation effect caused in at least two steps of the process[44]. Meanwhile, $\delta^{13}C$ values of a great variety of rocks, plants, biogenic matter and even meteorites were measured and documented by Harmon Craig in a monumental PhD study in the Chicago lab[45]. This revealed that low $\delta^{13}C$ values in plants and algae are inherited via the food chain by animals and preserved in all organic-rich sedimentary matter, including coal and oil. Carbon isotopes thus constitute an excellent tracer for biological processes on local and global scales. For example, $\delta^{13}C$ studies demonstrated the almost complete cessation of photosynthetic activity during global glaciations that occurred 600 to 700 million years ago[46]. They are also central to the debate on the age of photosynthesis (the minimum age of life) on Earth, discussed further in Section 7.

As many ore minerals are sulphides, sulphur isotope ratio variations have been of great interest in economic geology since their routine measurement became possible. After early analyses[47] had shown differences in $\delta^{34}S$ between individual ore deposits, indicating that S isotopes could thus be a potentially useful indicator for sources of mineralizing fluids, equilibrium fractionation between coexisting sulphides and sulphates also yielded thermometers for ore deposit formation processes[48,49].

The geochemical basis for the diversity of sulphur isotope ratios of different terrestrial systems and environments and its application to ore deposit geology, was defined by Thode et al. and Nakai and Jensen in the early 1960's[50,51]. Starting from a uniform isotope composition as shown by meteoritic matter, fractionation mainly occurred in partial (microbially mediated[52]) oxidation of sulphides or reduction of sulphates, in which the sulphates would be relatively enriched in the heavier isotope ^{34}S. This led to a large range of $\delta^{34}S$ values in sedimentary rocks, contrasting with narrow limits for igneous systems. Thus sulphur isotopes, apart from being useful to economic geology, provide a second tracer for early life on Earth alongside carbon isotopes.

Table 1: Stable isotope systems commonly used in geology

Element	Isotopes	% of total	Variation (o/oo)		Standard
Hydrogen	^{1}H	99.9844	700		SMOW*
	^{2}H ("D")	0.0156			
Carbon	^{12}C	98.89	100		PDB**
	^{13}C	1.11			
Nitrogen	^{14}N	99.64	50		Air
	^{15}N	0.36			
Oxygen	^{16}O	99.763	100	($^{18}O/^{16}O$)	SMOW, PDB
	^{17}O	0.0375			
	^{18}O	0.1995			
Sulfur	^{32}S	95.02	100	($^{34}S/^{32}S$)	Canyon Diablo Troilite***
	^{33}S	0.75			
	^{34}S	4.21			
	^{36}S	0.02			

* Standard Mean Ocean Water

** PeeDee formation belemnite (fossil marine carbonate)

*** Meteoritic material

4.
The age of the Earth revisited

In the 1940's and 1950's, the ability to measure isotope abundances heralded new approaches to solving the problem of the age of the Earth. Following the discovery[22,24] of the minor uranium isotope with mass 235, it became apparent that this isotope, also radioactive, gave rise to ^{207}Pb as an end product. As the two U isotopes had different decay rates, the exciting realization dawned that the U-Pb system includes two clocks – the very feature that makes U-Pb dating of zircon so robust. In these early days, the only type of natural lead sample that could be isotopically analyzed was galena, which is not a chronometer *per se* because it has a zero U/Pb ratio. However, for this very reason galena faithfully records the Pb isotope composition of the system from which it crystallized. Gerling[53], Holmes[54,55] and Houtermans[56] independently realized that this feature could be used to obtain an estimate for the age of the Earth.

The approach was based on the (reasonable) assumption that the Earth, upon its formation t_0 Ma ago, incorporated Pb with uniform $(^{206}Pb/^{204}Pb)_{t0}$ and $(^{207}Pb/^{204}Pb)_{t0}$ abundance ratios. As the amount of ^{204}Pb does not change, these ratios increased in the Earth over time by the accumulation of ^{206}Pb and ^{207}Pb through the decay of ^{238}U and ^{235}U, respectively. Assuming that there is no change in the U/Pb ratio through a chemical differentiation process, the isotope ratios at any time *t1* after the formation of the Earth are then given by

$$(^{206}Pb/^{204}Pb)_{t1} = (^{206}Pb/^{204}Pb)_{t0} + (^{238}U/^{204}Pb)\mathrm{today} \times (e^{(t0\times\lambda 238U)} - e^{(t1\times\lambda 238U)})$$

and

$$(^{207}Pb/^{204}Pb)t1 = (^{207}Pb/^{204}Pb)_{t0} + (^{235}U/^{204}Pb)\mathrm{today} \times (e^{(t0\times\lambda 235U)} - e^{(t1\times\lambda 235U)}) \qquad (3)$$

Here $\lambda 238U$ and $\lambda 235U$ are the decay constants of ^{238}U (1.55125×10^{-10}/yr) and ^{235}U (9.8485×10^{-10}/yr) respectively. Further, the abundance ratio $^{238}U/^{235}U$ had been determined by Nier[24] (his value of 139 has since been refined to 137.88). On the left of the equations are the isotope ratios measured on lead ores of known age *t1*. The independent unknowns are therefore the age of the Earth *t0* and the initial Pb isotope ratios $(^{206}Pb/^{204}Pb)_{t0}$ and $(^{207}Pb/^{204}Pb)_{t0}$ (the U/Pb ratios follow from these). The unknowns can be determined from any three Pb isotope analyses on ores of different age. Holmes[54,55], in an exhaustive numerical approach, found a value of 3350 ± 300 Ma for *t0* providing the best fit to results of 19 isotope analyses of galena samples of known age. Houtermans[56] used the same data in a more elegant approach; he realized that in a plot of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ all samples of the same age *t1* (and evolved in systems with different U/Pb ratios) would plot on a straight line (which he called an isochrone) with slope

$$s = 1/137.88 \times (e^{(t0\times\lambda 235U)} - e^{(t1\times\lambda 235U)})/(e^{(t0\times\lambda 238U)} - e^{(t1\times\lambda 238U)}) \qquad (4)$$

thus yielding *t0* if *t1* was known. The intersection of two such lines would yield the ratios $(^{206}Pb/^{204}Pb)_{t0}$ and $(^{207}Pb/^{204}Pb)_{t0}$. Houtermans (1947) obtained 2900 ± 300 Ma for *t0*, which he scrupulously called the age of uranium, and the uncertainly limits of Holmes's and Houtermans's results overlap comfortably. The average values for U/Pb and (using $^{208}Pb/^{204}Pb$ systematics) Th/U in the silicate Earth obtained by both authors from the same dataset are also close to what is known today.

As mass spectrometric and chemical separation methods for trace elements improved, it became possible to analyze Pb isotope compositions of trace lead in terrestrial rocks and also meteorites. In the first instance, work on phases of iron meteorites, particularly troilite (iron sulphide) material with extremely low U/Pb ratios, allowed direct determination of $(^{206}Pb/^{204}Pb)_{t0}$, $(^{207}Pb/^{204}Pb)_{t0}$ and $(^{208}Pb/^{204}Pb)_{t0}$ (Refs. 56,57). Further, trace Pb in rocks and meteorites reflects isotope evolution in systems where U has not been removed in geological history as it was in lead ores, and thus (referring to eqns. 3 and 4) *t1* = 0 and eqn. 4 becomes:

$$s = 1/137.88 \times (e^{(t0\times\lambda 235U)} - 1)/(e^{(t0\times\lambda 238U)} - 1) \qquad (5)$$

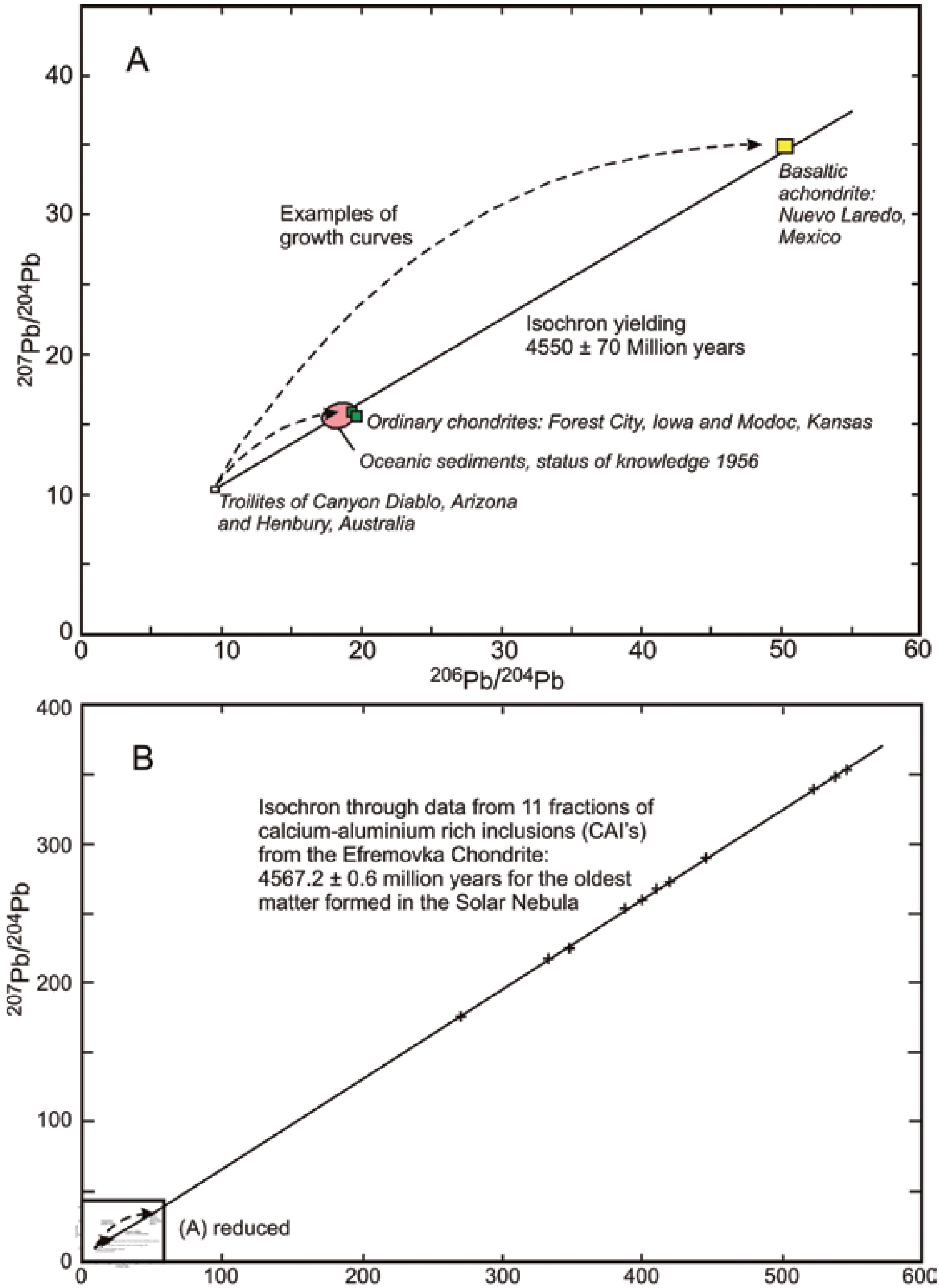


Fig. 3. Diagrams of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ showing data that yield the age of the solar system and (approximately) of the Earth.

A: Figure adapted from Patterson et al. [58] *showing their data with growth curves drawn. It is clear that terrestrial samples plot on the same isochron as various meteoritic material. B: these data combined with recent analyses of calcium-aluminium rich inclusions (CAI) from Efremovka meteorite from Amelin et al.*[59]*, greatly refining the age of the solar system.*

Patterson and coworkers[57] used an average of present-day terrestrial rock $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios in combination with those they had determined on troilite Pb to determine an age of approximately 4500 Ma, noting that "an approximate age value is sufficient and should be viewed with considerable skepticism until the basic assumptions that are involved in the method of calculation are verified." The most important of these basic assumptions was that the various materials analyzed should have remained chemically closed systems since their formation. Subsequently, Patterson[58] analyzed Pb from eucritic, chondritic and iron meteorites and found that together with the troilite sample, these defined an isochron yielding an age of 4550 ± 70 Ma (Figure 3A). Moreover, the cluster of terrestrial rock Pb isotope values, determined earlier, plotted onto this isochron within error, apparently confirming that the Earth is of broadly similar age to other solar system objects. The colinearity of the data (the isochron) further validated the closed system assumption for the extraterrestrial objects. Figure 3B shows, for comparison, a recent dataset[59] that constrains the age of formation of the oldest solar system objects with amazing precision, using the same principle.

The large discrepancy between the ages of the Earth obtained from ore leads and via the meteorite link can be well understood today: a basic assumption in the former, namely, that no differentiation events caused changes in the U/Pb ratios of the terrestrial system in which lead evolved prior to its incorporation in the galenas, was flawed. The Earth's internal and surface processes, which, from available evidence, operated at a faster rate in the Archean than they do today, have led to U/Pb fractionation throughout Earth history and have all but wiped out the geological record from before 3800 Ma. No precise age for the completion of Earth accretion will ever be determined from terrestrial material. Indeed there cannot be a precise age of the Earth: numerical modeling[60] has shown that the accretion of the terrestrial planets, involving giant collisions, must have required tens of millions of years.

5. Geochronology and understanding systems

After the U-Pb dating method, the ^{40}K-^{40}Ar and $^{87}Rb/^{87}Sr$ chronometers were next to be developed for geological use. Their validity was demonstrated, and the decay constants calibrated, by comparing $^{87}Rb/^{87}Sr$ and $^{40}K/^{40}Ar$ dates of micas and feldspars with each other and with U-Pb dates on coexisting U-rich minerals[61-63]. Added to the question raised already by Rutherford[1] and Holmes[7] of whether a radiogenic isotope can actually remain "imprisoned" in a mineral, the possibility that the apparent ages of samples could be affected by any kind of exchange or alteration processes in the course of their geological history has been considered from when geochronology first became a science. In one seminal study[63], ^{87}Rb-^{87}Sr and ^{40}K-^{40}Ar dates were consistent at c. 1350 Ma, while U-Pb apparent ages were younger. This presented a paradox, because apparently atoms of a noble gas (Ar) and a mobile alkaline Earth (Sr) had stayed in their mica "prison", whereas the heavy element Pb had partly escaped from the lattice of U-rich minerals. It was later shown that such (rather common) Pb loss in the case of zircons is mostly due to radiation changing the crystal structure progressively into a less ordered, more permeable state, known as "metamict". The serial decays of U and Th involve many energetic α-decays, where the recoiling heavy nuclei cause most of the damage. In contrast, the decays of ^{40}K (β and electron capture) and ^{87}Rb (β) involve no recoil and the crystal lattice remains intact. The problem of lead loss from zircons was treated theoretically by Wetherill[64], who exploited the fact that the U-Pb decay system includes two clocks, and devised a graphical method (the now universally used concordia plot, Figure 4) to extract the ages of primary formation and of lead loss from datasets affected by lead loss.

Nevertheless, in other early studies, it soon became apparent that K-Ar and Rb-Sr ages, even on unaltered minerals, also frequently appeared variable and too young for known geological constraints. Allsopp[65] investigated this problem for Rb-Sr systematics by comparing dates obtained on separated minerals with results obtained on a number of whole rock samples, for a granite from the Johannesburg Dome, South Africa. He considered that, if individual minerals had gained or lost radiogenic ^{87}Sr in some event after rock formation, the whole rock might still have remained a closed system. He also devised a simple graphical solution for finding the two unknowns, the age and initial amount of ^{87}Sr: "A convenient way of doing this

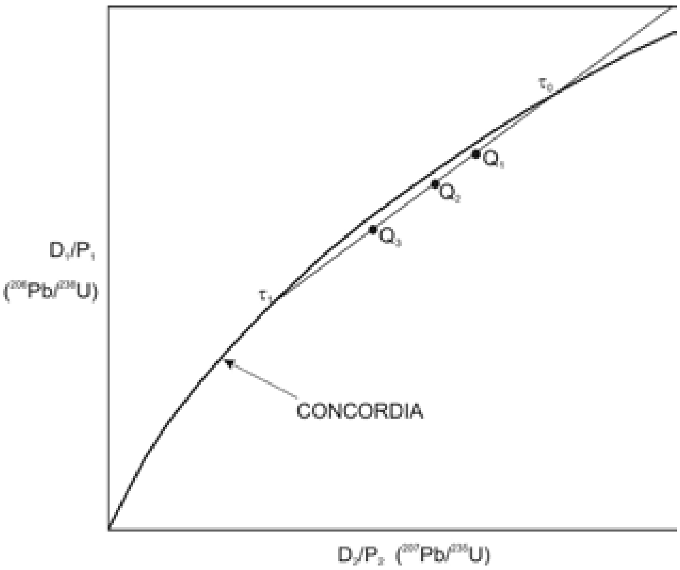


Fig. 4. Concordia diagram, adapted from Wetherill's[64] original publication. Axes are "daughter/parent" isotope ratios which each, independently, yield an age for an analyzed sample (e.g. zircon). The Concordia curve, so named by Wetherill, is where D_1/P_1 and D_2/P_2 plot if they give the same age for the sample. The points Q_1, Q_2 and Q_3 are examples of values that result if samples with original age τ0 lose variable amounts of lead at time τ1, shifting their D/P ratio values towards that at τ1, but still allowing the value of τ0 to be derived.

is to plot the present-day Sr^{87}/Sr^{86} ratios against the corresponding $^{87}Rb/^{86}Sr$ ratios, both being expressed as atomic ratios. A straight line is obtained, its slope being $^{87}Sr^{*}/^{87}Rb$ [* denotes *in situ* radiogenic], and from this the mean age of all the samples considered is calculated. From the intercept of the line with the Rb = 0 axis the primary abundance of ^{87}Sr is calculated." (Ref 64, p 1503; see Figure 5). The straight line referred to is the isochron, widely used ever since in Rb-Sr, Sm-Nd and Lu-Hf geochronology. Allsopp[65] obtained an age of 3200 ± 65 Ma for the Johannesburg Dome granite whole-rock samples (variously confirmed later), and noted that since its formation, K-feldspar and biotite had lost radiogenic 87Sr, while apatite and epidote had gained it. Qualitatively, this is easy to understand: a mineral is useful as a chronometer if the radioactive parent isotope is compatible in its structure and therefore abundant (such as Rb, the geochemical twin sister of K, in K-feldspar and the K-mica biotite) while the daughter isotope belongs to an element that is incompatible in it (Sr in the same minerals). Thus the notion that such isotopes would have a tendency to be lost from such minerals in the event of a disturbance is logical. In the case studied by Allsopp[65], the minerals

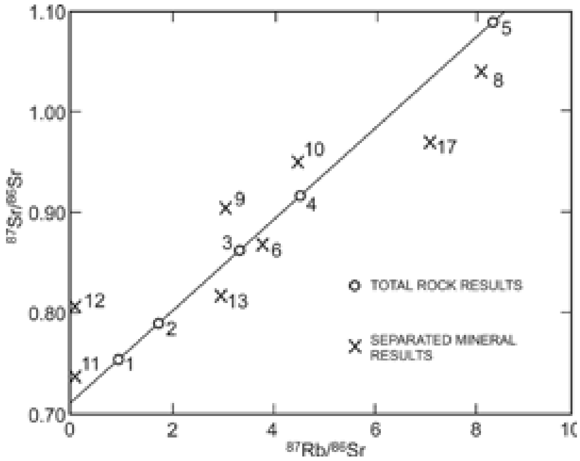


Fig. 5. The first Rb-Sr isochron diagram, redrawn from Allsopp[65], for samples from the Johannesburg Dome granite. The total rock results yield 3200 ± 65 Ma, whereas minerals separated from the rocks show various kinds of open-system behavior as discussed in the text.

receiving Sr are the Ca-minerals epidote and apatite, as Sr is the geochemical twin sister of Ca.

Such open-system behaviour of potential chronometer minerals has been intensively studied since the 1960's, not only because it might impede determining rock formation ages, but also as it could yield ages for the event in which it occurred, whatever its nature. In a classical study, Hart[66] determined Rb-Sr and K-Ar ages on biotite, K-feldspar and hornblende in the aureole of a Tertiary intrusion within Precambrian metamorphic rocks to 6 km from the contact. He found biotite ages to be "reset" at less than 3 km from the contact, whereas K-Ar ages of hornblende and Rb-Sr ages of feldspar were reset only at less than 30 m distance. Using heat flow modeling, Hart could estimate temperatures and calculated activation energies for diffusion for the daughter isotopes ^{87}Sr and ^{40}Ar in these minerals.

Based on the assumption that such loss of daughter isotopes was indeed a temperature-dependent diffusion process, Armstrong et al.[67] used biotite Rb-Sr and K-Ar ages from the central Alps to define a regional map of times of cooling through the temperature below which biotite became a closed system. This defined the rate of cooling (and therefore of uplift and erosion) of different zones in the Alps. It was the first application of what became known as thermochronology to the study of mountain belts. "Closure temperatures" were later assigned to given parent-daughter systematics in many host minerals and listed as more or less canonical values in textbooks, although Dodson[68] demonstrated that such values (in a diffusion scenario) were strongly dependent on grain size and the rate of cooling. Moreover, while in the young Alpine metamorphism the age range of apparent cooling ages of ca. 30 to 10 Ma made good geodynamic sense, in other cases it did not. For instance, in the 1000 Ma Grenville Orogeny, a cooling history apparently stretching over more than 200 Ma was defined[69], which is in conflict with the physics of uplift and cooling of mountain belts. The apparent younger parts of such very long "cooling histories" can now be understood as dating separate, later events, often involving fluid access[70]. Notwithstanding various controversies about details, it is clear that isotope geochronology can do much more than give ages for the formation of rock units: it can put time-markers on events in complicated geodynamic histories.

6.
Boost from the lunar programme and the microbeam revolution

At the end of the 1960's, the return of lunar samples from the Apollo programme brought with it a new challenge: extremely small samples had to be analyzed, and thus the contamination in sample handling, dissolution and chemical separation had to be minimized. Air filtering with the high efficiency particulate filters developed for the semiconductor industry became a standard feature in the isotope geologists' chemistry labs, along with the requirement for operators to wear special clothing. Pyrex beakers were replaced by silica glass and progressively by highly inert and HF-resistant Teflon®-ware. For the U-Pb dating of zircons grains, the approach was to miniaturize all chemical procedures, and switch from borate flux digestions to dissolution with ultrapure HF at high temperature and pressure in Teflon® bombs[71], ultimately enabling the analysis of single grains weighing 1 µg or less by the classical dissolution and thermal ionization mass spectrometry principle initiated by Nier.

Parallel to these advances, the lunar programme also stimulated the development of in situ analytical techniques for both geochronology and stable isotope work. Foremost among these was secondary ion mass spectrometry (SIMS), in which ions are produced directly from the polished surface of a solid sample by bombardment (sputtering) with an intense primary ion beam (O- to produce positive, and Cs+ to produce negative ions), followed by mass spectrometric analysis of these secondary ions. Even in early instruments[71,72] the primary ion beam could be focused on a spot as small as 10 µm diameter, enabling true microanalysis. But the problem was that in addition to ions of the pure elements, ionized compounds were also generated. For instance, there are Zr- and Hf oxides that add up to masses 204, 206, 207 and 208 and are thus superimposed on Pb isotopes. In order to measure the signal intensities for the four Pb isotopes accurately, the mass resolution R of the instrument had to be high enough ($R = M/\Delta M > 3000$) to separate these interfering molecules from them. To achieve this, and at the same time retain high sensitivity, an enormous SIMS with an ion path length of over 5 m was built at the Australian National University, the Sensitive High Resolution Ion Microprobe or SHRIMP[73]. This instrument and others based on the same principle (see Figure 1C) dominated zircon dating, and thus Precambrian geochronology, for the following 20 years. A whole new perspective was revealed by using prior cathodoluminescence imaging to guide the microspot analyses. This imaging can reveal the internal structure of zircons, enabling for instance to discriminate older cores and younger overgrowths, or distinguish magmatic domains from metamorphic ones.

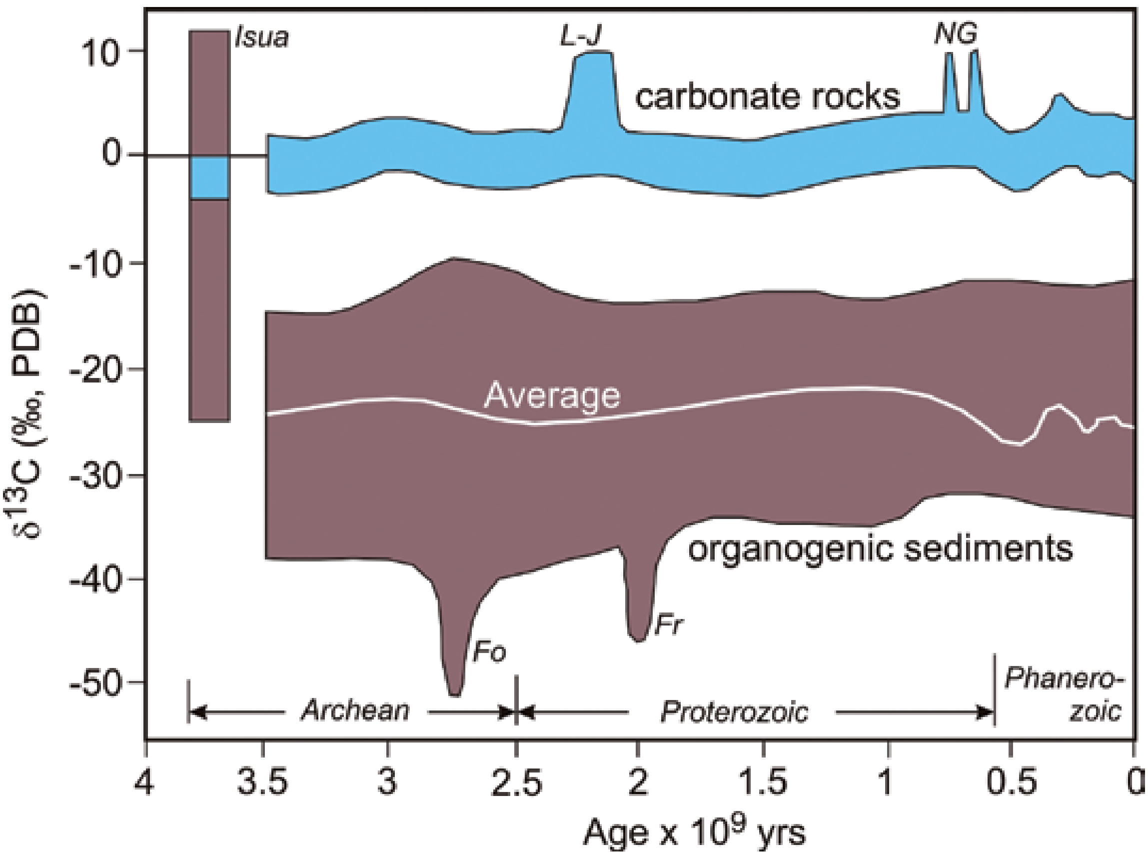
A further microspot development arose in the 1990's and was based on the earlier combination of inductively coupled plasma (ICP) torches with quadrupole mass spectrometers[74]. Inductively coupled Ar plasma has a very high temperature (> 6000 °C) and the first ionization energy of Ar (16eV) is higher than those of all elements making up rocks and minerals. Therefore any sample material (introduced into the central channel of the ICP torch as an aerosol) is ionized with higher efficiency than can be achieved by any other means. Once an interface was developed to introduce the sample plasma into ultrahigh vacuum, the ICP ionization method became available for mass spectrometry. Initially sample aerosols were only nebulized from solutions, but soon pulsed ultraviolet lasers were shown to enable direct, in situ U-Pb dating of zircons[75,76]. The sample is placed in a cell through which a He stream passes on its way to the ICP torch, and the laser is focused on a spot 10 to 50 μm in diameter, through a sapphire window. The combined instrumentation is much cheaper than SIMS, and when using high efficiency magnet-sector mass spectrometers, it equals the precision and accuracy of SIMS instruments. However, the laser rapidly drills a hole through the normally small (< 200 μm) zircon grains, so that little time (ca 1 minute) is available for analysis. Sample throughput is correspondingly high: the challenge of the lunar sample return has yielded quantity as well as quality.

7.
New horizons: forensic science of earliest Earth history

From the above, we could now be forgiven for thinking that isotope geology has become a mere tool to be used in the Earth and Planetary sciences whenever questions of age, or the mode of origin of a geological unit have to be answered. However, the discipline continues to reinvent itself in new ways at the centre of fundamental research. This is illustrated below using three examples. Since the age of the Earth cannot have a precise value, these all at least concern its earliest history.

The first example concerns the history of photosynthesis. This process was "invented" by bacteria, and inherited by plants and algae that evolved from them. Species-recognizable preservation of soft-body fossils, particularly microfossils, is very rare in the geological record, and absent in the eon preceding 2500 million years, known as the Archean. Thus the history of photosynthesis cannot be reconstructed from such data. But as discussed in Section 3, carbon in biomass and its derivatives (coal or disseminated organic carbon in sediments) is enriched in the light isotope ^{12}C relative to the atmosphere from which it is derived. It is on average ca 25‰ "lighter" than that in carbonate, which is derived from the atmosphere via the inorganic process of silicate weathering. Carbon isotope ratios preserved in sediments therefore remain as the only

Fig. 6. Carbon isotope δ^{13}C values of carbonate rocks and organogenic sediments through geological time, slightly adapted from Schidlowski[77]. The significance of differences in Isua, West Greenland (3.8-3.7 Ga) is still controversial, but data show photosynthesis occurred since 3.5 Ga. Anomalies: L-J Lomagundi-Jatulian, NG Neoproterozoic glaciations, Fo Fortescue, Fr Francevillian.



signal of photosynthesis in the remote geological past. A huge carbon isotope database of both organogenic carbon and carbonate rocks, ranging in age from 3.8 billion years to the present, summarized by Schidlowski[77,] shows that since 3.5 billion years ago the rates of sedimentation of carbonate of organogenic carbonaceous matter have remained in the same proportion, about 4:1 (Figure 6). The bulk Earth, and volcanic CO_2 being fed into the atmosphere, has δ13C = -5. In a world with no organic matter being sedimented, carbon in carbonates would have about that value. With light carbon being sequestered into organic-rich sediments, the atmosphere value (reflected in carbonate rocks) is "pushed up" – and at a remarkably constant rate, apart from some so-called excursions related mostly to global glacial episodes. The record clearly shows that photosynthesis was as important a process 3.5 billion years ago as it is today, although it does not reveal whether this was oxygenic or anoxygenic photosynthesis, and therefore cannot be unequivocally linked to the rise of oxygen in our atmosphere. Despite controversies about details, it is evident that the origin of life on Earth, is hidden in Earth's history prior to 3.5 billion years, where the rock record is scarce down to 3.8 billion years and nonexistent before that time.

In the second example, the question of the existence and nature of the Earth's crust in the period before 3.8 billion years ago is addressed. No geological formations dating from this eon, known as the Hadean, have yet been found: the only terrestrial Hadean samples in existence are grains of zircon known as "detrital", i.e. derived by erosion from an unknown source and now found in c. 3.3 billion year old quartzites from two localities (Jack Hills and Mount Narryer) in the Yilgarn Archean Craton of Western Australia[73]. These zircon crystals are time capsules preserving not only their age information through U/Pb and Pb isotope ratios, but also geochemical and oxygen isotope data revealing to some extent their origin and mode of formation. A significant parameter, measured similar to the U-Pb age on microscopic spots by LA-ICP-MS, is the $^{176}Hf/^{177}Hf$ isotope abundance ratio, which can reveal details about the earliest crust of the Earth.

How can this isotope ratio reveal secrets about the vanished terrains from which these zircons were derived? The $^{176}Hf/^{177}Hf$ ratio was initially uniform throughout the solar system, but ^{176}Hf is the daughter product of the β-decay of ^{176}Lu (Table 2). Therefore the ratio increased through geological time, at a rate proportional to the Lu/Hf element ratio. Zircon itself has an extremely low Lu/Hf ratio and therefore essentially retains the $^{176}Hf/^{177}Hf$ ratio it crystallized with, and this reflects the ambient time-integrated Lu/Hf element ratio prior to its formation (Figure 7). Through well-understood chemical differentiation during melting processes in the Earth's mantle, continental ("granitic") crust has a much lower Lu/Hf ratio than the bulk Earth and as a result its $^{176}Hf/^{177}Hf$ increases more slowly, while the remaining (somewhat Hf-depleted) mantle

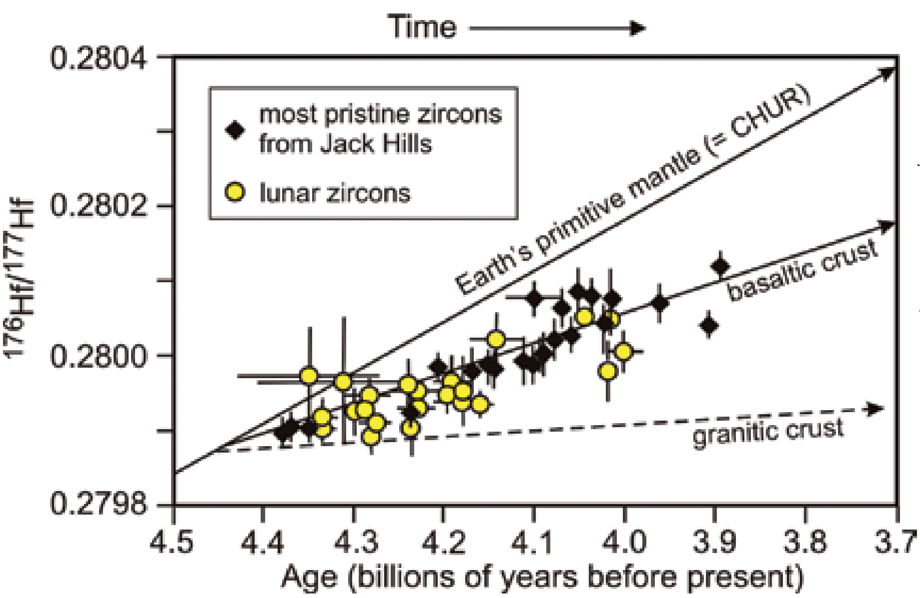


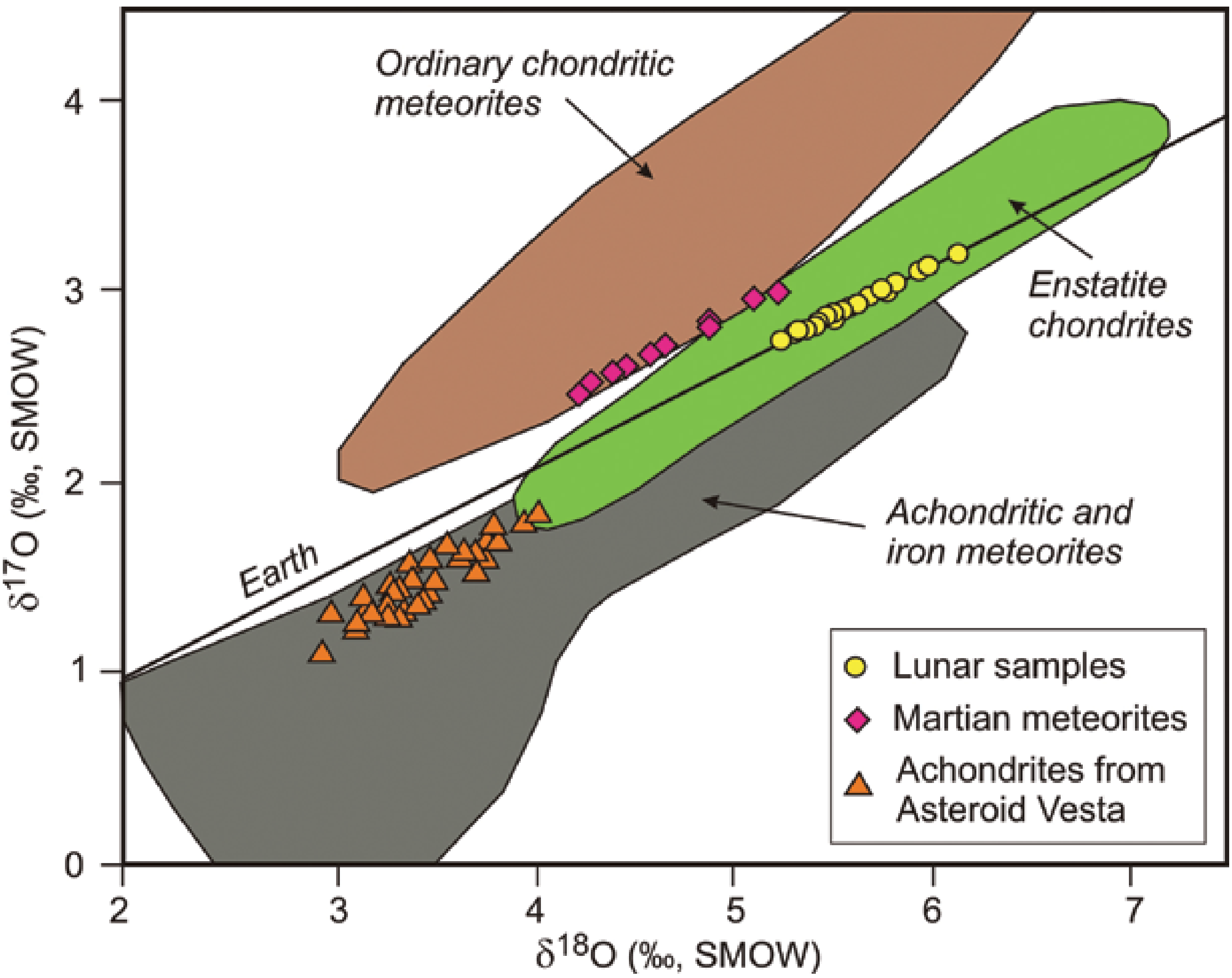
Fig. 7. Plot of hafnium isotope composition versus time, of most pristine detrital zircons found in the Jack Hills quartzite, Western Australia, and zircons from the Lunar highlands, adapted from Kemp et al.[78], indicating a generally basaltic chemistry of crust as it existed in the first 500 million years of Earth's history, and some similarity with the Moon's earliest crust.

shows enhanced $^{176}Hf/^{177}Hf$ growth. Basaltic crust is intermediate between the two.

The published $^{176}Hf/^{177}Hf$ ratio dataset on Hadean zircons, with ages going back to 4.4 billion years, has given rise to considerable controversy on Hadean geology and environment (referenced in ref. 78), but after careful consideration of possible analytical artifacts and effects of alteration, the remaining pristine dataset (Figure 7) shows that the Earth's crust in the Hadean eon, from which the Jack Hills zircons were derived, was essentially basaltic rather than granitic in composition – thus very different in character from today's continental crust[78]. Further, the apparent similarity in age and inferred Lu/Hf ratio of this crust to those of the so-called KREEP basalts of the lunar highlands is striking. Novel, non-actualistic modes for the geodynamics of earliest Earth history are called for in the light of these data.

In the third example, stable oxygen isotope data give rise to a contradiction in a preferred hypothesis on the origin of the Earth-Moon system in the context of planetary accretion, which will force a rethink. The last stage of planet formation is thought to have involved giant collisions, in a period lasting up to 100 million years after the formation of the Solar Nebula[60]. Depending on the energy of collisions, colliding protoplanets would either disintegrate, or merge into a larger planetary body, a set of processes that ultimately led to the stable configuration of the four inner, rocky ("terrestrial") planets existing today. Late in the history of Earth accretion, a collision with an approximately Mars-sized body is thought to have caused the ejection of debris into orbit around the planet, which ultimately accreted to form the moon. Given a specific set of parameters (masses, velocities, angles of impact), this hypothesis[79] can account for the angular momentum of the Earth-Moon system, the mass of the Moon, its

Fig. 8. Three-isotope plot for oxygen, showing the fractionation line for the Earth and data sets for lunar samples[81] as well as for three major groups of meteorites. The close fit of lunar data to those of the Earth is remarkable and presents a new challenge for modelling Moon formation as discussed in the text.



relatively small metal core and the fact that its distance to the Earth is gradually increasing. In all successful numerical models of the event, the Moon was formed chiefly from the material of the impactor. It is here that oxygen isotope data present us with a problem.

The extent of mass dependent fractionation between isotopes with masses $m_2>m_1$ is proportional to $\ln(m_2/m_1)$. Therefore the fractionation of the $^{17}O/^{16}O$ ratio is 0.516 × that of the $^{18}O/^{16}O$ ratio, and in a plot of $^{17}O/^{16}O$ vs. $^{18}O/^{16}O$ (Figure 8), data from samples related to each other by mass dependent isotope fractionation alone should plot on a line of that slope. In Figure 8 the line defined by all terrestrial samples is shown to have this slope. Meteorites from Mars define a parallel line with $\delta^{17}O$ offset to higher values, and various types of meteoritic matter plot on elongate arrays with various positive and negative $\delta^{17}O$ offsets relative to the Earth. While discussing the cause of the $\delta^{17}O$ offsets is beyond the scope of this paper (but see Clayton[80]), it is clear that there is a great deal of diversity. Against this background, the very close coincidence of data from lunar rocks with the terrestrial fractionation line[81] (Figure 8) is remarkable and unexpected. While it cannot be completely ruled out that the impacting body would have had precisely the same oxygen isotope fractionation line as the Earth on which it impacted, Occam's razor would rather suggest that the impact itself involved complete homogenization, and this is not an outcome of any of the published numerical models of moon formation: Here the best of current theories are still at odds with the best data.

These are but three of many examples. They illustrate however that isotopes, both stable and radiogenic, continue after 100 years to provide answers to questions beyond the reach of geology and non-isotope geochemistry, as well as to highlight apparent contradictions that, when addressed, will ultimately improve our understanding of how the Earth as we know it, and ourselves, came about.

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Hutton's unconformity outcrop at Siccar Point, Scotland. The Silurian strata in the lower part of the image were deposited as horizontal sand layers, solidified, and tilted to their present near-vertical state in a later event, then erosion created a flat surface once again, on which the Devonian sandstones in the upper part of the image were deposited. These processes occur so slowly that we cannot directly observe them. Hutton reasoned from the complicated sequence of events that geological time was immeasurably long. Image from www.lpp-foundation.nl

obituary:

Roelof van der Merwe †

The South African Geological community is mourning the loss of Dr. Roelof van der Merwe.

Roelof van der Merwe died unexpectedly in his sleep at his home in Waterkloof, Pretoria, in the early hours of Wednesday morning (23 December). He was 57 and is survived by his wife Willene, step-daughters Rachelle and Nini, Sister Elizabeth van der Merwe (Betsie), and mother Miems.

The evening before his death, van der Merwe had sent a festive season email message to his friends and acquaintances, urging them to greater conservation efforts in the coming year. Roelof was a generous donor to the BirdLife South Africa's seabird conservation, including sponsoring the organisation's Coastal Seabird Conservation Manager position. The private Charl van der Merwe Trust named after Roelof's late father was also "Species Champion" for the endangered African Penguin in BirdLife International's Preventing Extinction Programme, and supported WWF-SA's marine conservation work and EWT's raptor conservation work in the eastern Karoo, as well as conservation work on the Southern Ground Hornbill.

Roelof and his family trust had generously donated to BirdLife South Africa's seabird conservation work, including sponsoring the organisation's Coastal Seabird Conservation Manager position.

Roelof was an unsung conservation hero who did not want praise and recognition. He was a passionate conservationist and deeply committed to efforts to conserve penguins, other seabirds, and the marine environment.

Roelof van der Merwe trained as a geologist, completing his B.Sc (1982), Honours (1983), MSc (1986) and PhD (1994) at Rand Afrikaans University (now the University of Johannesburg) in structural geology under Profs Chris Roering and Jay Barton. Between 1990 and 1992 he worked in petroleum exploration for SOEKOR, before completing his PhD. From 1995 to 2002 he was on the staff of the Geology Department at the University of Pretoria, as Senior Lecturer in structural geology, before taking early retirement to manage the family trust and pursue his passions of conservation, travel and wildlife photography. Roelof's commitment to structural geological education continued after he left the University of Pretoria, as he remained an extraordinary lecturer, and generously sponsored the Roelof van der Merwe prize for the best performing student in the undergraduate structural geology course, and the Dirk Visser prize for the best structural-based honours project.

Dr Roelof van der Merwe receiving the BirdLife International Conservation Achievement Awards from HIH Princess Takamado in 2013.

An accomplished birder and photographer, he travelled widely in pursuit of his passion, including several times to Antarctica. He was further a lover of good wine and dining and tasted the flavours of the world, including Lima, Peru, one of his last stop-overs on his way to the Galapagos Islands. He was a collector of model trains, a past chairman of the Tectonic Division and a Fellow of the Geological Society of Africa.

Our thoughts are with his wife Willene, step-daughters Rachelle and Nini, Sister Elizabeth van der Merwe (Betsie), and mother Miems. Roelof will be remembered by his family and friends for his humbleness and generosity.

Andreas Rompel & Adam Bumby

obituary:

Ian Robert McLachlan †

Ian Robert McLachlan 1942 - 2015.

Ian McLachlan passed away unexpectedly in Cape Town on 22 September, 2015, after complications during surgery. He is survived by his wife Wendy, his daughter Katherine and his elder brother Athol.

Ian grew up in Johannesburg, and after attending Longwood House boarding school he graduated from Witwatersrand University in 1963 with a BSc (Hons) in Economic Geology. At Wits he excelled in gymnastics and became an expert rock climber, climbing in the Magaliesberg and Drakensberg. Ian and his friend Matt Makowski opened the climb "Boggle" in Cedarberg Kloof in the Magaliesberg, which today remains a 5-star "must" climb. He also enjoyed snorkel diving in Mozambique.

After university he worked in mineral exploration in Botswana, Zimbabwe, Swaziland and the Transvaal, first for Rhodesian Selection Trust Exploration and later for Union Corporation where he was seconded to Australia to conduct mineral exploration and to assist in opening a new office in Sydney.

Ian's interest in the palaeontology of the Karoo Basin started in 1970 when he joined SOEKOR Pty Ltd as a petroleum geologist, based at their offices in Braamfontein, Johannesburg. This was the start of Ian's life- long involvement with the petroleum industry. Thereafter his career and life's work were inextricably entwined with South Africa's oil and gas exploration and he played an integral role in its development through the years and was intimately involved in its many successes.

Ian's first task was to upgrade and supervise the SOEKOR laboratory at the Bernard Price Institute for Palaeontological Research where he initially worked with Dr Edna Plumstead and John Anderson on the palynology of the Karoo Basin in order to provide a basis for the dating and correlation of SOEKOR's onshore exploration wells. It was here that he met and worked with Ann Anderson, whom he subsequently married in 1977. Ann was registered for a PhD and was studying the arthropod and fish trace-fossils that are preserved in the shales of the Dwyka and Ecca Groups of the Karoo Supergroup. Ian's particular interest was in determining whether fossil evidence could be found for marine sediments within these sedimentary rocks. The two jointly published six papers on the geology of the Dwyka and Ecca groups, especially the Whitehill Formation.

In the early 1970s Ian set up SOEKOR's new micropalaeontology division to provide age-dating, correlation, environmental interpretation and palynological services for exploration wells drilled in the Karoo Basin. He also established a new laboratory for processing foraminifera and ostracod microfossils. This was only a year after the dramatic results of the first well drilled offshore South Africa when Superior Oil discovered gas with some condensate 60 km off the coastline at Plettenberg Bay. There was nationwide jubilation and The Cape Times ran the story on the front page with the headlines "South Africa's historic gas find" and "Pipelines to Cape Town and P.E. possible" as well as "Oil firms cautiously optimistic over find". Although subsequently shown to be non-commercial, this discovery ushered in a new era and opened the door for foreign explorers. The foreign companies looked to SOEKOR for guidance.

In the late 1970's Ian was involved with the Geological Survey's project on the shale-oil potential of the Whitehill Formation in the lower Ecca Group and conducted Rock-Eval analysis of core samples. During the study he and Doug Cole spent several days logging core in Hertzogville where Ian had the uncanny ability to split core in the correct place to reveal fossils of the arthropod Notocaris tapscotti and leaves of Glossopteris. He found that the best oil potential was associated with amorphous organic material thought to be related to benthic microbial mats. Ian presented the results at Geocongress '90 in Cape Town. At the time of his death, he was again working on the Whitehill Formation for a resource analysis of shale gas in the Karoo Basin for the CSIR Strategic Environmental Assessment Team.

In 1974 Ian was made Head: Palaeontology. This was the year in which the Kudu gas field was discovered in offshore Namibia, drilled by a consortium consisting of Chevron, Regent and SOEKOR.

In 1979 Ian was promoted to Assistant Technical Manager. He was now responsible for micropalaeontology, geochemistry, petrography, core analysis labs and sample stores as well as source rock and sedimentological studies. This was the year in which SOEKOR ceased drilling onshore, having drilled 79 wells without commercial success although some oil and gas shows had been encountered in the Karoo Basin and some minor oil shows in the Algoa Basin. From now on SOEKOR focussed its efforts entirely on the offshore Jurassic and Cretaceous basins. In order to deal with this new frontier Ian established a new Drilling Geology Section to provide wellsite mudlogging and geological services for offshore drilling operations. In keeping with rapidly developing industry norms the geochemistry lab was expanded to include gas chromatography, Rock-Eval pyrolysis analysis of source rock samples and vitrinite reflectance thermal maturity studies. The latter involved preparation of polished samples of extracted kerogen which were examined under reflected light in order to establish the thermal maturity of source and reservoir rocks.

From 1979 to 1983 SOEKOR expanded its offshore drilling programme from an average of three wells per year to ten per year. Then in 1986 the company was relocated to Parow, Cape Town. Ian was responsible for designing expanded laboratories and sample stores as well as managing the relocation of laboratory equipment and core and cuttings samples. Despite innumerable teething problems, through perseverance and meticulous attention to detail Ian ensured that SOEKOR had world class laboratories and drilling services as well as technically competent staff to run them.

Between 1987 and 1989 the SOEKOR exploration department embraced the new discipline of sequence stratigraphy as an exploration tool. This new methodology provided a further stimulus to the development of the Micropalaeontology Department which was now required to provide more accurate age-dating in order to identify sequence boundaries and flooding events and to compile chronostratigraphic data for correlation with world - wide eustatic events.

Working in almost total isolation at that time, SOEKOR micropalaeontologists, under Ian's guidance, refined laboratory procedures and independently developed high resolution dating and correlation techniques which were comparable with, if not superior to, those in use overseas. Application of sequence stratigraphic principles, particularly the recognition of maximum flooding events, together with seismic and other geophysical techniques resulted in remarkable success in pin-pointing the habitat of oil, gas and condensate in the central Bredasdorp sub-basin within the Outeniqua Basin located off the south coast on the Agulhas Bank.

In 1989 Ian was promoted to Chief Consulting Geologist. The offshore drilling programme was extremely active and expanded to an average of eighteen wells per year during 1984 to 1991. At one time Ian had more than one hundred staff reporting to him. It was a period of frenetic drilling activity with three offshore rigs in operation. Numerous minor and some major oil discoveries were made, for example the F-A (Mossgas) and E-M gas fields which began production in 1992, and the Oryx, Oribi and Sable oilfields which began production in 1997, 2000 and 2003, respectively.

In 1992 to 1994, with political changes on the horizon, SOEKOR began a rationalization process and the staff compliment was reduced from 860 to 120. Ian was seconded to the newly formed SOEKOR Oilfield Services Division which was tasked with providing commercial services in all the disciplines that he was currently managing. ENH, the Mozambique national oil company, was the main client and used SOEKOR's services in their exploration programme over the Pande gas field in Mozambique.

In 1996 further rationalization took place with the establishment of SOEKOR's Petroleum Licensing Unit (PLU) which was tasked with promoting and facilitating the exploration and exploitation of South Africa's petroleum resources for nearly all onshore and offshore areas. The entire offshore area of the continental shelf and deeper water was sub-divided into 19 exploration blocks. Foreign exploration companies were keen to get involved with the new democratic South Africa and began to apply for technical study agreements in order to evaluate for themselves the petroleum potential of these under- explored and little known geological basins.

Ian was appointed Concessions Manager and was responsible for monitoring the technical compliance of all oil companies exploring in South Africa. This was not easy because many companies wanted to do it their own way, sometimes using their own proprietary technology, but they were all required to comply with the South African regulations in addition to generally accepted oilfield practice.

Also in 1996, Ian took part in the East African Regional Hydrocarbon Study (EARHS) based in Calgary, Canada which was tasked with evaluating the petroleum potential of the offshore East Africa sedimentary basins including the Zululand Cretaceous Basin of South Africa .

In 1999 the PLU was reconstituted as the Petroleum Agency SA and was designated in terms of the Mineral and Petroleum Resources Development Act (2002). Its mandate was, and still is, to promote exploration for oil and gas resources, as well as their optimal development on behalf of the State. The Agency regulates the activities of exploration and production companies and is the custodian of the national exploration and production database for petroleum. In effect the Agency was mandated by government to be the national petroleum regulator. (It is not to be confused with PetroSA which is the national oil company formed in 2002 by the merger of SOEKOR E and P, Mossgas and parts of the Strategic Fuel Fund.) Ian continued as Concessions Manager. With companies now applying for permits to study data, acquire new data, or to drill, Ian became aware of the need for a more cohesive approach and was instrumental in establishing the Offshore Petroleum Operators Association (OPASA) to serve the mutual interests of explorers and to facilitate easier communication with government.

There was also a need to monitor the offshore marine environment in which the various exploration companies

Petroleum Agency team signing a Technical Cooperation Agreement with Global Offshore Oil Exploration in 2000. Left to right: Ian McLachlan, Reed Gilmore Jr, Neil Oates, Alan Williams, Dave Broad, Jack Holliday, Chris Traeger, Randall Thompson, Eric Jungslager, Jeremy Berry, Steve Mills (photo by P Quinn).

were now operating. Ian helped establish the Generic Environmental Management Programme for offshore petroleum exploration and production operations, writing many of the requirements himself. He also made important contributions to the compilation of the Mineral and Petroleum Resources Development Act of 2002 and the associated Regulations.

The companies applying for study agreements and exploration licences required access to South African petroleum exploration data and Ian played a major role in facilitating the accessing, copying and archiving of the vast amount of geological and geophysical data which was, and still is, looked after by the Petroleum Agency on behalf of the State. He also provided reports to the Minister of Mineral and Petroleum Resources on the petroleum potential of the Karoo Basin.

In recent years there can be little doubt that Ian's most important role was as project manager for South Africa's Extended Continental Shelf Claim Project, a position he was appointed to in 2003. This project was a national strategic response to the United Nations Convention on the Law of the Sea (UNCLOS) (1982, Article 76) which gave coastal states the right to extend their sovereignty beyond the 200 nautical mile limit of the juridical continental slope (the Exclusive Economic Zone, or EEZ). The Petroleum Agency was mandated by government to manage the project and to provide resources which included a small team which

On his way to the UN in New York to submit South Africa's Shelf Claim. (photo by M Xiphu)

varied from three to five geologists/geophysicists. The deadline for national submissions was May 2009.

This was a tight deadline in view of the scope of work required but in characteristic style Ian threw himself wholeheartedly into this huge project. To his colleagues at the Agency it seemed that he lived at the office - he was always first to arrive and last to leave, always working late into the evenings, and on occasion expecting his team to do the same. He achieved an enormous amount and it is to Ian's credit that South Africa's final submission was delivered on schedule and was of a supremely high technical standard.

However, it was not an easy task and there were many obstacles which had to be overcome including major political considerations. It was important to establish appropriate structures and Ian set up a steering committee with representatives of government - a total of eight government departments were eventually involved in the project including the South African Navy, the Council for Geoscience, the Department of Environmental Affairs and Tourism and the Department of Foreign Affairs. Ian motivated for, and obtained government funding, planned and directed operations and established collaboration with the French oceanographic institute Ifremer and the Scott Polar Research Institute based in Cambridge, and liaised widely with many local and international experts. He successfully promoted an agreement at diplomatic level under which South Africa and France established a joint project to optimise the acquisition and interpretation of data around the South African Prince Edward Islands and the French Crozet Islands which led to the submission of a joint claim by South Africa and France for this region.

The Extended Continental Shelf Claim Project team. Left to right: Jenny Marot, Capt Abrie Kampher, Sean Johnson, Mthozami Xiphu, Sidney Osborne, Ian McLachlan, Tshifhiwa Mabidi, Anthony Fielies, Nazley Parker, Shahied Russon (photo by M Xiphu).

Ian's enthusiastic approach was infectious and inspirational to not only the Shelf Claim Team but also his colleagues at the Petroleum Agency. He was always keen to mentor and advise younger geologists. He would sometimes accost colleagues in the passage and direct their attention to the brightly displayed newly acquired geophysical data hanging on the walls. He would remind us that it was a cold, dark and alien world at the bottom of the sea and that even the surface of Mars is more accurately mapped, and would further point out that until today these deep ocean floors had previously been seen only by God himself. He was also fond of reminding his colleagues that South Africa and France shared an international boundary - albeit in the sub-Antarctic.

Ian's approach to the Shelf Claim Project was collaborative and he established working relationships with the equivalent national project teams in Australia, New Zealand, Norway, Ireland, Namibia, Mozambique and Madagascar, and liaised with a large number of foreign academic surveys in order to optimise the acquisition of data relevant to the South African project.

He also initiated a collaborative project with the South African Navy Hydrographic Survey Office and the Directorate of Mapping to compile, for the first time, a digital highwater- mark shoreline for the whole of South Africa and its Prince Edward Islands. This led to diplomatic agreements with Namibia and Mozambique regarding the practical use of median lines as international marine boundaries.

A lasting legacy of the Shelf Claim Project is the enormous amount of data which Ian was able to acquire and assemble and which is now available for future researchers. This includes all geophysical, bathymetric and geological survey data in a 350 nautical mile zone around the margins of the South African mainland and also around the sub-Antarctic Marion and Prince Edward islands. Much new data was acquired. Ian planned, contracted and managed ten extensive marine surveys and acted as onboard Chief Scientist on four deep marine surveys. The new surveys were designed primarily to acquire multibeam echosounder data, but they also collected magnetic, gravity, and seismic reflection and refraction data.

The area of extended continental shelf claimed for South Africa including its Prince Edward Islands, is approximately 1.87 million square kilometres. If successful and endorsed by United Nations, this claim will more than double the size of South Africa's marine territory and furthermore will rank amongst the ten largest claims in the world. Few geologists can claim that their labours resulted in the increased the size of their country! With his wry sense of humour Ian noted that the international shelf claim project is the biggest ever distribution of territory in the world - and so far without bloodshed. However, he was quick to point out that the claim includes only what is on or under the sea floor and does not include fish stocks or fishing rights. During these frenetic years working on the Shelf Claim Project Ian also found time to develop an interest in

Packaging the Shelf Claim Project data in New York (photo by M Xiphu)

Coal Bed Methane and in 2006 he visited Australia's CBM development programme. While there he presented a poster on southern Karoo deep shale gas opportunities at an AAPG conference in Perth.

Ian had an intense love for the natural world, and a deep knowledge of nature in all its wondrous variety. Curiosity was a cardinal virtue for him, and he had lots of it. He knew more about birds, plants, bees, beetles, bugs, fish, than one could imagine. On one occasion when visiting Zimbabwe he spent a night nestled in the branches of a tree next to a river in order to observe elephant and buffalo passing beneath him on their way to drink.

Field work in the Tanqua Karoo

Over his lifetime he made many trips to game reserves in Botswana and Zimbabwe in his two-wheel-drive Combi, and in later years in his Landrover. He became an expert at digging his vehicle out of the Kalahari sand when it got stuck. As a young man he undertook three expeditions crossing the Okavango swamps in makoro dugout canoes with the help of local inhabitants, each trip taking about three months to complete. Ian lamented the loss of wilderness territory and he felt that he was living through the final extinction of the large mammals in the world.

Ian was a workaholic, and he loved what he did. He strove for excellence in everything he did, because he cared deeply. All his life he was a collector. He had a wonderful rock and fossil collection, including beautifully shaped pieces of weathered dolomite from Namibia and a large rounded boulder of amygdaloidal Ventersdorp lava that had been deposited in the southern Cape as an inclusion in the Dwyka tillite. He amassed a large collection of fossils, all meticulously catalogued. Many of them were fish fossils from the Whitehill Formation in the lower Ecca Group in the southwestern and northern Cape. He had hoped to write a thesis on the fossils and palaeo environment of the Whitehill Formation, but sadly was never able to complete it. He was a registered natural scientist, a life member of the Geological Society of South Africa and for many years he was an associate of the Bernard Price Institute of Palaeontology under whose aegis he acquired much of his collection.

Ian and Ann had wonderful times adventuring all over the wild parts of Southern Africa, collecting specimens and looking at whatever the world presented to them. Their happiness was completed with the birth of their daughter Katherine. She too travelled all over in their red Landrover and shared many of her father's adventures.

Sadly, Ann died in 1986 from a long-term congenital condition, which they both bore bravely. In 1987 when the SOEKOR office moved to Parow, Ian and Katherine moved to Cape Town, into a lovely house in Pinelands.

Ian met Wendy Coleman in 1988, and they were married in 2001. He and Wendy also had many wonderful holidays exploring remote places in Southern Africa. Ian retired eventually in 2010, at the age of 68 years, and devoted himself to his house, his garden, and his wife.

Ian deserves a special place in the history of South African geology. He contributed to, or was referee for, many important works on South African and non-South African geology over several decades, even up to recent times. His critical but constructive views and excellent use of English always greatly improved any manuscript - his peers were well aware of this and frequently sought his editorial input. He jointly or individually published at least 41 papers on his work on the Karoo Basin, the onshore and offshore Jurassic-Cretaceous basins and the Extended Continental Shelf Claim project, in addition to 48 internal company reports.

Ian was a private person but had a dry, somewhat eccentric sense of humour. A dinner invitation to his house in Johannesburg was always interesting. His swimming pool was full of fish, and the uninitiated would be ambushed by two pet skunks, rescued from the side of the road, who loved to play tricks on

OBITUARY

unsuspecting guests. Colleagues remember sharing a bag of delicious fine "biltong" only to find out later they had been sampling crushed termites, sent by his brother Athol from Malawi. Indeed, Athol and Ian were inseparable companions and were often to be found together in the veld studying wildlife of all kinds.

Discovery of a fossil tree trunk, Douglas, Northern Cape

In addition to a passion for sharing knowledge, Ian was generous with his time, and visiting scientists from around the world will remember him for his hospitality and guidance which were exemplary and well appreciated by them.

Ian was proud of his Scottish heritage, and when visiting Scotland he would immediately head for the highlands and islands to enjoy the magnificent scenery and to study Scottish geology. For relaxation he read prodigiously and widely, particularly enjoying history, especially military history.

Ian's lasting and indelible legacy is in the enormous contribution he made to South African geology in a variety of disciplines. Ian has left his mark. He will be sorely missed as a scientist, leader, colleague, mentor, friend, brother, father and husband.

Dave Broad, Jan Fatti, Wendy McLachlan, Bill McAloon and Doug Cole.

media monitor

MINING AND EXPLORATION NEWS

Copper

Ivanhoe Mines announced a new high-grade copper discovery at Kakula, approximately 5 km southwest of the currently defined resources at the Kamoa copper deposit in the DRC. Two exploration drill-holes completed in late 2015 intersected some of the highest grade-thickness values drilled to date within the Kamoa licence area, with 3.48% Cu over 24.13 m and 4.64% over 18.47 m. Completion of an 800 m spacing infill grid over the area is planned for 2016. The company said that discovery not only shows the potential to substantially increase the size of the Kamoa Copper Deposit; it also highlights the potential for new discoveries to the west of Kolwezi in the DRC Copperbelt.

Diamonds

Lucara Diamond Corporation recovered a 1111 carat (222 g), gem-quality white Type IIa diamond at its Karowe mine in Botswana. The magnificent stone, measuring 65 × 56 × 40 mm, is the second largest gem-quality diamond in history, eclipsed by only the famous Cullinan Diamond, discovered in 1905 and weighing 3106 carats. It is also the largest ever to be recovered through a modern processing facility, in this case Karowe's newly installed Large Diamond Recovery X-ray transmission (XRT) sorters. Less than a week later, Karowe recovered two more exceptional white stones, one of 813 carats – the sixth largest gem-quality diamond ever mined – and one of 347 carats.

Gold

Alecto Minerals plc has acquired the historic Matala and Dunrobin gold mines, together with satellite prospects, in Zambia for a total of £1.54 million. The two deposits have, in aggregate, a JORC-compliant resource of 760 000 gold ounces at an average grade of 2.3 g/t. US$20 million has been invested in drilling and test work on the project to date, culminating in a scoping study on Matala and a feasibility study on Dunrobin prepared by Coffey Mining in 2013. Alecto

The 1111 carat Type IIa diamond from Karowe (Lucara Diamond Corporation) has completed an updated internal scoping study for an initial three-year, 400 kt/a open pit operation at Matala.

Industrial minerals

Montero Mining and Exploration and Ovation Capital have teamed up to evaluate an extensive marine phosphate deposit off the west coast of South Africa. The project area is 30 km from Saldanha Bay and a similar distance from Montero's onshore Duyker Eiland phosphate project. Exploration of the area for diamonds started in the 1980s, and a major drilling programme was carried out in the 1990s. The phosphorite potential was identified during research studies of the offshore geology and the drill core samples by the Council for Geoscience and the Marine Geoscience Group at the University of Cape Town. The mineralisation forms a sediment layer on the sea bed between 2 m and 4 m thick, at a water depth between 200 m and 260 m water depth, and reaches concentrations of greater than 5% P_2O_5 in places. Montero is currently assessing the core and existing geological information to better understand the phosphate potential, and will review the results with Ovation i to determine whether Ovation will fund a resource study.

Danakili Ltd announced the results of a definitive feasibility study for the Colluli potash project in Eritrea, resulting in a 30% reduction in Phase I development capital to US$298 million, a 'market-leading capital intensity' of US$702 per ton sulphate of potash (SOP), and an accelerated phase I payback period of 3.5 years. Phase I is expected to produce approximately 425 kt/a of premium SOP product (>98% purity), with commissioning targeted for the fourth quarter of 2018. Phase II, beginning production in year 6, will increase total SOP production to 850 kt/a at an additional capital cost of US$175 million. The projected mine life of Colluli currently exceeds 200 years. The Danakil region is one of the largest unexploited potash basins globally, with over 6 billion tons of potassium-bearing salts suitable for the production of potash fertilisers identified in the region so far.

Uranium

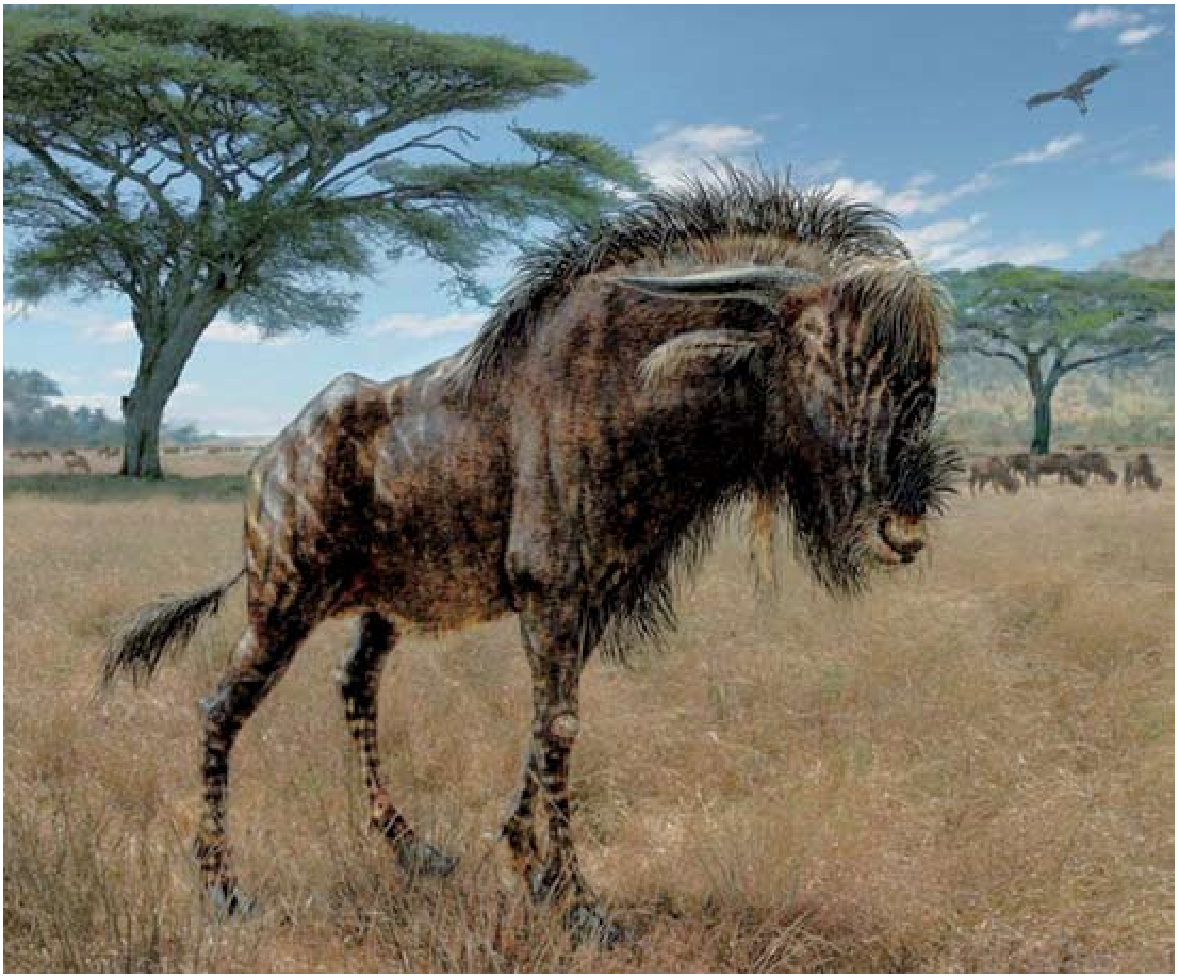
Bannerman Resources completed an optimisation study of its Etango project in Namibia. The study proposes an average annual production of 7.2 million pounds U_3O_8 over an initial 15.7 years open pit mine life, with average life-of-mine cash operating costs of US$38 per pound. The pre-production capital is estimated at US$793 million.

Vanadium

Bushveld Minerals released the results of a pre-feasibility study at its Mokopane vanadium project in South Africa. According to the study, a 1.0 Mt/a run-of-mine operation could produce on average 9525 t of 99.5% purity vanadium pentoxide flakes per annum, based on an ore reserve of 28.56 Mt. The project would contribute approximately 6% of the world's annual vanadium output, at a life-of-mine cash cost of US$3.28 per pound V_2O_5. Bushveld is hoping to secure a strategic partner to take the project forward towards a definitive feasibility study.

Other geoscience news

A recent investigation of three Archaean placer diamonds, recovered from Witwatersrand Supergroup rocks between about 1890 and 1930 and housed in Museum Africa in Johannesburg, has provided evidence that modern-style plate tectonics could have been operating as early as 3.0–3.5 billion years ago. Researchers from the University of the Witwatersrand, University of Johannesburg, and University of Alberta determined the nitrogen abundance and the $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios of the specimens using a state-of-the-art ion microprobe, with a spatial resolution capability of <20 μm, at the Canadian Centre for Isotopic Microanalysis at the University of Alberta, Edmonton, Alberta. The findings were published in the journal Nature Geoscience [doi: 10.1038/ngeo2628]. The diamonds were found to have enriched nitrogen contents and isotopic compositions compared with typical mantle values, which could be due to contamination of the mantle by nitrogen-rich Archaean



Artist's interpretation of Rusingoryx atopocranion (Todd S. Marshall, www.marshalls-art.com)

sediments. Furthermore, the carbon isotopic signature suggests that the diamonds formed by reduction of an oxidized fluid or melt. Assuming that the Archaean mantle was more reduced than the modern mantle, the researchers argue that the oxidized components were introduced into the mantle by crustal recycling at subduction zones. Further support for an early onset of plate tectonics is provided by a recent study from the University of Maryland, published in Science [doi: 10.1126/science.aad5513], in which Ni/Co and Cr/Zn ratios were used as a proxy to track the bulk MgO content of the Archean upper continental crust. This crust appears to have evolved from a highly mafic bulk composition before 3.0 billion years ago to a felsic bulk composition by 2.5 billion years ago. This compositional change was attended by a fivefold increase in the mass of the upper continental crust due to addition of granitic rocks, suggesting the onset of global plate tectonics at about 3.0 billion years ago.

A study of the fossilized skulls of an extinct Pleistocene-age wildebeest-like animal (Rusingoryx atopocranion) unearthed in the Lake Victoria district of Kenya has revealed that the creatures, previously known only from incomplete specimens, had a very unusual large, hollow, bony nasal crest. This is a completely novel feature for a mammal, and is similar only to the nasal crests of hadrosaur dinosaurs. The findings, reported in the journal Current Biology [doi: 10.1016/j.cub.2015.12.050], provide 'a spectacular example of convergent evolution between two very distantly related taxa and across tens of millions of years'. Based on the anatomical investigations, which included computed tomographic imaging, and acoustical modelling, the researchers conclude that the trumpet-like nasal passage may have allowed Rusingoryx to deepen its normal vocal calls, perhaps to frequencies close to infrasound, which may have been below the range audible to predators.

THE SAMREC/SAMVAL COMPANION VOLUME CONFERENCE

An Industry Standard for Mining Professionals in South Africa

17–18 May 2016, Johannesburg

BACKGROUND

The SAMREC and SAMVAL Codes have been updated and will be released in 2016. In the process of updating these Codes numerous aspects were discussed that required more explanation and guidelines than could be included in the codes. In addition it was noted that the SAMCODES have no recognised guidelines or recognised standards, besides the coal commodity specific SANS 10320 National Standard

OBJECTIVES

The conference provides Competent Persons and Competent Valuators the opportunity to prepare and present details of recognised standards and industry benchmarks in all aspects of the SAMREC and SAMVAL Codes. These contributions will be collated into a Companion Volume to provide a guideline and industry standard for the public reporting of Exploration Results, Mineral Resources and Mineral Reserves and the Valuation of Mineral Projects.

The conference will provide a wide range of information pertaining to industry best practice including aspects of a various geological deposit types, commodities, permitting and legal obligations, resource estimation, mining engineering methodologies, metallurgical and process arrangements, engineering/infrastructure design, social and environmental factors etc for SAMREC Code reporting. Other papers will cover the application of the various methods of valuation and where and when they should be applied in accordance with the SAMVAL Code.

This is a valuable opportunity to be involved in the compilation of industry standards and benchmarks to support in all fields related to the SAMREC and SAMVAL Codes.

WHO SHOULD ATTEND

The conference provides a platform for:

- Resource geologists
- Resource investors
- Project Finance Practitioners
- Exploration geologists
- Geoscientists
- Mining engineers
- Mineral Resource and Reserve managers
- Mineral Resource and Reserve practitioners
- Competent Valuators.

SAMREC CODE

Exploration Targets

Reporting of Exploration Results
Exploration Targets
Target generation

Mineral Resources

Geological data collection
Drilling techniques and drilling density
Bulk density
Sampling theory
QA/QC
Sampling and analysis protocols
Geological interpretation and geological modelling
Mineral Resource estimation
Conditional simulation
Mineral Resource estimation
Classification and reporting
Audits and reviews
Deleterious elements/minerals

Mineral Reserves

The modifying factors
Selecting a mining method
Metallurgy
Markets
Optimal mine scheduling
Cut-off grades
Feasibility studies
Risk assessment in Resource and Reserve Classification and reporting
Grade reconciliation

Other Aspects

Legal aspects
Environmental
Sustainability issues
Social and labour planning

Diamond Resource and Reserve Reporting

Coal Resource and Reserve Reporting

SAMVAL CODE

Cost Approach

Valuation of exploration properties using the cost approach

Market Approach

A review of market-based approaches
Valuation of mineral properties without Mineral Resources
Valuation methods for exploration properties and undeveloped Mineral Resources

Cashflow Approach

A Review of cashflow approaches
Discounted cash flow analysis input parameters and sensitivity
Discounted cash flow analysis methodology and discount rates
The valuation of advanced mining projects and operating mines
Valuing mineral opportunities as options

SPONSORSHIP

Sponsorship opportunities are available. Companies wishing to sponsor should contact the Conference Co-ordinator.

THE SOUTH AFRICAN MINERAL CODES

THE SAMREC/SAMVAL COMPANION VOLUME CONFERENCE

An Industry Standard for Mining Professionals in South Africa

17–18 May 2016, Johannesburg

Call for papers

CALL FOR PAPERS

Prospective authors are invited to submit titles and abstracts of their papers, in English. The abstracts should be no longer than 500 words.

Authors will be required to register for the conference and present their papers.

For further information contact:
Head of Conferencing, Raymond van der Berg
SAIMM, P O Box 61127, Marshalltown 2107
Tel: (011) 834-1273/7, Fax: (011) 833-8156 or (011) 838-5923
E-mail: raymond@saimm.co.za · Website: http://www.saimm.co.za

KEY DATES

31 July 2015	Submission of abstracts
15 August 2015	Acceptance of abstracts
30 October 2015	Submission of papers
17–18 May 2016	Conference

The Southern African Institute of Mining and Metallurgy
Head of Conferencing, Raymond van der Berg
THE SAMREC/SAMVAL COMPANION VOLUME CONFERENCE
P.O. Box 61127, Marshalltown, 2107, Tel: +27 11 834-1273/7
THE DETAILS OF THIS FORM CAN BE E-MAILED TO: yolanda@saimm.co.za
or FAXED TO: +27 11 838-5923 / 833-8156

☐ I am interested in attending the conference
☐ I intend to submit an abstract of the proposed paper entitled:

Title of paper: . . . .

Personal Details: Name . . . .

Address . . . .

Tel: . . . . Fax: . . . .

E-mail: . . . .

Kilimanjaro

THE GEOTRAVELLER

By Roger Scoon

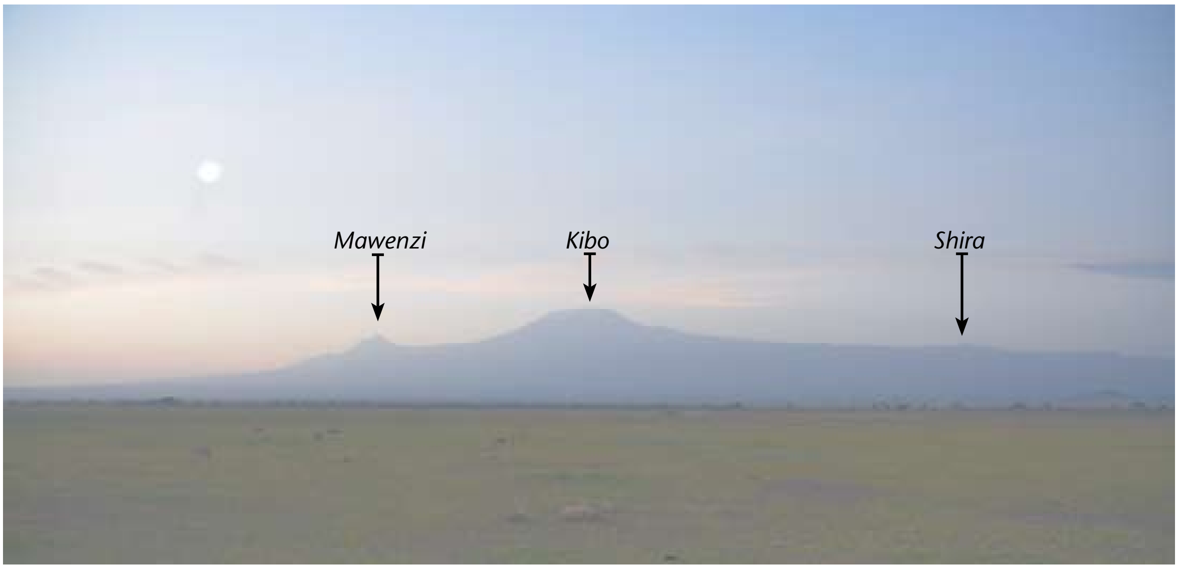
KILIMANJARO: Volcanism and Ice

View of the western slopes of Kibo from Mount Meru. Uhuru Peak is situated on the southern side of the caldera rim (right). Parts of the northern (left) and southern (right) icefields are visible (2004).

The spectacular massif of Kilimanjaro occurs 80 km to the east of the Gregory Rift Valley in a faulted terrane characterized by Neogene volcanism. One of the world's largest free-standing mountains, Kilimanjaro crops out over an area measuring 80 km by 48 km and towers some 5,000 m above the East African plateau. Three discrete volcanic centres are identified. The lowest peaks, Shira (4,006 m) and Mawenzi (5,149) are eroded remnants of extinct cones. The highest peak, Kibo (5,895 m) is dormant with minor fumaroles in the relatively young summit crater. The main episodes of volcanism at Kibo overlapped with Pleistocene glacial epochs. The fast-receding icefields and glaciers are remnants of younger ice that formed prior to onset of the Holocene.

Reports in 1848 by Johannes Rebmann of an ice-capped peak near the Equator were treated with scepticism in Europe, despite references to an African "Moon Mountain" in classical literature. The Greek geographer Strabo and the Roman mathematician Ptolemy probably based their descriptions on information from Ancient Egypt. The first ascents of Kibo were made by Hans Meyer, who reached the summit plateau in 1887 and Uhuru Peak in 1889. Large parts of the massif are included in the Kilimanjaro National Park which is also a World Heritage Site. The park is an important contributor of foreign earnings to the country and is visited by large numbers of hikers. The mountain is generally approached from the regional town of Moshi (altitude of 854 m) on the southern side, although views from the northern (Kenya) side are equally spectacular.

The faulted terrane to the east of the Gregory Rift Valley in northern Tanzania is associated with the petering



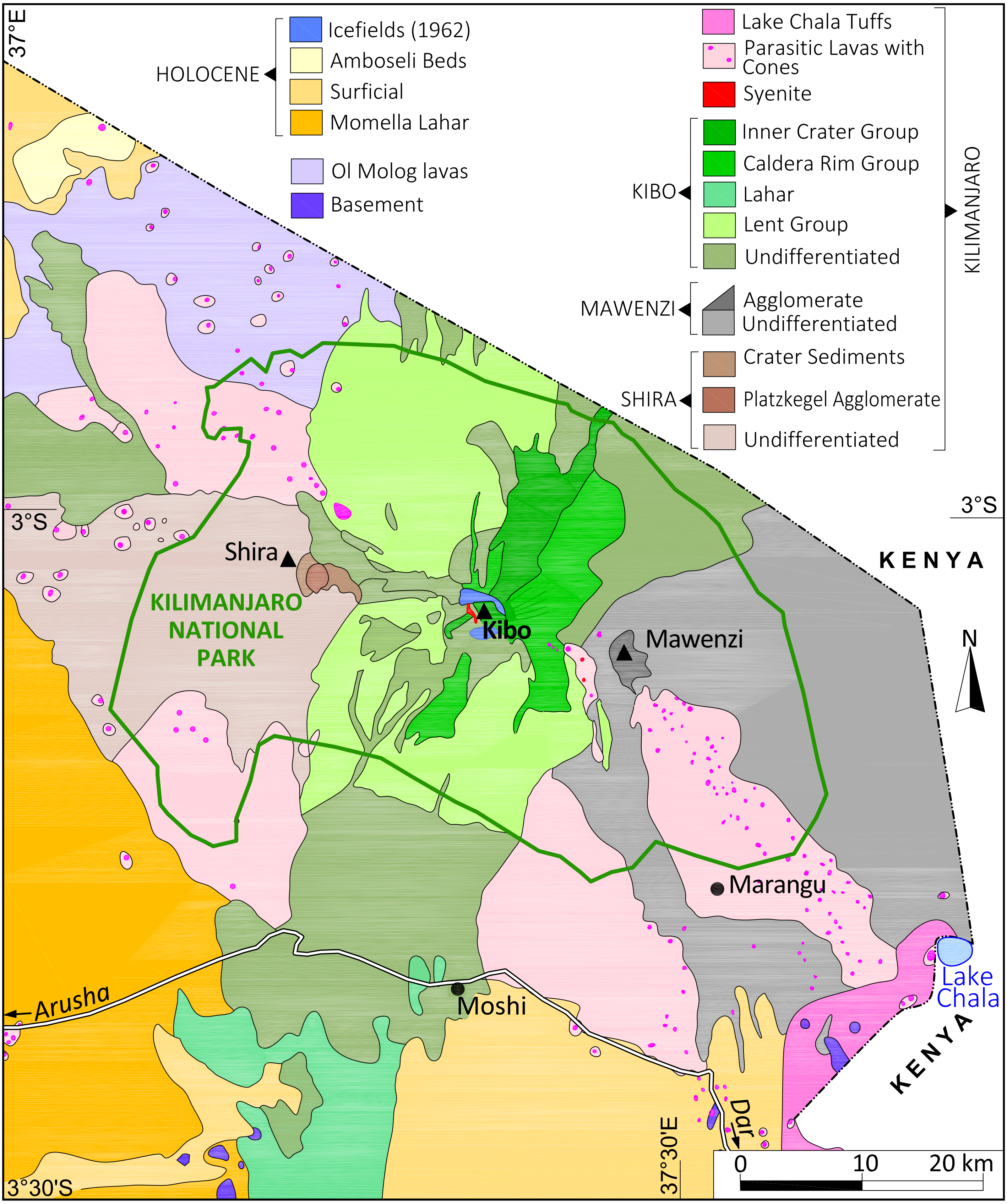
View of the three volcanoes from the northern (Kenya) side.

out and divergence of the southward-propagating rift. Intense volcanism occurs within a 100 km-belt striking almost at right angles to the N-S aligned rift. This area is characterized by huge stratovolcanoes - they include Mount Meru and Kilimanjaro - that are built upon a slightly older volcanic terrane. Volcanism, including flood basalts occurred in a structurally depressed section of the ancient plateau. The Kilimanjaro edifice occurs where a NW-SE striking fault has intersected a lineament aligned at 080^0 on which several volcanoes to the west (including Meru) are aligned. The three centres within Kilimanjaro, Shira (west), Kibo, and Mawenzi (east) are aligned 30 km apart on an axis striking at 110^0.

K-Ar ages have been determined by Nonnotte and colleagues for the three massifs. Shira (2.5-1.9 Ma) is part of the Pliocene and Upper Pleistocene volcanism that is so extensive in northern Tanzania and southern Kenya, both within the rift and the juxtaposed platforms. After a long period of quiescence, the activity shifted from Shira, initially to Mawenzi (1.0-0.45 Ma) and then to Kibo (0.48-0.15 Ma). The Kilimanjaro massif was mapped in 1953 and 1957 by a joint University of Sheffield and Geological Survey of Tanganyika expedition. This resulted in an extremely detailed report by Downie and Wilkinson and a 1:125,000 scale map. Volcanism covers an area of 6,000 Km^2, considerably larger than the massif as lavas and lahars extend onto the surrounding plateaus. The Basement is mostly obscured but the neo-Proterozoic Mozambique Mobile Belt crops out south and south-east of the mountain. A total volume of 4,790 km^3 was erupted: 500 km^3 from each of Shira and Mawenzi and 3,790 km^3 from Kibo.

The simplified map presented here reveals six volcanic groups, as defined by age. The oldest is the Ol Molog basalts although whether they are part of the plateau volcanism or related to Shira is not known. Shira and Mawenzi are partly obscured by Kibo and for this reason, as well as technical difficulties with the ascent of the latter, they are rather poorly known. The volcanism associated with Kibo is extensive. The dominant flow directions are as follows: Shira (southwest), Mawenzi (east), and Kibo (north, south and west). A younger group, dominated by parasitic cones and localized flows is also significant. The Momella Lahar, one of the worlds' largest debris avalanche deposits (DADs) has spread onto the south-western slopes. This feature is associated with the partial collapse of Mount Meru around 7,800 BP.

The Kilimanjaro volcanism is dominated by lava with minor tephra. The two older centres produced mostly basalt and trachybasalt. Kibo displays a differentiation trend that culminates in silica undersaturated lavas. Trachyandesite gives way initially to phonolite and then to nephelinite. Lahars or DADs are associated with Mawenzi (an area of 1,000 Km^2 within Kenya – not shown on the map) and Kibo, the latter occurring on the southern slopes.



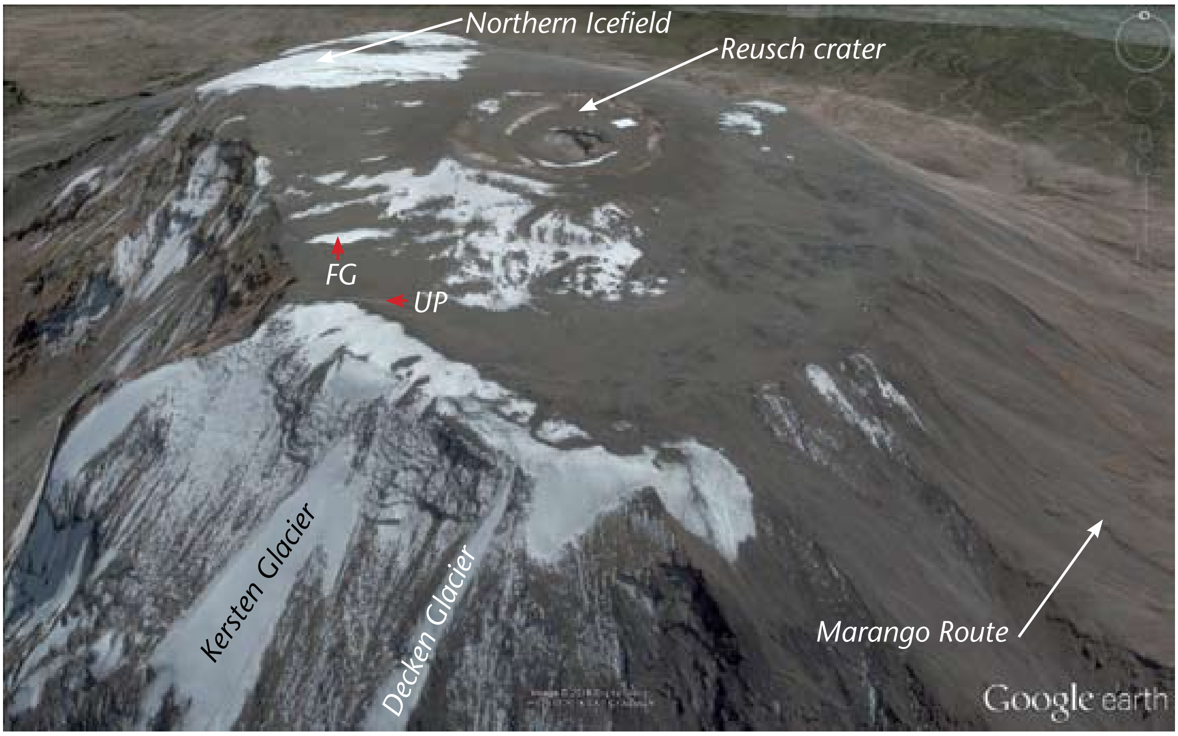
Regional geological map simplified from Downey and Wilkinson (1972). The Small-rhomb Porphyry Group is included with the Lent Group. The Kilimanjaro volcanism (2.5 - 0.15 Ma) overlies the 01 Molog lavas but is younger than the Momella Lahar

The insignificant peak of Shira is located on the broad, western shoulder of Kibo. The highest point on the Shira Ridge is the western rim of an eroded crater. The northern and eastern parts of the crater are covered by lava flows associated with Kibo. Plazkegel is a prominent cone-shaped hill rising some 240 m above the crater floor a few km east of the ridge. The cone is an agglomerate plug and is associated with a radial dyke swarm. The crater is partly filled with younger sediments.

The precipitous cone of Mawenzi is capped by a horseshoe-shaped ridge, the remnants of an eroded crater. The summit ridge on the western and southern sides is precipitous with near-vertical outer cliffs. Steep ravines on the outer slopes include two large features known as the Greater and Lesser Barrancos. They are associated with collapse of the crater wall on the eastern side, an event that triggered the lahar. Two main vents have been identified: Mawenzi and Neumann Tower (located 2 km to the east of the summit). A number of intrusive gabbroic plugs occur. The ribbed appearance of the main cone is ascribed to erosion of a swarm of radial and concentric dykes (estimated between 600 and 800).

View of the Saddle on the Marangu Route looking towards the outer walls of the caldera on Kibo (internet).

The broad outer shoulders of Kibo terminate abruptly at an elevation of 4,500 m where they give way to the steep outer slopes of the upper cone. This section of the mountain, an eroded caldera resembles an upturned basin. The outer slopes include the Barranco, a deep gorge with high cliffs on the western slopes. The interior walls of the caldera rise some 180 m above an elliptical summit plateau that measures 2.7 by 1.9 km. The most popular path, the Marangu Route attains the plateau at Gillman's Point. The caldera has an estimated age of 0.17 Ma and is tilted slightly to the south. Thus, the highest point, Uhuru Peak is on the southern rim and overlooks the inner (and younger) features of the summit plateau. A scarp associated with the caldera fault has been mapped on the southern and western sides of the summit plateau. The Kibo lahar was triggered by caldera



Google Earth image of the summit plateau, Kibo. *FG = Furtwängler Glacier UP = Uhuru Peak* *collapse and carved the Barranco prior to spreading onto the southern slopes.*

The Reusch Crater (diameter 820 m) is located asymmetrically on the summit plateau. This feature is rimmed by the severely eroded walls of the Inner Cone, the altitude of which is 60 m lower than Uhuru Peak. The Reusch Crater hosts the Ash Cone with a central vent, the Ash Pit. The Ash Pit is circular (diameter of 340 m) and with a depth of 130 m. The inner slopes are steep, becoming vertical with depth. This is the youngest volcanic feature identified and has been interpreted as hosting a lava lake which withdrew so rapidly as to preserve the conduit. Active sulphur-rich fumaroles (temperatures of 77-1040C) and steam vents have been reported from the Reusch Crater, on the fractured western wall and the "Terrace". There is, however, debate as to whether they are still active. A deposit of 6-7,000 tonnes of sulphur has been located here. The sulphur forms a thin crust (0.15 m).

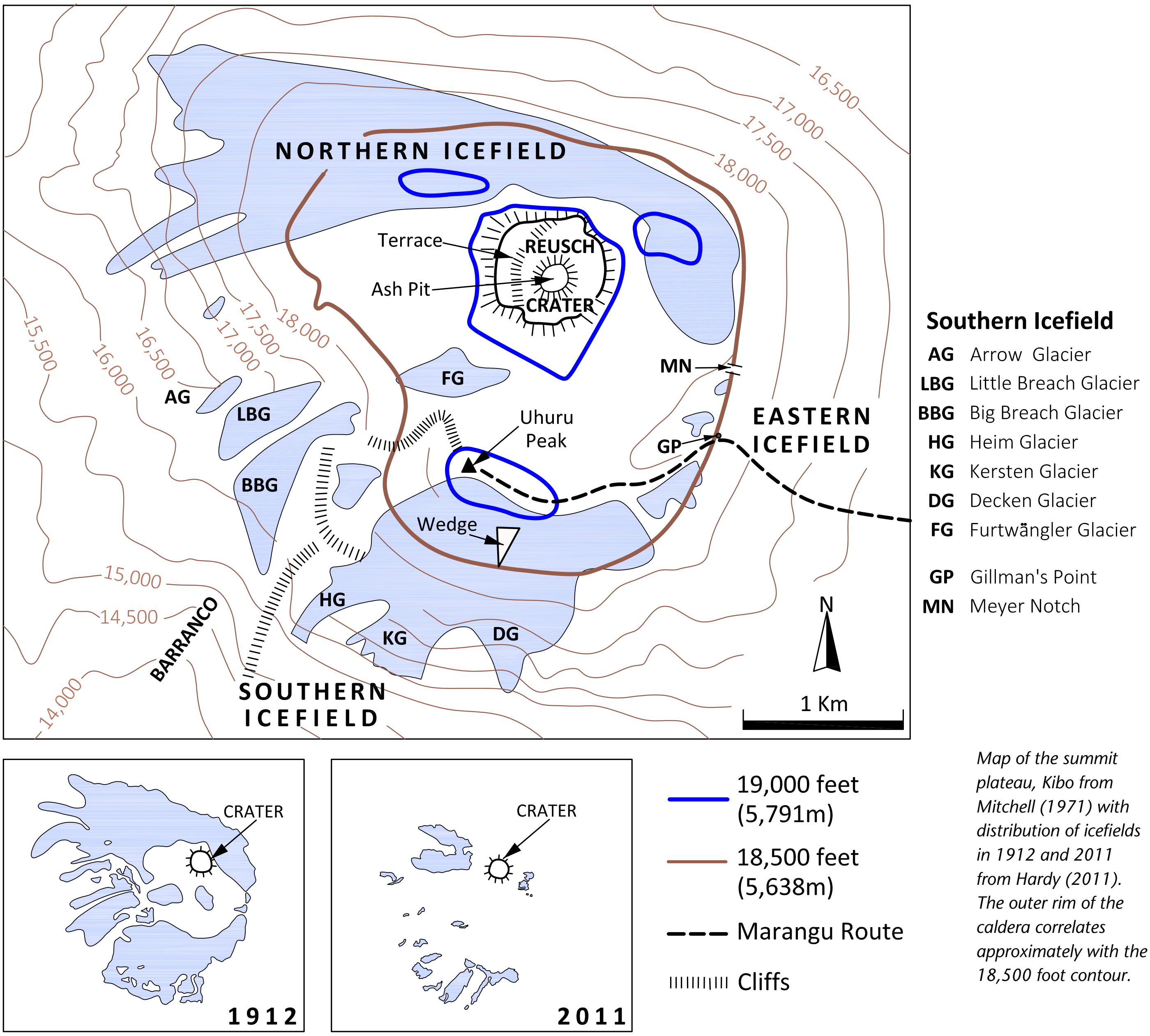
Many of the older lava flows on Kibo are covered by younger flows that originated near the summit. Older flows are only exposed on the lower south-western slopes. Downie and Wilkinson identified ten groups of lavas, most of which are separated by cycles of erosion. The youngest flows are intercalated with glacial deposits (see below). The older lavas are grouped together for simplicity on the map. They include trachyandesite, often with a distinctive porphyritic texture (0.48 Ma). The distribution of the Lent and Small-rhomb Porphyry (0.36-0.38 Ma), Caldera Rim (0.23-0.17 Ma), and Inner Crater (0.15 Ma) groups are shown on the map. They are dominated by trachyte and phonolite with nepheline-bearing phonolite partially filling the Reusch Crater and Ash Pit. A large nephelinite flow, part of the Inner Crater Group has overflowed the caldera and extends down the north-eastern slopes to an altitude of 3,700 m. The caldera fault scarp reveals beds of agglomerate and cinder. A body of syenite some 150-m in thickness has intruded the outer rim of the caldera in the Barranco. The syenite is related to the Small-rhomb Porphyry Group.

Some 250 parasitic cones occur on the lower and intermediate slopes. They are dated at between 0.20 and 0.15 Ma and may in part be contemporaneous with the Reusch Crater. They are associated with Stombolian-type activity that formed cinder and ashes 60-100 m in height. They reveal a broad compositional range (picrobasalt, trachybasalt, ankaramite, and basanite). Lake Chala on the Kenyan border is filling a crater from which an extensive calcareous tuff was ejected. These eruptions are thought to have destroyed a settlement several hundreds of years ago, providing the most recent evidence of volcanic activity on Kilimanjaro.

Kilimanjaro reveals successive botanical and climatic zones defined by height. The lower slopes (1,800-2,900 m) are covered by dense montane forests although sections have been replaced by commercial farms and shambas. The southern and western slopes are the most favourable for cultivation as they receive the highest rainfall and have the most nutrient-rich soils. The wetter forests are dominated by camphor, podocarpus, and fig trees, with junipers and olive trees occurring in drier sections. Vines, Old Mans Beard, and ferns are important components. The forest is terminated, initially by a belt of bamboo, and then by a zone of heather leading to upper moorlands with giant groundsels that are unique to East African mountains. Alpine desert prevails above 4,000 m together with high-altitude tundra, notably in the area known as the Saddle between Kibo and Mawenzi.

The earliest reports described Kibo as covered by a large icecap. The first ascent was made via the Hans Meyer Notch when the summit plateau was almost entirely ice-covered. Only the Reusch Crater was ice-free. Slope glaciers at this time extended to altitudes of 4,500 m. This "historical" icecap covered an area of 20 km^2. An aerial photograph in 1938 revealed the icecap to have shrunk to 11.4 km^2. A map of the summit plateau (based on the 1971 guide) demarcates three icefields with glaciers named after the early German explorers and geographers. The extent of the ice cap at this time can be compared with the earliest (1912) and latest (2011) maps.

The distribution of the ice on Kibo has been widely studied, with recent contributions by Hardy (2011), Cullen et al.



Map of the summit plateau, Kibo from Mitchell (1971) with distribution of icefields in 1912 and 2011 from Hardy (2011). The outer rim of the caldera correlates approximately with the 18,500 foot contour.

(2011) and Pepin et al. (2014). Only eight ice sheets and glaciers survive. They have a combined area of 1.76 km². The Heim, Great Barranco, and Little Penck are now static ice sheets on the caldera rim. The Kersten, Decken, Rebmann, and Credner are slope glaciers; the minimum altitude that ice is now found is approximately 5,000 m. The Furtwängler is the last ice sheet remaining on the summit plateau. Recession during the last 100 years has occurred at approximately 1% annually, with some 40% of the ice having disappeared since 1998. The possibility of an increased rate since the 1950's is discounted. Despite air temperatures at 5,000 m of –70^C, the ice is melting due to solar radiation on exposed vertical walls. Most ice is predicted to have disappeared by 2040, in part as surface areas are persistently shrinking. The absence of permanent ice from the Reusch Crater over long periods of time is evidence of localized heat associated with the fumaroles and steam vents. The summit plateau has a relatively high geothermal flux and meltwater with an average temperature of -1.2°C is transporting heat into the glaciers.

The distribution of ice has changed repeatedly since the Pleistocene. The early glaciations (680,000-130,000 BP) and Main Ice Age (110,000-12,000 BP) resulted in extensive ice sheets. D. W. Humphries, as part of the 1953 and 1957 expeditions identified four (old) glaciations. Thick outwash deposits with giant

Aerial photograph of the Kibo ice cap (1938). View looking approximately south illustrates the raised southern rim of the caldera.

boulders are associated with the second glaciations. The most extensive moraines are, however, related to the Last Glacial Maximum (20,000 BP) when the ice cap measured some 400 Km^2. Moraines, typically some 5 m thick and 6 km in length are particularly well-developed in valleys on the southern slopes of Kibo. They occur at elevations of between 3,350 and 3,960 m and were deposited by glaciers associated with the Southern Ice Fields. Moraines associated with the Little Ice Age and Mini-Ice Age were also identified. Moraines have not been dated, but discrete glacial episodes were recognized on the basis that they are intercalated between the different lava groups. Extensive moraines occur in the radial valleys surrounding Mawenzi, but there is only minor evidence of ice having affected Shira.

View of the Southern Icefields from the Marungu Route (1980).

Ice cores drilled into the Northern Icefield have indicated a maximum age of only 11,700 BP. The older ice sheets disappeared entirely around 12,000 BP due to an extremely dry period just prior to the Holocene. These cores are an important record of climate change in Africa. Slope glaciers occurred throughout the last 10,000 years, but the summit icefield appeared and disappeared repeatedly. The latter is ascribed to dry cycles that occurred every several hundred years due to precession of the Earth's orbit. The African Humid Period (11,000-4,500 BP) is recognized as a time when ice sheets and glaciers expanded considerably. During this period, lakes in the Gregory Rift deepened by as much as 100 m. Evidence from variations in the Na and F content of the aerosol, important components of alkaline lakes, indicates an anomalously dry period occurred at 8,300 BP. A second dry period, which caused recession of the ice at 4,000-3,700 BP, is known as the First Dark Age. This was so widespread as to have affected civilizations around the the Nile River and in the Middle East.

Kilimanjaro provides an opportunity to ascend a substantial peak with no technical difficulty. There are seven main trekking routes of which the most popular is the 5 day Marangu Route. The relative ease of ascent coupled with a rapid gain in altitude can lead to serious problems and acclimatisation by ascending slowly is essential. There is also a danger of avalanche; a fatal incident occurred in 2006 at the base of the Arrow Glacier. Downie and Wilkinson described a large part of the area below the southern and western icefields as being subjected to severe avalanches in the 1950's.

During the past several thousand years the world climate has been relatively settled but is still subjected to natural decade-long cycles that have overprinted longer cycles such as Medieval Warming (800-1250 AD) and the Mini-Ice Age (1250-1850 AD). The potential disappearance of ice from Kibo would be unprecedented during the Holocene as even in the extreme 300 year long drought of the First Dark Age, some ice survived. The conditions currently being experienced have not been replicated during the past 10,000 years.

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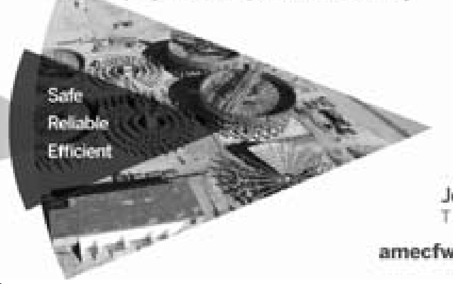

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