GEOSCIENCE CANADA
JOURNAL OF THE GEOLOGICAL ASSOCIATION OF CANADA
JOURNAL DE L'ASSOCIATION GÉOLOGIQUE DU CANADA

Geoscience in the time of Covid

Tectonics, time and topography at the tip of Africa

Earth Science roles for our epoch-making times

Chile - Deep below the Andes sights

Holy petrology in a hidden Highland glen

2020 VOLUME 47

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Cover Image: Maarten de Wit in front of Table Mountain in 2002 when he was showing Andrew Hynes around Cape Province geology. Photo credit: Andrew Hynes

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EDITORIAL

A TRIBUTE

ANDREW HYNES SERIES: TECTONIC PROCESSES:

COMMENTARY

SERIES

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EDITORIAL

Geoscience in the Time of Covid

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SUMMARY

If one thing is beyond discussion in June of 2020, it is that we are living in unique times, even if pandemics are far from unique in longer Human history. A short article in this issue on the topical concept of the Anthropocene closes with a quote that (in part) reads that "*....some humility is in order about our, thus far, infinitesimal part in the history of the planet*". Our high-technology society has certainly received a stark reminder of the power of the natural world, as it struggles to prevail over one of the most primitive of life forms. Few previous analyses of the pandemic threat that I have read fully captured the economic impacts and ethical dilemmas that confront us in this time of Covid. Many in the Canadian Geoscience Community suffered these impacts and some are now directly touched by illness or bereavement. On behalf of those involved in *Geoscience Canada*, I extend sympathies and condolences, and the hope that the time of Covid will be brief.

The American Geological Institute (AGI) recently initiated a study on the impacts of Covid-19 on the Geosciences and invited contributions from member organizations (see *www.americangeosciences.org/workforce/covid19*). No great insight is needed to see how the prohibition of large gatherings and the need for physical distancing could have far-reaching implications for many of the things that we typically do. We will need to think about how to conduct important field work, especially in remote and isolated areas, how to mount our vital professional conferences, and how to educate the next generation of Geoscientists. We should expect that the global pandemic will wreak changes to many other things that we have not yet considered. AGI's initiative is a good step, and one that will hopefully provide some direction and context as we move into next year. There are of course much wider questions to consider, such as whether this global crisis might force society to better confront the threat of climate change or even to rethink the relationship between the Human and Natural worlds. These are not really subjects suited to an editorial, but issues surrounding professional development and education are definitely relevant to *Geoscience Canada*. Even if the time of Covid turns out to be transient, impacts we now see may reverberate through the coming decades.

Geoscience Canada has to date seen only minor impacts from the pandemic. Our small editorial and production team rarely ever meets in person, so our work could continue, but important in-kind support from Universities and Geological Surveys was disrupted by closures in March and April. Suddenly, it seemed as if every process was suddenly two or three times slower than usual, likely reflecting the distraction that accompanies a loss of a sense of certainty. Our decision to defer the first issue of Volume 47 was easy because there really was no other option. We are now happy to present a combined summer issue, even though we would have liked for it to also include some other papers that are still impacted by delays. The various lockdowns around the world might even have some positive side effects – for example, two weeks of mandatory self-isolation in late March finally forced me to finally complete an article that was in some danger of becoming lost. Nobody I know actually likes the idea of being told to stay home, but such circumstances *might* encourage writing, so perhaps we might yet be deluged with high-quality submissions. If nothing else, the preceding sentence illustrates that optimism is a necessary attribute for all editors of small journals. In almost every editorial over the last few years, I point out somewhere that journals like ours simply cannot exist unless readers are also writers and so I will reiterate it, yet again. This is our most important requirement if we are to survive and hopefully grow in the years to come. *Geoscience Canada* needs to maintain and grow the subscriptions that help to sustain us and expand our readership – to do so we must provide high-quality material that is relevant to a wide audience. We cannot do that without our most important contributors – *the authors*.

The Geological Association of Canada (GAC) has taken some direct steps to assist the Geoscience Community in these challenging times. The pandemic has closed libraries around the world, and we have all now discovered that some literature still does not exist online, or is not accessible. In April, many GAC publications were granted interim open-access status to assist users and this includes recent issues of *Geoscience Canada*. Currently, all material published in the journal since its foundation 46 years ago is available without restriction. Recent issues are most easily accessed at *www.geosciencecanada.ca*, and

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older material can be searched and accessed through the more comprehensive site at *https://journals.lib.unb.ca/index.php/GC*. Judging by a recent communication that I received concerning bandwidth issues for our website, this initiative has been welcomed, and it will continue for the foreseeable future. This is perhaps a good time to point out that we are *already* an open-access journal to a large extent, because all content more than 12 months old is freely available under normal policy. For those of you who receive external research funding that requires open-access considerations, this is another good reason to publish with us.

Geoscience Canada is an important part of GAC's Professional Development and Educational agendas, as we encourage the preparation of review-type papers that have long-term value in the training and enlightenment of Geoscientists. We encourage authors to keep non-specialist or undergraduate student audiences in mind as they write, to make their papers clear, and not to inundate readers with unnecessary jargon and acronyms. We also have a role in terms of outreach, to try and inform readers with limited formal training in our science. This is a very wide mandate, and it is perhaps worth thinking about how the time of Covid will affect these key areas, and how we might be better able to assist in adaptation.

As a part-time educator, I am coming to terms with the fact that the entire teaching experience will be very different, at least for a while. I am now considering how to adapt existing materials for online and remote delivery and, like many others, I am struck by the challenges of delivering a 'hands-on' subject in a 'hands-off' environment. So much of what we do in Geoscience, especially in our field work and in observational lab work, is not readily amenable to distance learning strategies. Knowledge of field geology skills is accumulated from direct experience over multiple years and simply cannot be gained from theory alone. A considerable portion of my knowledge was acquired by getting things wrong more than once and learning from mistakes, rather than learning from books. If learning comes largely from computer screens and texts for more than a few years, a coming generation of Geoscientists will be disadvantaged. There is already concern over the limited acquisition of field-related skills such as mapping in our educational systems, and these will be exacerbated by a lack of hands-on learning. We do not want to be a discipline learned largely from computer screens and innovative thinking is required to avoid this fate. Some University Departments are shipping out rock and mineral kits to students enrolled in introductory courses, and some have sent upper-year and graduate students home with petrographic microscopes or other equipment. Other approaches include adjusting schedules for field schools and finding ways to accommodate smaller groups in face-to-face laboratory sessions. Health and community well-being are obviously the first priority, but there may be ways to work within these constraints.

I am less than enthusiastic about the prospect of swapping a real classroom for the computer in my own basement, and probably not meeting or getting to know any students in the coming semester, but online and remote instruction do offer some advantages. I have heard some claims that it might reduce instructor workload, but I do not believe those for a minute. However, it does make it possible for more students to enroll in a course, especially if material can be delivered in an asynchronous manner, allowing them to work at their own pace from elsewhere. It can also remove some of the high associated costs of attending University in person. However, remote instruction is not necessarily more efficient or less expensive than in-person teaching. The challenges of building 'connections' between instructors and students in large classes are greater, and not all students will have the same access to technology or broadband internet. If we are not careful, we might design online instruction that magnifies existing inequities. As I think about how to approach this challenge, I realize that material for online course delivery needs to be more self-contained and comprehensive than material that I typically have used in person. I suspect that many others are coming to the very same conclusion and recognizing the need to prepare in this way. Thus, there may be opportunities in this transition for the development of material that might serve as a starting point for topical review papers – which, naturally, could and should be submitted to *Geoscience Canada*. There is nothing novel about this, as our previous thematic series such as *Facies Models* and *Ore Deposit Models* are well known as educational resources. There is now an opportunity for us to revisit and expand this role, and I encourage those engaged in preparation for online and remote teaching to consider eventually adapting such materials for publication. This might be one positive outcome from a set of circumstances that might presently seem unwelcome to some of us. To convey aspects of field geology without 'being there' is a more significant challenge, but some informative field areas could be framed as self-guided excursions that students might be able to undertake alone, or in smaller groups. *Geoscience Canada's* 'Classic Rock Tours' series, initiated in 2018, is an ideal vehicle for doing just this, although it was not an application that we had in mind at the time. If you have a favourite area that really should be shared more widely with others for any purpose, please consider the idea of contributing to this series.

Conferences and related activities are a vital part of professional development in Geoscience, and they are an important part of GAC's annual agenda. They also contribute vital revenue that provides a foundation for a wide range of activities, including publishing journals like ours. Conferences in all professions have effectively disappeared in the time of Covid, as large gatherings of international delegates propagate viruses as much as they do knowledge. There will be no major on-site Geoscience conferences in 2020 and there is understandable concern about the outlook for 2021. Our annual conference for 2020, integrated with the *Geoconvention 2020* initiative, did not occur in Calgary, and is now reframed as an 'online conference' in late summer. The large European Geoscience Union (EGU) conference in May met a similar fate, becoming a free online event, and the Geological Society of America (GSA) conference originally planned for Montreal this October will also be a 'virtual conference'. This small selection of examples is probably a taste of what is to come. The next GAC-MAC in 2021 (London, Ontario), may be a 'hybrid' conference involving both on-site gatherings and wider online participation, but details have yet to be decided. It is not exactly clear how such a hybrid model will work in practice, but this is likely the way of the future. If an in-person conference can successfully and seamlessly incorporate virtual components it may enjoy wider participation. There will be potential to attract those who may not be able to attend in-person, bring in more students, and perhaps connect scientists whose paths would not otherwise cross.

Scientific conferences serve many roles beyond the science that is presented in lectures and poster sessions. The administrative business of Geoscience societies is conducted there, they serve as vehicles for technical courses, and – most importantly – they serve to connect people from around the world in person. Unfortunately, the latter attribute is exactly what we are now required to avoid at all costs. Field trips at Geoscience conferences provide unparalleled opportunities for discussion and collaboration. They are often where important geological correlations are made, as well as important personal contacts. The long-distance friendships that start at conferences or field trips lead to collaborative research, opportunities for students and to many other outcomes. Students often first meet the professionals who influence their career paths at conferences, and this is where many students get their first jobs. For *Geoscience Canada*, the symposia and special sessions at conferences are where many of the thematic papers that we eventually publish are first formulated. Many of these contributions may be gone, at least for a while. National and regional initiatives that present and disseminate research and ideas across Canada may also be impacted. Depending on the situation in the coming winter, GAC medallist lectures may have to be facilitated by online conferencing tools, at least in part. Similar approaches will be needed for all the technical aspects of Geoscience conferences, and there is a wide range of opinion about the chances of success for virtual conferencing. There is likely some correlation between these opinions and age, so it is probable that the organization of conferences will increasingly be the responsibility of a younger demographic group in our Community. This is probably a good thing in the long run, and the time of Covid may in the end open opportunities and lead to much-needed renewal.

Participation in science is a motivation to attend a conference, but any honest analysis would admit that it is not the *only* reason to attend. The ability to physically travel to a different location, to reunite with friends and colleagues and make new contacts is equally important for many delegates. Not to mention going on field trips. The idea of 'virtual' field trips has been suggested, but it is hard to summon enthusiasm for that prospect, even if it might preclude getting soaked or multiple insect bites. Would potential delegates be prepared to part with registration fees in order to sit in front of their own computers in their own offices? If conferences are designed as synchronous events, i.e. in which online presentations are accessed in specific time slots, will this complicate international participation? If conferences are designed as asynchronous events that you take in at whatever time is convenient (like an online course, perhaps), would they actually qualify as conferences at all? We will not know the answers to these and other questions until we start to work through the process. In the end, conferences and travel are not linked by simple necessity – realistically, many delegates attend because they want to travel, and want to visit and explore a new place. The restrictions and challenges to travel that the time of Covid has imposed will not prove easy for Geoscientists to accept or adapt to, because we tend to be enthusiastic travellers and explorers. I am probably biased, but ours is surely one of the most international of professions.

The above is perhaps a rather pessimistic view and for those of you who do not know me, it likely betrays my age. In the end, we need to put away misgivings and objections and try to find out how to make old things work as best they can in new ways, at least for a while. Just as there is a new normal of mostly online and remote teaching, there will be a new normal for conferences and professional development. Everyone understands that we will all miss many aspects of in-person conferences, and may find it difficult to replace some things. But some things are quite literally out of our hands, and we have no choice but to adapt and embrace changes that may at first seem radical, but will in time feel routine. When the time of Covid comes to an end, we will perhaps return to the old ways of doing things (or at least, I hope we will) but we will hopefully keep many useful and valuable things that come from involuntary adaptations. Above all, we must always remember that we are not making a choice between an idealized "in-person conference" or a "virtual conference", as these are false equivalents. The third option of not holding conferences at all is obviously unpalatable, and the risks presently involved in traditional in-person conferences are simply unacceptable. To paraphrase a well-known axiom, we must hope that necessity turns out to be the mother of innovation, and rely on our well-known reputation for adaptability and resourcefulness.

We can find some good examples of innovation and adaptation in the first few months of this year, which have done much to keep our community connected. The lockdowns imposed in the spring of 2020 led to many online seminars and lectures, delivered via Zoom, Webex and similar tools. Of particular note in Canada are the excellent talks organized by GAC's Volcanology and Igneous Petrology (VIP) division. An international example is the "Ore Deposits Hub" that facilitates topical online seminars related to economic geology (*www.oredepositshub.com*). At the other end of the spectrum is a more local initiative by the Atlantic Geoscience Society and the Newfoundland-Labrador Section of GAC. These are just three examples of initiatives that have served us well in a time when workplaces were closed and social gatherings were impossible. Many similar initiatives have emerged across the world, and in disciplines that I am less familiar with. There is generally little or no cost to participate, but software licenses commonly impose restrictions on the numbers of participants in each session. In some cases, presentations are available as recordings, to reach people who cannot participate directly. If the practical considerations can be resolved, there is potential to involve large numbers of participants, who could never meet in person under normal circumstances. The information about such online professional development ventures is presently circulating to a large extent through informal channels. *Geoscience Canada* might be able to provide a resource centre for information about such initiatives, through our website. Obviously, we are more than happy to encourage more visits, so that more of our papers can be read and downloaded. The seminar series noted above also include many excellent broad-interest lectures that would make excellent topics for thematic series papers. So we certainly have a vested interest, and encourage support for such ventures. Even if physical lectures do eventually resume, virtual equivalents or simultaneous online sessions should probably be an expected requirement in the future.

If there is a statutory limit on the length of an editorial, I have undoubtedly exceeded it, but I must add a few lines to thank those whose efforts make *Geoscience Canada* happen. As scientific editor, I truly depend on contributions from others. My greatest debt is to managing editor Cindy Murphy, who coordinates the long pipeline that leads us from first drafts to the final formatted product. This requires organization, self-discipline, insight and more than a touch of diplomacy, and I greatly value her advice. We also benefit from work by associate editors, who coordinate thematic series papers. I would particularly like to thank Jarda Dostal, Brendan Murphy and David Lentz for their efforts in 2019. We are always interested in recruiting new associate editors – so if you have an idea for a thematic series and are interested in coordinating such an effort, please get in touch. I must also thank tireless volunteer copy editors, who patrol for grammar infractions and do much tedious work to get papers into shape for production. Robert Raeside, Lawson Dickson, Stephen Amor and Janice Allen have all made important contributions. Beverly Strickland and Joanne Rooney are responsible for the attractive layout of the articles in this issue and many previous contributions, and Evelise Bourlon provides our thoughtful French translations. Peter Russell provides the graphic icons that accompany many of our papers, and it is remiss on our part not to acknowledge him each time that they appear. We are very grateful for his time and creative energy. I must also thank Karen Dawe at GAC headquarters in St. John's for support with the administrative aspects of our work. Cindy and I receive institutional support from St. Francis Xavier University and Memorial University, respectively, and the journal also receives institutional support from the University of New Brunswick.

The forty-seventh volume of *Geoscience Canada* did not get off to the best start in 2020, but we hope that these frustrations and delays are now behind us, and that we will be able to bring you diverse and interesting content through the remainder of the year. We also fervently hope that by the time we publish the first issue of volume 48 in March of 2021, the time of Covid will be behind us. In the meantime, we hope that all our readers will stay safe and healthy, adapt to an increasingly online Geoscience world, but also find the time to write a paper for us. We exist to help you share your ideas as well as to help you share in the ideas of others.

ACKNOWLEDGEMENTS

I would like to acknowledge comments and suggestions from incoming GAC president Deanne van Rooyen on the content of this editorial and, as always, valuable advice from Cindy Murphy.

A TRIBUTE

Maarten de Wit: 1947–2020

Maarten de Wit was born in 1947 in the Netherlands, but spent much of his childhood in Ireland. He obtained a BSc from Trinity College, Dublin, and a PhD from the University of Cambridge, where he worked with John Dewey on tectonic problems in western Newfoundland, and where I first came to know him as a fellow graduate student.

Following his PhD, he was a postdoctoral fellow at Lamont and the University of Santiago, where he worked on the tectonics of the Antarctic Peninsula and the southern Andes. From 1976 to 1978 he worked for the UNDP on a project in Ethiopia. Maarten's experiences in 1970s Chile and Ethiopia laid the firm groundwork for a lifelong commitment to improving the lives of the world's less fortunate peoples.

Following a chance encounter with the renowned geochronologist Louis Nicolaysen in Amsterdam in 1979, Maarten moved to the Bernard Price Institute of Geophysics at the University of Witwatersrand. During his 10 years there he worked primarily on the tectonics of the Barberton Greenstone Belt while also becoming deeply involved in the global movement to resist the uncontrolled commercial exploitation of Antarctica. In 1989, he moved to the University of Cape Town where he spent 22 years. During his time at Cape Town, Maarten continued his work on the tectonics of the early Earth but also branched out spectacularly into studies of the evolution of Gondwana, preparation of a compilation map of the geology of Gondwana, the nature of Archean life, the erosional history of the African continent, the potential for shale-gas development in South Africa, the need to establish sustainable practices for the Earth system and, above all, the need to ensure that the activities of the university community were designed to deliver benefits to students from all kinds of background. These interests led him to establish the African Earth Observation Network and later the Earth Stewardship Science Research Institute (AEON-ESSRI). On retirement from the University of Cape Town in 2011, Maarten became the Chair of Earth Stewardship Science at Nelson Mandela University in Port Elizabeth, where he pursued a vigorous program of interdisciplinary studies, supervising graduate students from many different departments and faculties at the University.

Over his career, Maarten supervised more than 75 graduate students and published more than 200 papers. He was a founding member of the South Africa Academy of Science, an Honorary Fellow of the Geological Society of America, and an Honorary Fellow of the Geological Society of London. This paper, to which he and Bastien were putting the final touches when he passed away, nicely illustrates Maarten's long-term activities in the encouragement of student participation in research, the wide scope of the scientific methods he was willing to enlist, and his abiding interest in regional tectonics. His enthusiasm, his energy, and the breadth of his interests were an inspiration to all who knew him. He leaves behind his partner Lynne, his children Thandi and Tjaart and a granddaughter Emma.

Andrew Hynes, 2020 June 10

Maarten de Wit and Andrew Hynes enjoying themselves, Nova Scotia field trip, May 2014. Photo credit: Myrna Hynes.

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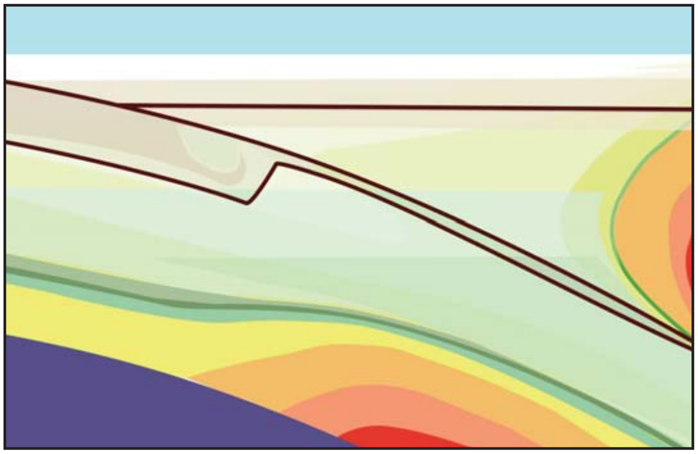
Maarten was full of good intentions to help young students to become scientists, especially the odd ones, and I was one of them. He was dedicated to field geology and he really enjoyed the wildness. His works were mostly maps, collages, painting and handwriting; the computers and cell phones often challenged him. Maarten constantly cultivated new ideas by interconnecting a wealth of readings, experiences, and memories to make research vibrant and attractive. He aimed to bring more together Earth and life scientists, with engineers, sociologists, artists, and the local communities. This new way of doing transdisciplinary research and 'Earth Stewardship Science' will continue forward at AEON-ESSRI.

Bastien Linol, 2020 June 23

The geological field mapping schools in the Cango with Maarten from 1996 to 2018 were fun and mind opening to many South African students. This included geomorphology, sedimentology, structural geology and of course a nice braai (barbecue) together every night at the Campsite (photo credit: Bastien Linol). Bottom left: Nova Scotia field trip, May 2014 (photo credit: Myrna Hynes).

ANDREW HYNES SERIES: TECTONIC PROCESSES



Proterozoic–Paleozoic Sedimentary Rocks and Mesozoic–Cenozoic Landscapes of the Cape Mountains Across the Kango Complex Reveal 'More Gaps Than Record' from Rodinia and Gondwana to Africa

Maarten J. de Wit*, Bastien Linol and Vhuhwavhohau Nengovhela

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SUMMARY

The Kango (Cango) region flanks the northern margins of the Klein Karoo and the Cape Mountains across the Western Cape Province of South Africa. It preserves a condensed Proterozoic–Paleozoic stratigraphy exposed via a Mesozoic–Cenozoic morphology with a present Alpine-like topography. Its rocks and landscapes have been repeatedly mapped and documented for the past 150 years. Over the last 25 years, we remapped and dated a central-eastern section of this region. The subvertically bedded and cleaved rocks reveal an 8–10 km thick stratigraphy covering more than 700 million years between ca. 1200 and 500 Ma with several unconformities and disconformities. At ca. 252 Ma, during the Cape orogeny, this Kango Complex was deformed along thrusts and sub-isoclinal folds producing steeply dipping phyllites and slates. It was uplifted by 3–5 km during the Kalahari epeirogeny between 140 and 60 Ma while eroding at ca. 100–200 m/m.y. (120–80 Ma). During the Cenozoic, the rate of uplift decreased by an order of magnitude and today is ca. 0.4–0.7 m/m.y. across steep slopes and canyons in contrast to the Himalayas where erosion rates are about hundred times faster. A recent publication about this central-eastern section of the Kango region disputes the existence of regional isoclinal folds and suggests that deposition of the oldest sedimentary successions, including carbonate rocks of the Cango Caves (limestone-marble with enigmatic microfossils) was simple, continuous and restricted to between ca. 700 and 500 Ma, decreasing earlier estimates of the stratigraphic age range by 60–80%. Similarly, recent interpretations of the complex landscapes link the northern contact between the Kango and Table Mountain rock sequences to Quaternary faults. We present a new geological database, mapped between 1:500 and 1:10,000 scales, and twelve stratigraphic sections with younging directions linked to structural and isotopic data that support repetitions along regional isoclinal folds and thrust zones of the Kango sequences during the Permo–Triassic Cape orogeny, and geomorphic data that link the origin of its landscapes to weathering and erosion during the Cretaceous–Cenozoic Kalahari epeirogeny. During its evolution, the Kango Basin directly flanked both Grenvillian and Pan-African Mountain systems. But, at an average sedimentation rate of ca. 1 mm/70 years (0.014 mm/year) and with present low erosion rates (0.005 mm/year), there is likely more time missing than preserved of the tectono-erosion across these different regions of Rodinia and Gondwana before Africa emerged. To further evaluate the geodynamic significance of these time gaps requires more field mapping linked to new transdisciplinary geosciences.

RÉSUMÉ

La région du Kango (Cango) flanque les marges nord du petit Karoo et des montagnes du Cap dans la province du Western Cape en Afrique du Sud. Elle préserve une stratigraphie con-

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GC Data Repository: Andrew Hynes Series at https://GAC.ca/GC-data-repository/

densée protérozoïque–paléozoïque exposée via une morphologie mésozoïque–cénozoïque avec une topographie actuelle de type alpin. Ses roches et ses paysages ont été cartographiés et documentés durant les 150 dernières années. Au cours des 25 dernières années, nous avons re-cartographié et daté une section du centre-est de cette région. Les roches litées de manière subverticale et clivées révèlent une stratigraphie de 8 à 10 km d'épaisseur couvrant plus de 700 millions d'années entre environ 1200 et 500 Ma avec plusieurs non-conformités et disconformités. À 252 Ma, au cours de l'orogenèse du Cap, ce Complexe du Kango s'est déformé le long de chevauchements et de plis isoclinaux produisant des schistes à fort pendage. Il a été soulevé de 3 à 5 km au cours de l'épirogenèse du Kalahari entre 140 et 60 Ma, tout en s'érodant à 100–200 m/m.a. (120–80 Ma). Pendant le Cénozoïque, le taux de soulèvement a diminué d'un ordre de grandeur et il est aujourd'hui d'environ 0,4 à 0,7 m/m.a. à travers des pentes abruptes et des canyons, contrairement à l'Himalaya où les taux d'érosion sont environ cent fois plus rapides. Une publication récente sur cette section du centre-est de la région du Kango conteste l'existence de plis isoclinaux régionaux et suggère que le dépôt des plus anciennes successions sédimentaires, y compris les roches carbonatées des Grottes du Cango (marbre calcaire avec des microfossiles énigmatiques) était simple, continu et limité entre environ 700 et 500 Ma, diminuant les estimations antérieures de la tranche d'âge stratigraphique de 60–80%. De même, des interprétations récentes des paysages complexes relient le contact nord entre les séquences rocheuses du Kango et de Table Mountain à des failles quaternaires. Nous présentons une nouvelle base de données géologiques, cartographiée à des échelles entre 1:500 et 1:10,000, et douze coupes stratigraphiques avec des directions de superposition liées à des données structurales et isotopiques qui concordent avec les répétitions le long des plis isoclinaux régionaux et des zones de chevauchement des séquences du Kango pendant l'orogenèse permo–triassique du Cap, et des données géomorphiques qui relient l'origine de ses paysages à l'altération et à l'érosion au cours de l'épirogenèse du Kalahari au Crétacé–Cénozoïque. Au cours de son évolution, le bassin du Kango flanquait les systèmes montagneux grenvillien et panafricain. Mais, à un taux de sédimentation moyen d'environ 1 mm/70 ans (0,014 mm/an) et avec les faibles taux d'érosion actuels (0,005 mm/an), il manque probablement plus d'enregistrements de la tectonique et érosion de ces différentes régions de Rodinia et Gondwana avant l'émergence de l'Afrique que ce qui est actuellement préservé. Pour évaluer la signification géodynamique de ces intervalles de temps manquant, il faut d'avantage de cartographie de terrain associée à de nouvelles géosciences transdisciplinaires.

Traduit par la Traductrice

INTRODUCTION

Geographically, the topography of the Kango (in Afrikaans) or Cango (in English) across the Klein Karoo and Cape Mountains of southern South Africa comprises a paleo-plateau about 1200–1000 m above sea level (asl), incised by dendritic drainage valleys up to 400 m deep that originate along the southern flanks of the ca. 2000 m asl Swartberg Mountains (Fig. 1A), and from which tributaries, such as the Grobbelaars River, meander along the present east–west Cango Valley at ca. 600 m asl. In a few places along the Cango Valley, rivers diverge south in steep canyons that cut through this paleo-Cango plateau and in more open valleys across the lower Oudtshoorn Plateau at ca. 500 m asl, to join the larger Olifants River near Oudtshoorn at ca. 300 m asl (Figs. 1B and 2).

Lester King (1951; pers. comm. 1980) first suggested that the geomorphology of the Cango Valley, including the famous Cango Caves, represents a 'Tertiary' erosion surface with subsurfaces (caves) excavated along old fault zones linked to Cenozoic uplift of southern Africa. More recently, Geoffrey King (pers. comm. 2005; King and Bailey 2006) suggested that the distinct different elevations and geomorphic features separating the hard quartzites of the Swartberg Mountains and the softer sedimentary rocks of the lower lying Cango sequences are linked to Tertiary normal faulting along this contact.

More recent seismic and magnetic data (Stankiewicz et al. 2007; Lindeque et al. 2007, 2011; Weckmann et al. 2012) and fission track and cosmogenic geochronology (Tinker et al. 2008; Decker et al. 2011, 2013; Scharf et al. 2013; Kounov et al. 2015) across this area have shown that the uplift and erosion of the Cango Valley and adjacent mountain systems were linked to epeirogeny with rapid erosion rates (100–200 m/m.y.) during relatively wet conditions of the Early Cretaceous to mid-Cenozoic era, and decreased more than ten-fold during drier climate conditions in the late Cenozoic, reaching very low erosion rates of less than 0.4–1.5 m/m.y. today and over the last 2 to 5 m.y. Thus, the rugged present-day topography across the Cango Valley and the Swartberg Mountains is inherited predominantly from the Cretaceous and has been only minimally re-sculptured by 200–300 m denudation during the late Cenozoic (Kounov et al. 2015). Lester King's 'Tertiary' surfaces, often covered by large quartzite pebbles and boulders are consequently late Mesozoic in age (Fig. 1C).

The famous Cango Caves formed within limestone and marble are massive sinkholes up to 2000 m long and 15–20 m high (Luttman-Johnson 1897), with a number of chambers along a subhorizontal shaft about 270 m below the surface of a well-preserved part of the paleo-Cango plateau ca. 1000 m asl. The caves are incised by a modern drainage that links to the more recent low-eroding surfaces (< 2 m/m.y.) and dendritic drainage valleys (3–6 m/m.y.; see Fig. 2b and details below; for general information and images of the caves see https://en.wikipedia.org/wiki/Cango_Caves). Stalagmites within the Cango Caves are abundant and relatively recent in age (< 200 ka; de Wit et al. unpublished).

Geologically, the Kango rocks across the Cango Valley were originally reported to be older than the Malmesbury Series (Ediacaran; Nama System) and thus linked to parts of the Namaqualand Schist (Dunn 1887), and named the 'Cango Beds' by Corstorphine (1886). Thereafter these rock sequences were mapped as 'a series of slates, grits and sheared conglomerates, among which bands of dolomite of very varying thickness occur', with 'quartz–feldspar-grit or porphyroids, and diabase in the form of numerous dykes, often much altered by

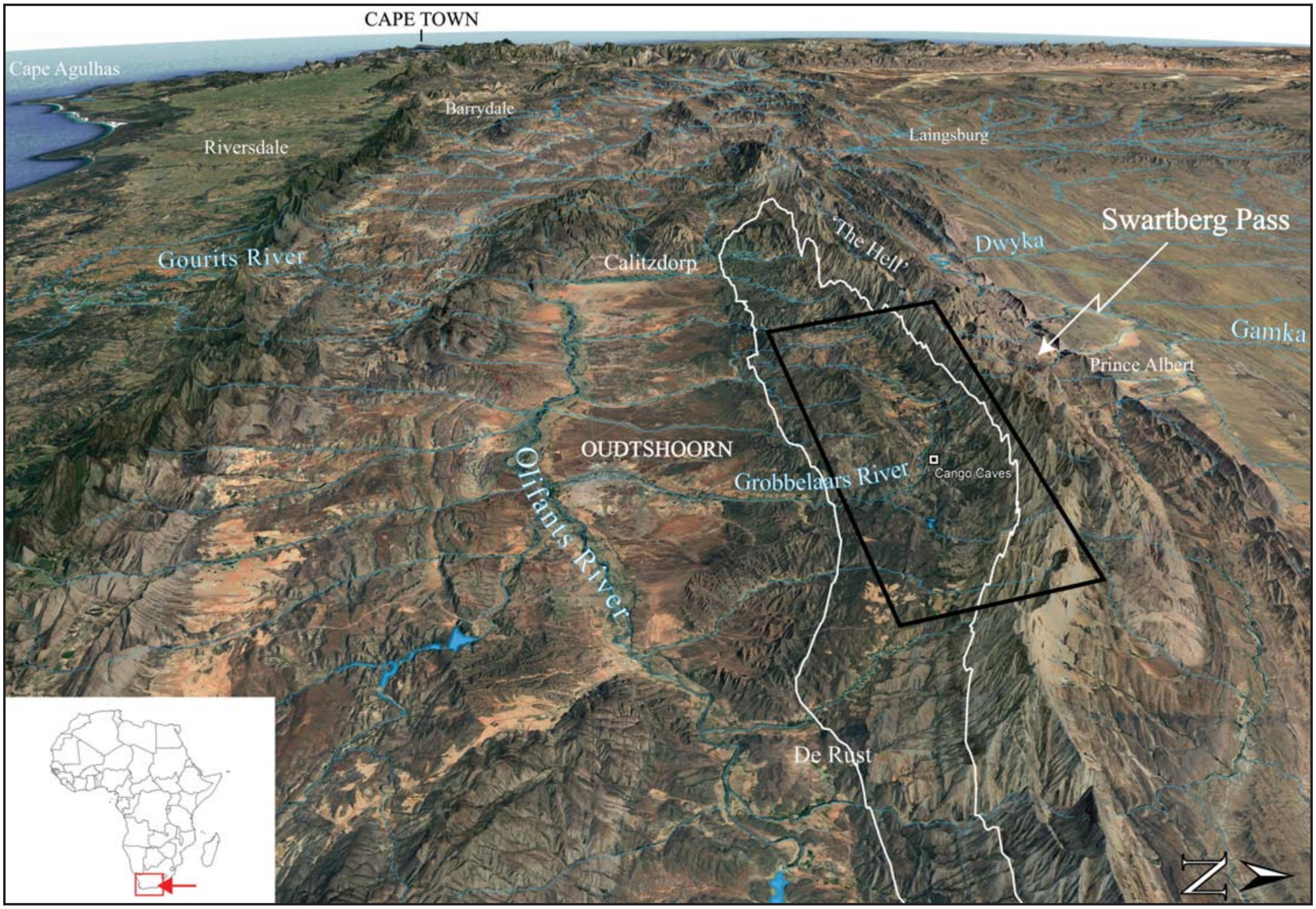


Figure 1A. Topographic image of the Proterozoic Kango Inlier (white outline) in southern South Africa, highlighting the elongate mountain range of the Swartberg (quartzite) from which small dendritic river systems flow to the north and south; the latter at relatively low catchment-averaged denudation rates of ca. 3–6 m/m.y. Two deep meandering rivers that cut across Swartberg quartzite terminate along the northern flanks of the Swartberg Mountains. A third major meandering river system (the Gamga–Dwyka rivers) cuts across the entire mountain range and joins the Olifants River near Calitzdorp. In the centre of the Swartberg, to the southwest of Prince Albert, a sequence of younger Paleozoic shales has eroded to create the subparallel Gamkas-kloof (-valley), locally known as 'The Hell'. These regional geomorphologic features illustrate a complex erosion history, linked to variable uplift and climate changes from the Cretaceous to the present (see text), and which is well preserved across the present reported area of the Kango Complex (black rectangle).

shearing', and recorded as the 'Cango Series' (Corstorphine and Rogers 1897; Rogers and Schwartz 1900; McIntyre 1932).

Tectono-stratigraphically, the Kango sequences comprise folded and cleaved meta-sedimentary rocks interpreted to underlie unconformably the near-vertical conglomerates and quartzites of the Table Mountain Group (TMG) across the narrow Swartberg Range. A similar south-dipping tectonic sequence of TMG (with conglomerates) flanks the southern margin of the Kango rocks. The latter, in turn, is tectonically overlain by Upper Mesozoic 'Enon' red sandstones and conglomerates of the Uitenhage Group, exposed at the contact with the TMG quartzites by a listric fault that today is still seismically active (Fig. 2c; Söhne and Hälbich 1983; Gresse et al. 1993; Goedhart and Booth 2016; Linol and de Wit 2016).

The first detailed geological map (1:50,000) with sections across the central Cango region was produced by Stocken (1954). This is an exceptional map in that, for the first time, the lower sequences were recognised as a series of structurally repeated, subvertical limestone and shale units along east–west regional isoclinal folds and refolds, separated from younger sequences by large-scale thrusts. In particular, a major isoclinal antiform, with an axial strike length of ca. 7 km, was shown to duplicate the lowermost stratigraphy of the Cango Group, then named the Hilda Series. However, no dips of the fold limbs or fold axis, nor their plunges are shown on Stocken's map.

Subsequently, the structural complexity of these tectonic features was mapped in greater detail across the entire Cango region (Le Roux 1977, 1983; Le Roux and Gresse 1983), as recorded in a special publication of South Africa's National Geodynamics Programme (Söhne and Hälbich 1983; Nicolaysen 1983). This field work established a more detailed stratigraphy of seven formations (Fig. 3), in which, for example, the Hilda Series was renamed the Matjies River Formation, as part of a Goegamma Subgroup that, together with an overlying Kansa Subgroup, were referred to as the Kango Group and

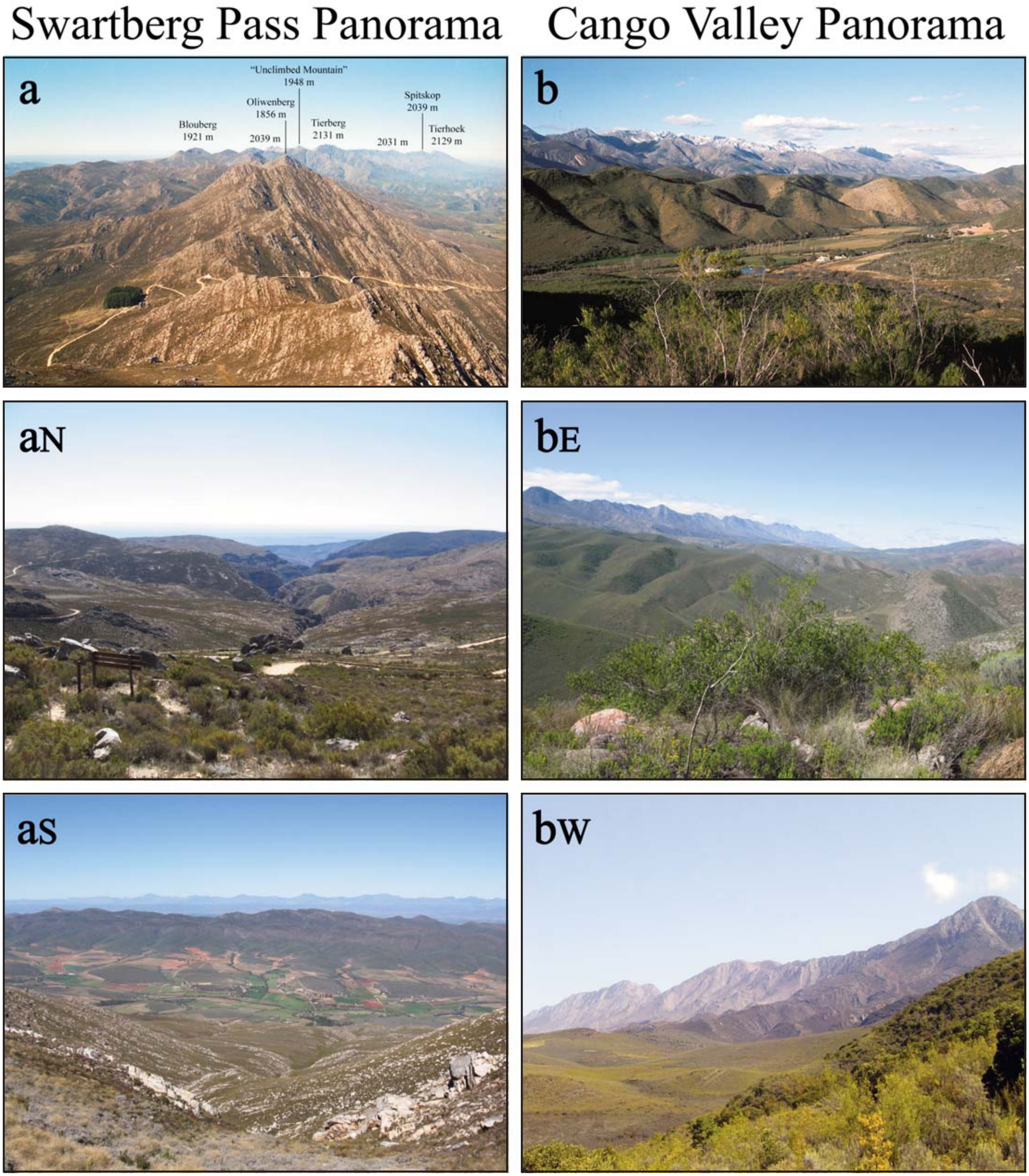


Figure 1B. Landscape photographs flanking the Cango Valley. (a) Northeast-focused view across the Swartberg Mountains near the road crossing the Swartberg Pass at 1583 m asl along the road towards Prince Albert and the Karoo Basin (to the north; a_N) and the Kango Basin (to the south; a_S). Beds of Table Mountain Group (TMG) rocks (quartzites of the Lower Paleozoic Cape Supergroup) are overturned, dipping steeply south and younging north. (b) Views across the Cango Valley taken 15 km to the south of the Swartberg Pass, highlighting remnants of a wide open, relatively flat erosion surface near 1000 m asl across the Kango rocks and presently cut by the Grobbelaars River meandering across another flat surface, with farmland, at ca. 750 m asl (b_E, view to east and b_W, view to west).

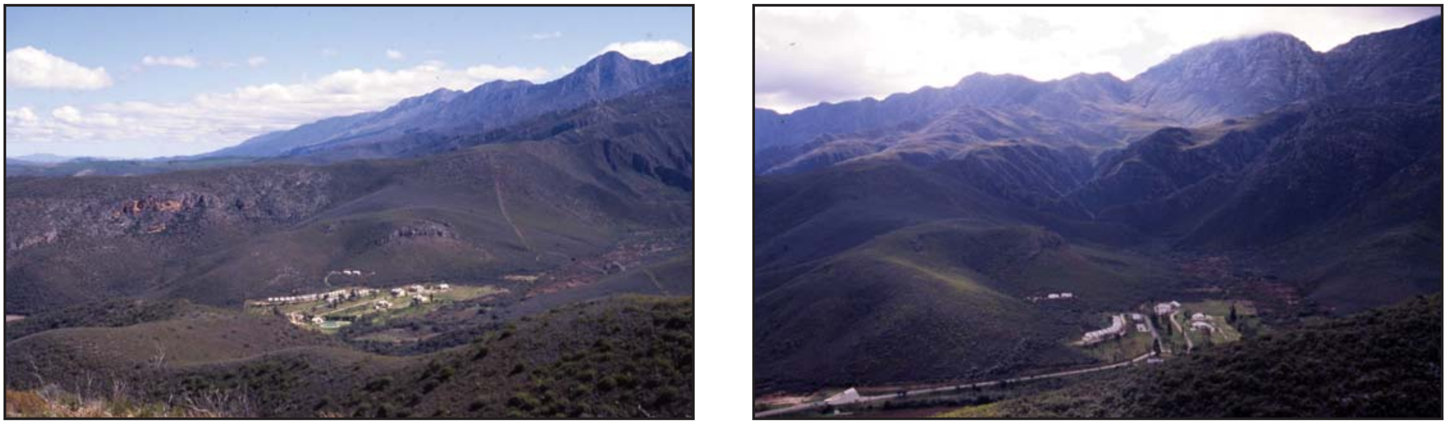


Figure 1C. West-facing views, taken from slightly different angles, across the 1200 m asl paleo-Cango Valley (ca. 200 m above De Hoek Camping Resort – pale green grass) linked to the Swartberg Mountains (top right) along gentle to open paleoslopes. These remnant flat surfaces of Late Mesozoic age are incised by steep dendritic drainage valleys linked to wider sections like near the resort. There is no field evidence of faults that might have initiated these younger geomorphologic valleys. The changes in valley systems are linked to precipitation and tectonic changes during the Kalahari epeirogeny from around 140 to 60 Ma (see text).

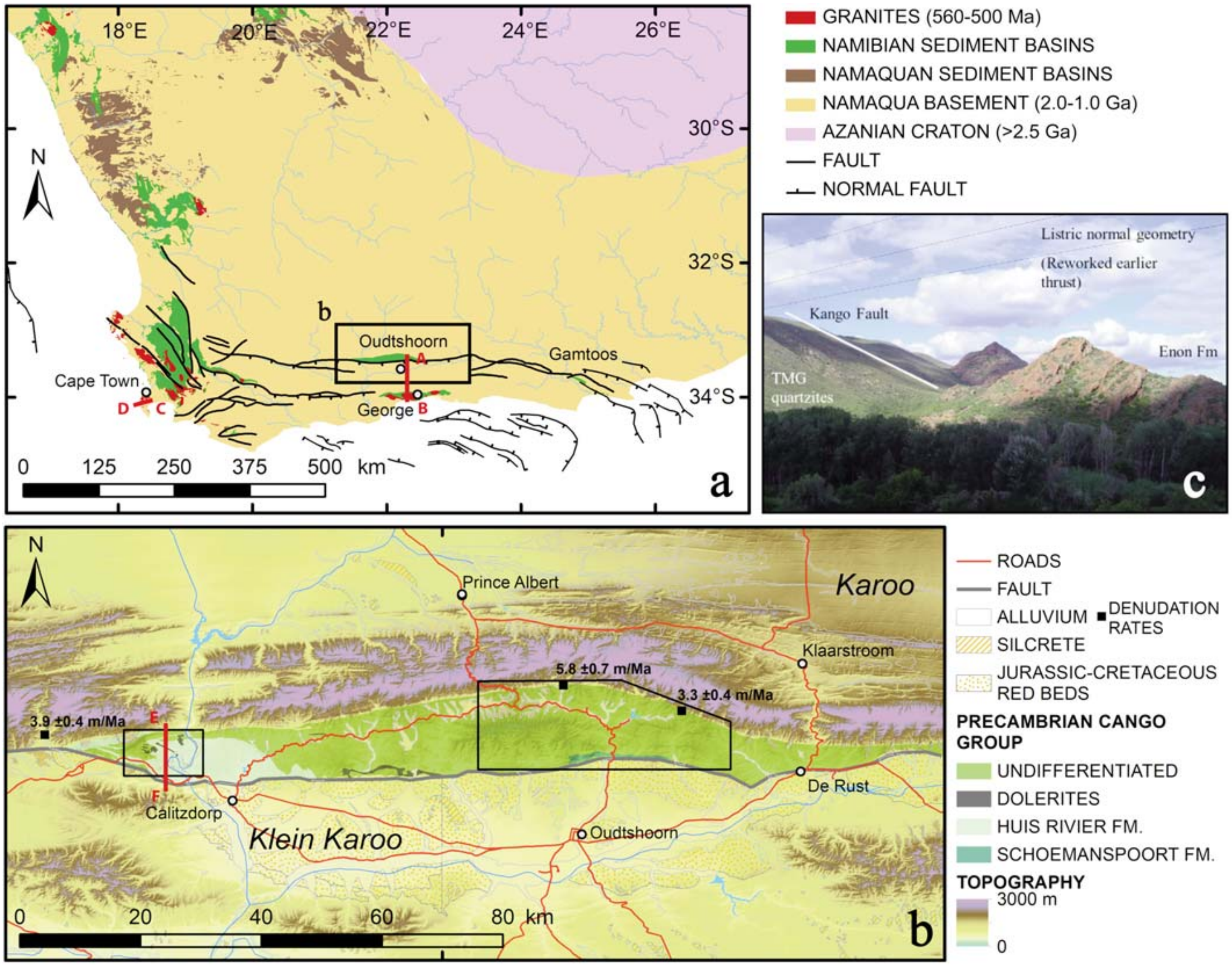


Figure 2. (a) Simplified geological map of the Cango/Kango region across Paleo- to Neoproterozoic crust of the Namaqua Natal Belt bordering the southern margin of the Archean Azanian craton; cross-sections A–B and C–D are shown in Figure 37. (b) The Proterozoic to Paleozoic Cango Group forms the southern flank of the Swartberg Range of the Cape Mountains, bounded to the south by a major Mesozoic–Cenozoic fault system (c). Black polygons delineate the study areas; cross-section E–F is shown in Figure 30. The low denudation rates across a number of variable river systems are from Scharf et al. (2013).

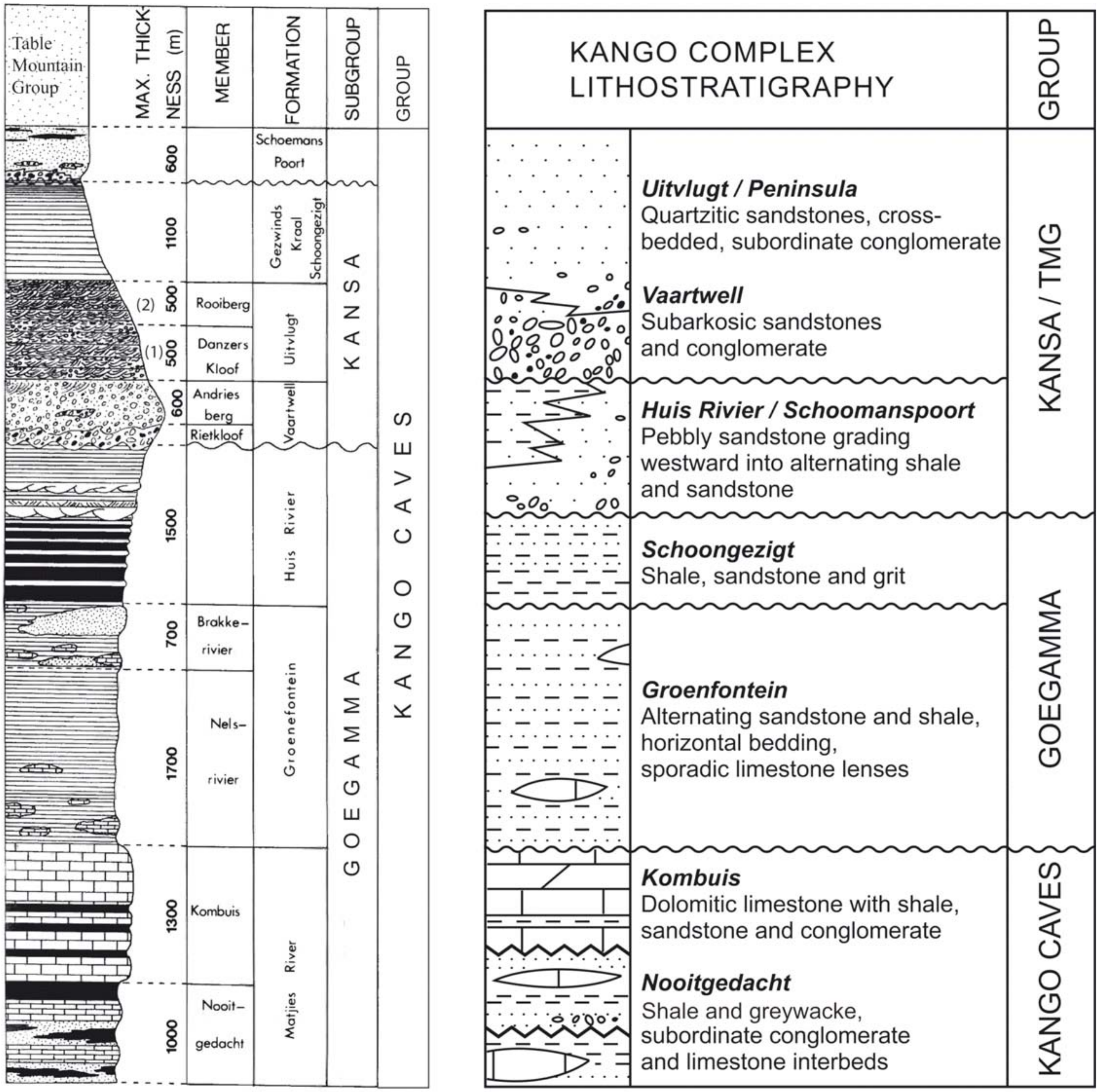


Figure 3. Stratigraphy of the Kango Complex. (Left) Modified from Le Roux and Gresse (1983), with subgroup (Goegamma and Kansa) renamed, and with members Danzerkloof (1) and Rooiberg (2) as inverted by Naidoo et al. (2013). (Right) Simplified lithostratigraphy redivided here into three groups as described in detail across twelve field sections in this study. In this new framework the Schoongezigt Formation is part of the Goegamma Group; the Schoemanspoort Formation links to the base of the Kansa Group; and the Uitvlugt Formation of the upper Kansa Group is of equivalent age to the lower TMG (Table Mountain Group). Major unconformities: wavy lines = previous work; angular lines = this work.

separated by a major unconformity (Le Roux and Gresse 1983; Gresse et al. 1993). Both the subgroups were shown to be unconformably overlain at different localities and stratigraphic levels by the TMG.

This previous work also yielded a map with eight detailed sections that cover the exposed stratigraphy of the Kango inlier west of 23°E (from east to west, ca. 150 km long and 14 km wide across the central Cango region; Le Roux et al. 1983).

The sections highlight the regional south-dipping folds and fault systems, but on which the major fold closure recognised by Stocken is poorly displayed. This fold, and many sub-folds along its limbs, was later remapped and measured in detail as a steep (> 70°) west-plunging anticline by numerous groups of students at UCT and NMU.

The Kango stratigraphy has since been subdivided further through more local mapping and petrology, often linked to new metamorphic analyses, geochemistry, and dating techniques that confirmed a Neoproterozoic–Early Paleozoic age range of the upper sequences using detrital zircons (e.g. Le Roux and Smit 1995; Barnett et al. 1997; Fölling 2000; Frimmel et al. 2001; Frimmel 2009; Van Staden 2011; Naidoo et al. 2013).

Sedimentary structures preserved in many field sections across the Kango sequences are commonly overprinted and replaced by macroscopic regional schistosity/cleavage, linked to microscopic minerals such as sericite, chlorite and carbonate flakes of low-grade metamorphism (Stocken 1954; Le Roux 1983; Hälbich 1983a, b; Barnett et al. 1997; Frimmel et al. 2001), at about 350°C (Halbich 1983a, b), consistent with isochore data from oxygen isotopes in quartz–calcite veins that yield trapping temperatures up to 410°C (Egle et al. 1995, 1998; Egle 1996).

All Kango rocks reveal moderate paleo-weathering based on CIA (Chemical Index of Alteration) with arenite showing slightly higher CIA than carbonate rocks. Overall, the alteration values are relatively homogeneous with slightly increased alteration stratigraphically upward across the siliciclastic sequences of the Kansa Subgroup (Naidoo 2008; Naidoo et al. 2013).

U/Pb Geochronology

Detrital Zircon Dates from the Kango Sequences

Stocken (1954) was the first to describe in detail zircons in both sedimentary rocks and intrusions across the Cango region. Typically sandstone (arenite) is rich in zircon (30–60% of all non-opaque heavy minerals), apatite (up to 50%), and rutile (minor), and there is a marked similarity in heavy minerals from different formations that range from well-rounded to angular, all commonly coated with iron oxide (e.g. Stoken 1954; Barnett 1995; Naidoo 2008).

U–Pb analysis of detrital zircons to test an age difference between the lowermost sandstone of the Kansa Subgroup (Rietkloof Unit of the Vaartwell Formation; Fig. 3, left) and subvertical shales of the underlying Groenfontein Formation of the Goegamma Subgroup yielded a maximum Late Cambrian age in the former, with a $^{206}Pb/^{238}U$ date of ca. 518 ± 9 Ma found directly above the unconformity separating these two sequences (Barnett et al. 1997). The samples also revealed a subset of well-rounded zircon grains with Mesoproterozoic dates around 1100 Ma.

By contrast, near euhedral zircon grains from a coarse feldspathic grit near the bottom of the Kango Caves Group (Nooitgedacht Member; Fig. 3, left) only yielded $^{206}Pb/^{238}U$ dates between 1200 and 1050 Ma; and a number of detrital zircons from carbonate conglomerate (diamictite) of the Matjies River Formation along the road to the Cango Caves yielded dates between 1360 and 1060 Ma (Barnett 1995; Barnett et al. 1997; de Wit et al. unpublished).

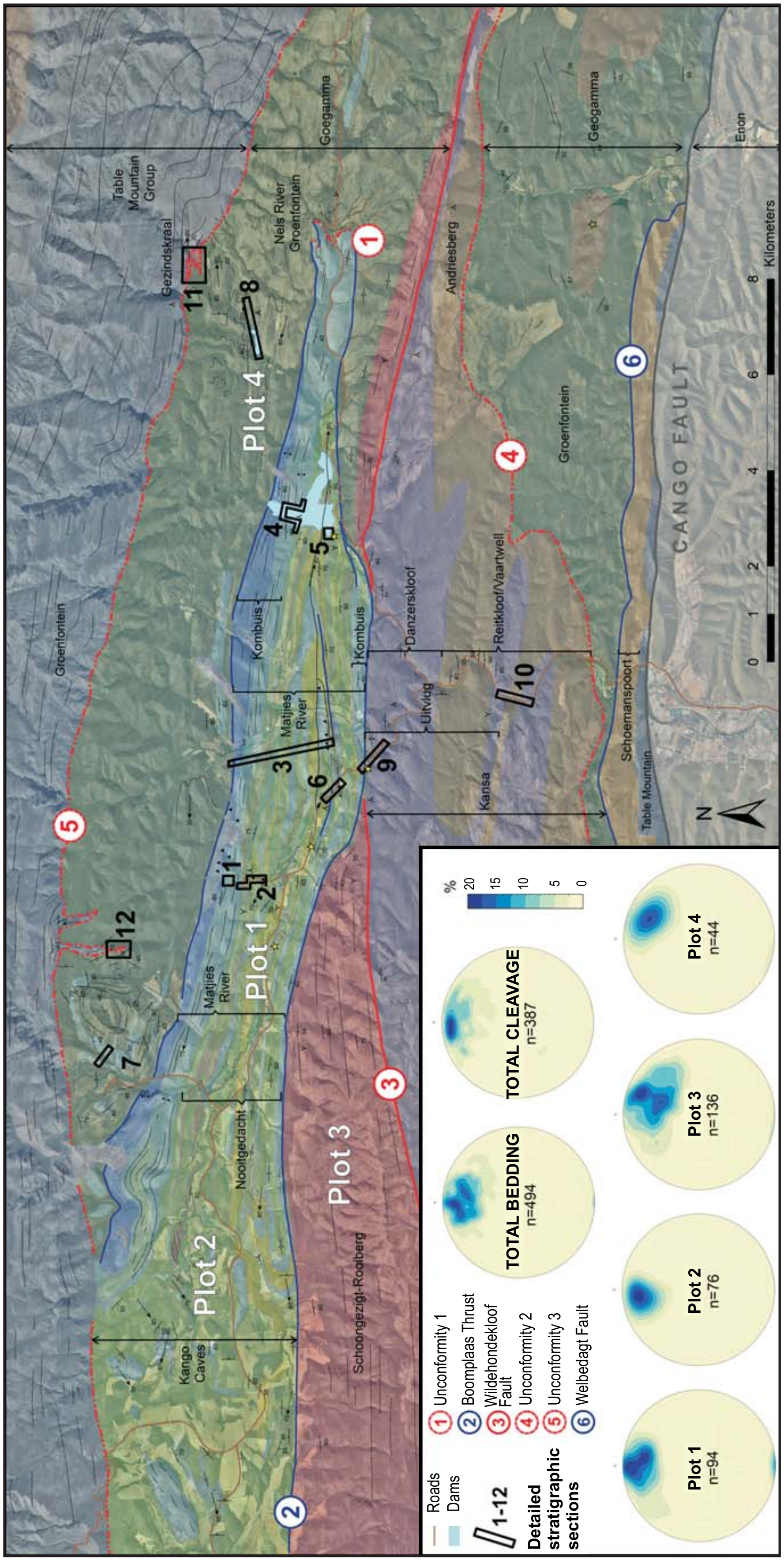
U–Pb detrital zircon dates from a much larger number of sampled sequences across the Cango region confirm the Cambro-Ordovician age of the Kansa Subgroup, with a predominance of Early to Middle Cambrian zircons, and with older Mesoproterozoic grains ranging from ca. 1034 ± 2 to 1377 ± 14 Ma and 1800–1900 Ma. In addition, a number of Neoproterozoic zircons in the Kansa and the lower TMG sequences were recorded with dates ranging from 620 to 911 Ma (Naidoo et al. 2013) and abundant Mesoproterozoic and Neoproterozoic ages were found in the Huis Rivier Formation of the Goegamma Group to the west of the present study area (ca. 1029 ± 7 to 1083 ± 40 Ma, and 571 to 911 Ma; Naidoo et al. 2013). A lack of GPS locations for these samples does not allow further detailed analysis and stratigraphic comparison.

Igneous Zircon Dates from Felsic and Mafic Dykes

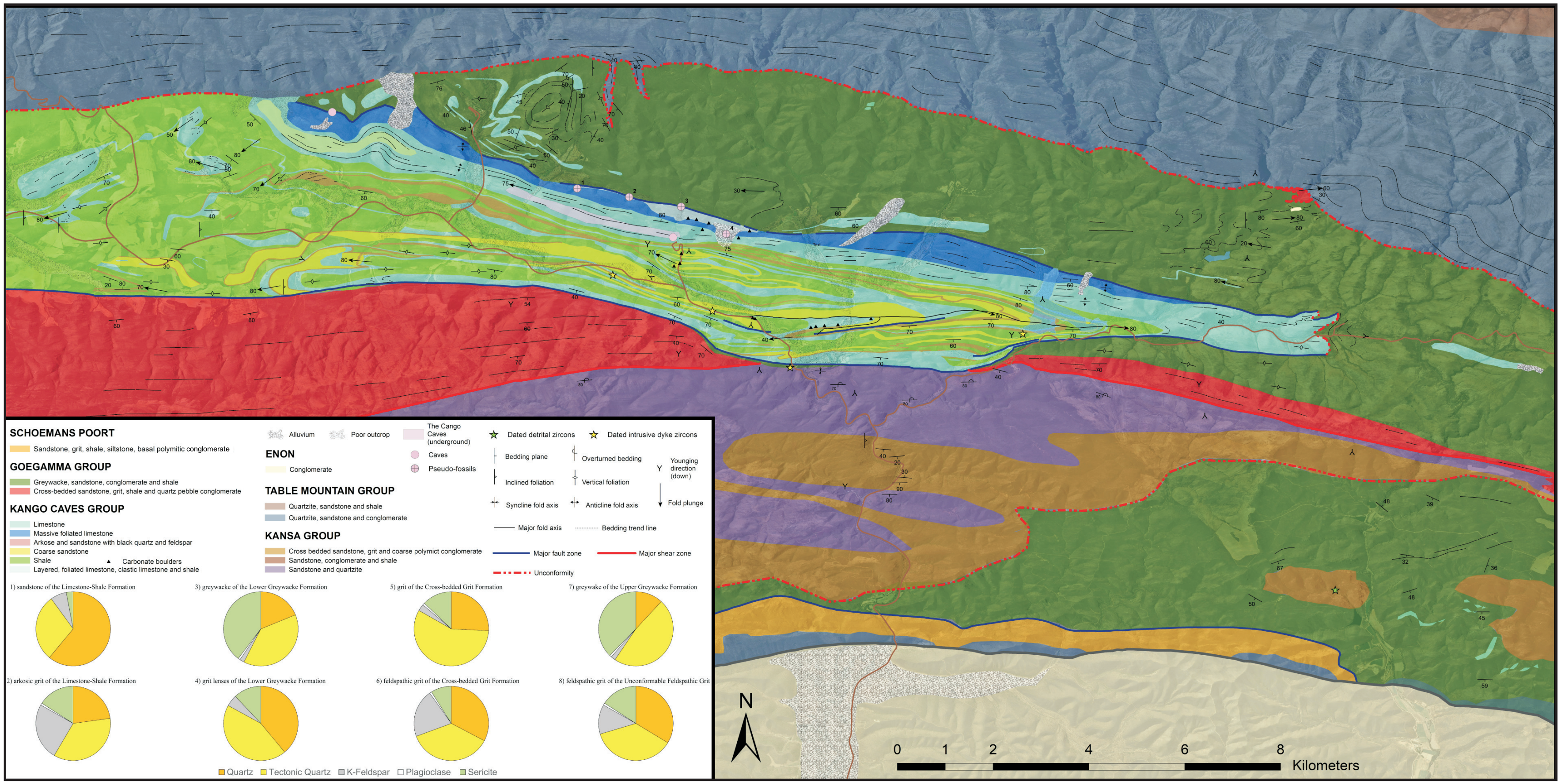
In two places across the lowermost Kango Caves Group, felsic dykes cut the Nooitgedacht sequences. These dykes have not been described or reported on before. The best exposed dykes are found along the southern section of the Raubenheimer Dam (see Map 1 and Section 5), where they cut across thick bedded sandstone. Zircons from two of these felsic dykes, both of which are cleaved and partially weathered, yield a concordant U–Pb date of ca. 1072 ± 5 Ma. At a second locality, along the road section 700 m before the turn-off to the Cango Caves (see Map 1 and Section 6), at least five thin subvertical felsic dykes cut across thinly bedded, folded (vertical axis) sandstone and carbonate rocks. Zircons from three of these dykes yielded a concordant U–Pb date of ca. 1078 ±5 Ma. Thus, the lower sequences of the Kango Complex are Mesoproterozoic in age.

A number of mafic dykes across the Kansa rocks in the eastern section of the Kango Complex (see Fig. 2b) yielded younger ages: the first, a dolerite-gabbro with a U–Pb zircon date of ca. 512 ± 10 Ma (Haas 1998); and the second, a schistose dyke with a U–Pb zircon date of ca. 460 ± 5 Ma (de Wit et al. unpublished). Thus, these mafic dykes are Early Paleozoic in age, although the date of the second dyke may have been partially reset during the formation of its schistosity at 252 Ma (Booth 2011; Blewett and Phillips 2016; and see below).

While the precise ages of the stratigraphic sequences between the upper and lower Kango Complex remain unknown, our mapping confirms a relatively thin, but complex tectono-stratigraphy over a period of more than 700 million years. In contrast, more recent work questions the fold and fault systems, and recognises only unconformities mapped previously. This results in a simplified stratigraphy, confining the age of the lower Cango sequences between ca. 700 and 500 Ma (Nel et al. 2018). Previous Pb–Pb double spike isochron data from the Kombuis carbonate units yielded an age of ca. 553 ± 30 Ma, and C and Sr isotope signatures similar to those found in sequences separating a pre-Ediacaran from a Vendian (Ediacaran) age (Fölling 2000; Frimmel et al. 2001; Frimmel 2009). However, the clastic nature of the carbonate rocks



Map 1. General map highlighting names of stratigraphic sections as in previous publications, and the new stratigraphic sections of this study, shown in black polygons (Sections 1 to 12) and described in the text. Stereoplots 1 to 4 summarize local bedding and cleavage of four areas, shown with white labels.



Map 2. New geological map of the central-eastern Kango Complex (Fig. 2 for location), based on data collected between 1996 and 2018. In many of the outcropping sandstones, turbidites, silicic and limestone conglomerates, sedimentary features such as cross-bedding, grading and erosion are locally well preserved, providing uncontested evidence for younging direction. Such younging information is commonly absent in sections where deformation has created slates and schists, including across most igneous dykes (Figs. 4 and 5); and all formations are affected to varying degrees by a subvertical fracture/cleavage/schistosity in siliciclastics, and foliations in 'limestones' (such as well-preserved across the Cango Caves – Section 1). This was recorded in earlier work (e.g. Stocken 1954; Hälbich 1983a; Barnett 1995), but often neglected in more recent publications that concentrate on sedimentary and stratigraphic analyses. These tectonic planes and their linked lineations, folds and thrusts cut across the contacts of the Kango with the Table Mountain Group (TMG) rocks, and thus are related to the formation of the Cape Fold Belt at ca. 252 Ma. Average mineral compositions of the siliciclastic formations are shown in pie chart-plots modified from extensive quantified data of Stocken (1954).

(detailed below and in Section 2) questions the primary nature of these different data.

These major disagreements justify stratigraphic testing which we present here based on long-term field mapping across the central-eastern Cango region and geochemical analyses in RSA, Australia, USA, Canada, and Europe over the last 22 years. We provide a detailed geological map (Map 2) and twelve sections, two of which are linked to new U–Pb zircon dates on felsic igneous intrusions, and we re-examine the stratigraphy and tectonic history of this unique inlier within the Cape Mountains.

REVISED GEOLOGICAL MAP

Mapping was conducted using various sets of aerial photographs, enlarged at scales between 1:500 and 1:10,000 over 22 years (1997–2019) and consolidated at a scale of 1:25,000 (GIS available online: www.aeon.org.za/cangomap). The results, including measured planar fabric, dip and fold axis, are summarized here on condensed maps with linked stereoplots (Maps 1 and 2). This work reveals four major stratigraphic sequences with strikingly different ages, separated by three regional unconformities and two major tectono-sedimentary boundaries, one of which links to a major molasse-type sequence (simplified on Fig. 3; and see below).

Tectonic structures complicate reconstruction of precise stratigraphy, locally and regionally (Fig. 4). The two oldest sequences (formerly the Matjies River and Groenfontein formations) are isoclinally folded with major fold axes plunging steeply east and west, which makes the measurement of total thicknesses difficult, something that was clearly recognised by Stocken (1954). These are tectonically overlain along the Boomplaas Thrust to the south by a sequence of red beds (the Schoongezigt and Gezwinds Kraal formations, in total about 1000 m thick), and in turn unconformably overlain across the Wildehondekloof Fault by more than 1500 m thick conglomerates and greywackes, referred to as the Vaartwell and Uitvlugt formations (Le Roux and Gresse 1983). To the north, this 'Kango Complex' underlies north-younging quartzites of the Peninsula Formation, the lowermost unit of the TMG, but which in places is overturned, dipping 40–70° to the south (Fig. 1B). A sliver of hard quartzites, also from the TMG, bounds the southern edge of this complex along the Cango Fault (Map 1).

Before reporting on twelve detailed new sections, we first summarize below the wide range of ductile–brittle deformational features and structures, especially cleavage and schistosity, that occur throughout most of the study area, but which are generally not reported and/or interpreted as sedimentary structures.

Variable Regional Deformation Structures – Shear Zones, Schists and Faults

Published geology of the Cango region generally underplays the existence of major deformational features such as folds, shear zones and faults. Here we highlight some of these structures and elaborate on them in the following field sections and on Map 2.

Deformational features in thick limestone and marble are particularly difficult to quantify because of limited preservation of original bedding and low strain recrystallization. Occasional carbonate (dolomite) beds of dark colour reveal internal isoclinal folding (Fig. 4A). Deformed limestone and carbonate conglomerate are well preserved throughout the lower sequences (Fig. 4B). In many places, these foliated carbonate rocks locally reveal mylonitic textures, including in and adjacent to the Cango Caves (Fig. 4C).

General Regional Stratigraphy

We have changed the stratigraphic successions of the Cango region by recasting the present two subgroups and one group into three groups: the Kansa, Goegamma and Kango Cave Groups, based on the identification of major unconformities and several tectonic boundaries (Fig. 3, right; and detailed below). In addition, our new mapping is consistent with recent detrital zircon data (e.g. Naidoo et al. 2013), which confirm that the upper Kansa Group overlaps in age with the Table Mountain Group (TMG).

The two oldest sequences of the Kansa Group are separated by two major unconformities, commonly tectonically overprinted, the younger sequence of which, with sandstones and conglomerates of the Andriesberg Formation (formerly a member), has detrital zircons dated at 518 Ma (Barnett et al. 1997), and is thus Cambrian (or younger) in age. This age is similar to that of detrital zircons in the lowermost formation (Peninsula Formation) of the TMG along Table Mountain in Cape Town, dated at 520 Ma in the same laboratory (Armstrong et al. 1996; Scheepers and Armstrong 2002), and from the same lowermost TMG quartzite in the Swartberg Mountains flanking the Kango rocks (518 to 504 Ma; Naidoo et al. 2013). Stratigraphically younger zircon grains (ca. 471 Ma) occur in conglomerate and sandstone sequences of the Gezindskraal Formation, the lowermost section of which is unconformably below the TMG, and directly above the Groenfontein Formation (Map 2).

Elsewhere the Huis Rivier and Schoemanspoort formations have detrital zircons dated between 620 and 485 Ma (Naidoo et al. 2013). Thus, the entire Kansa Group is younger than ca. 520 Ma (Cambrian) and possibly ca. 470 Ma (Silurian), predominantly derived from Late Neoproterozoic sources dated between 650 and 620 Ma (Barnett et al. 1997; Naidoo et al. 2013).

The overlying Vaartwell and Uitvlugt sequences comprise thick conglomerates (with various granite clasts) interbedded with and fining upwards into cross-bedded sandstones and siltstones (Section 9). The large-scale ripple cross-laminations with mud drapes and common rip-up clasts suggest a shallow marine, wave-dominated paleo-environment (e.g. Walker and James 1992). This is similar to, albeit deeper than, the coastal marine setting generally proposed for sedimentation of the more mature quartzites of the Peninsula Formation (Shone and Booth 2005).

In general, pre-Goegamma arenites have microscopic textures of quartz-rich tectonites modified by fracturing and recrystallization of a crenulated chlorite–sericite matrix (Fig.

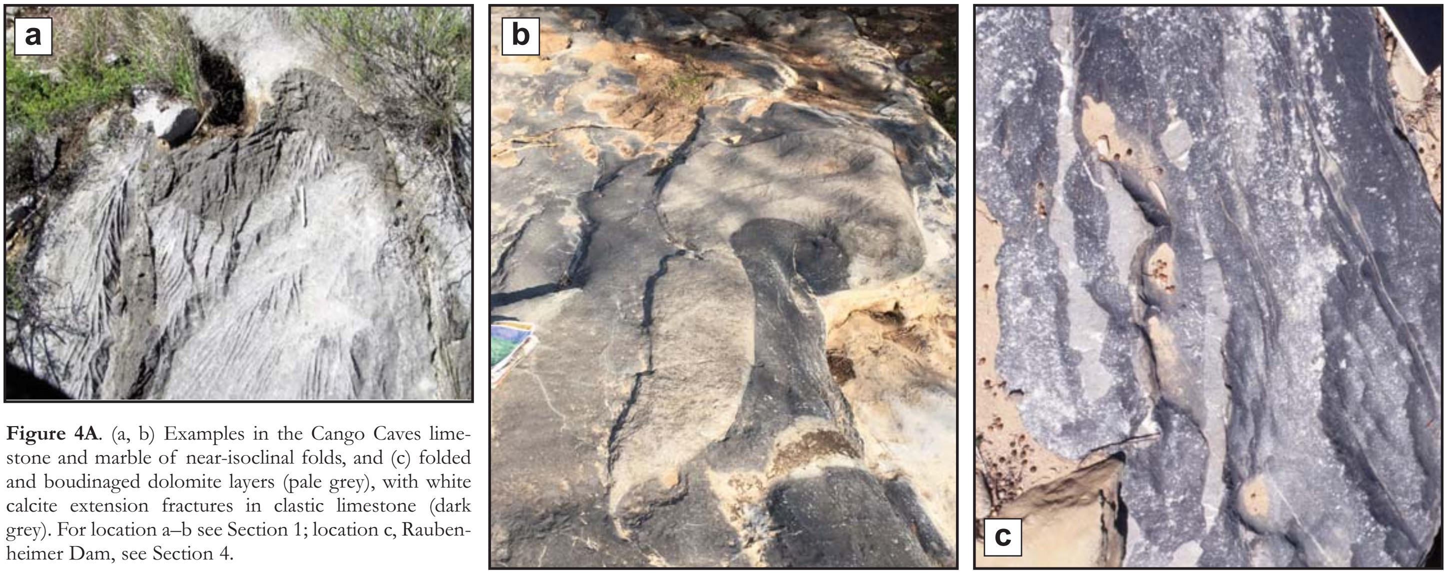


Figure 4A. (a, b) Examples in the Cango Caves limestone and marble of near-isoclinal folds, and (c) folded and boudinaged dolomite layers (pale grey), with white calcite extension fractures in clastic limestone (dark grey). For location a–b see Section 1; location c, Raubenheimer Dam, see Section 4.

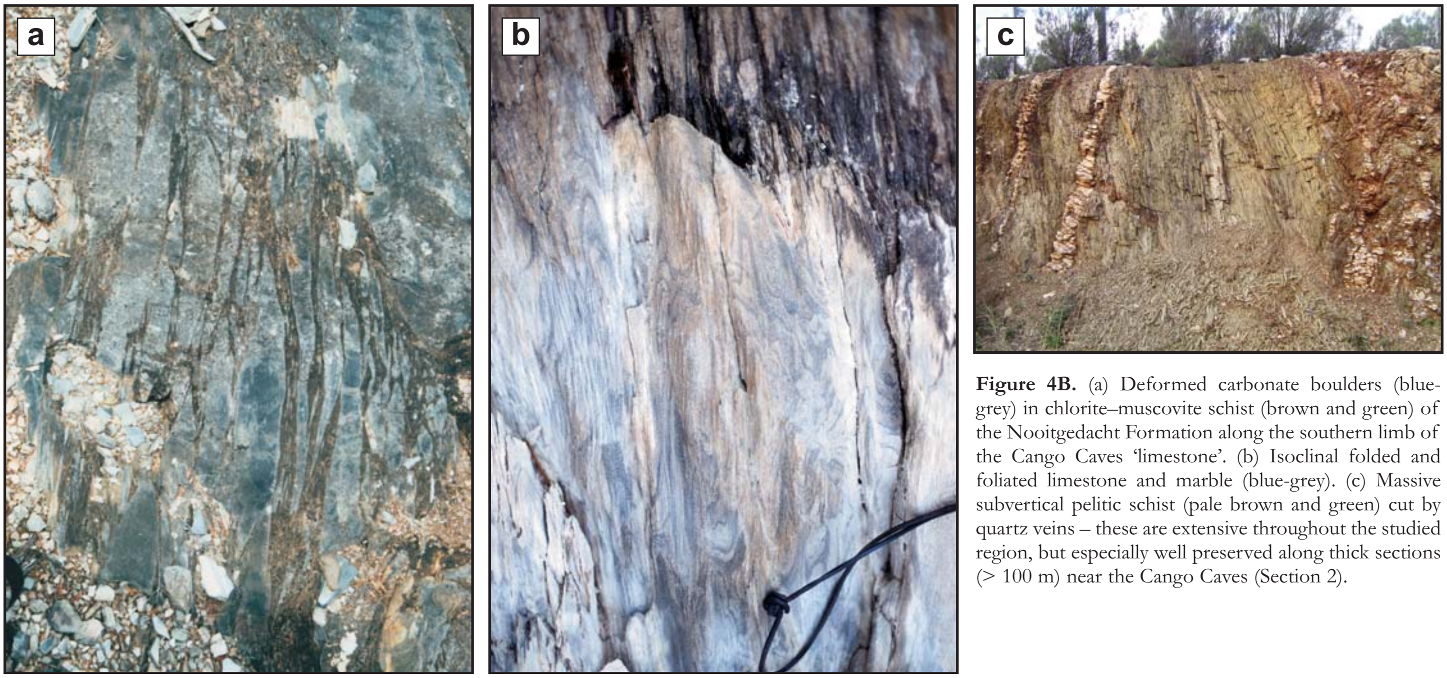


Figure 4B. (a) Deformed carbonate boulders (blue-grey) in chlorite–muscovite schist (brown and green) of the Nooitgedacht Formation along the southern limb of the Cango Caves 'limestone'. (b) Isoclinal folded and foliated limestone and marble (blue-grey). (c) Massive subvertical pelitic schist (pale brown and green) cut by quartz veins – these are extensive throughout the studied region, but especially well preserved along thick sections (> 100 m) near the Cango Caves (Section 2).

Figure 4C. Typical example of subvertical shear zones separating two different folds styles, both with subvertical axes, in two tectonically separated stratigraphic sequences of the Kango Caves Group. (a, b) Left, grey-blue marble with white calcite veins; and right, shallow dipping pale brown sandstone with minor shale, separated by schist and mylonite (highlighted sections in red) of vertical shear in the lower sequences. (c) Close-up of the subvertical, sub-isoclinal fold of marble in (b) (black outline), with variably angled white calcite veins from axial planar to nearly orthogonal across bedding planes.

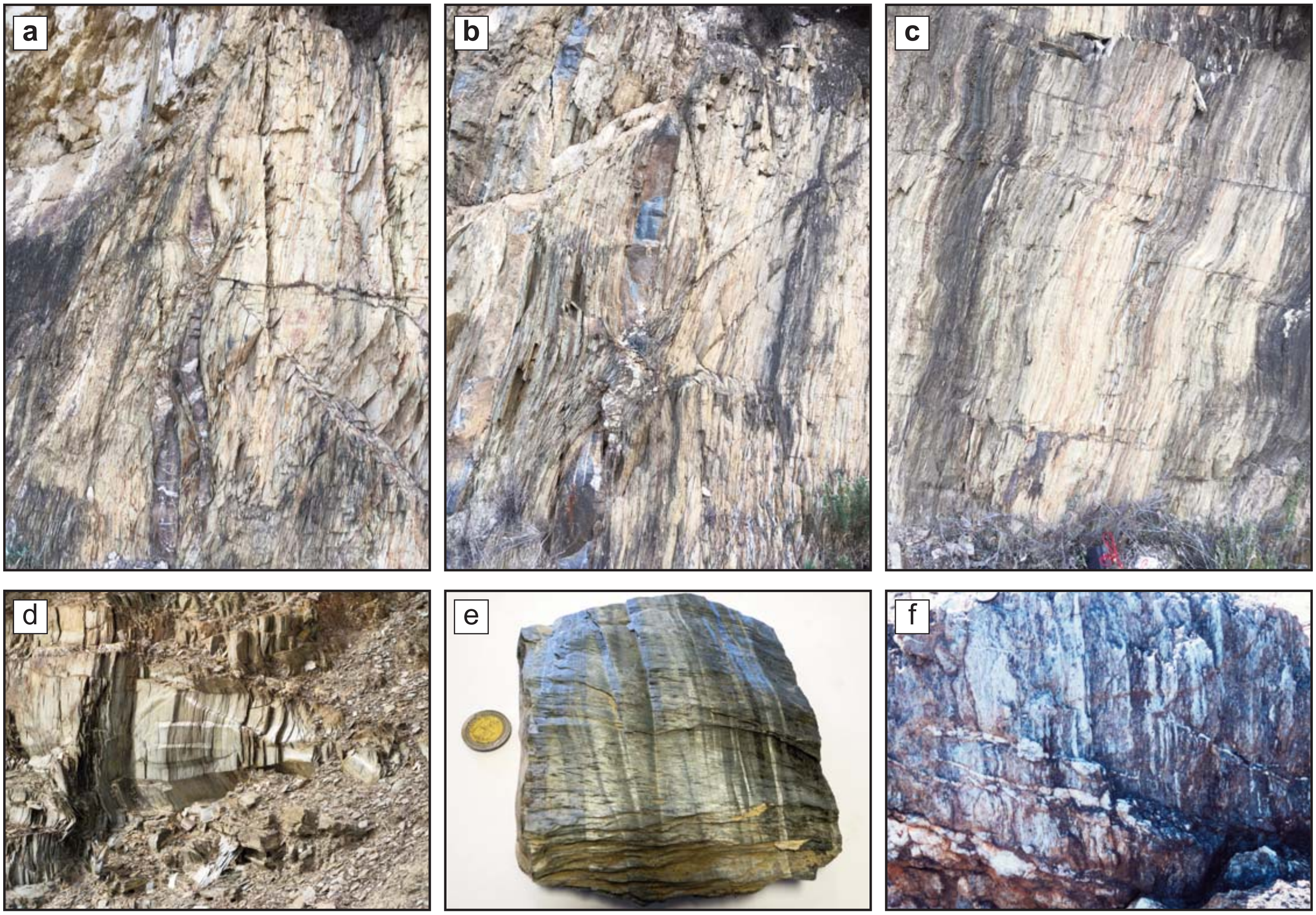


Figure 4D. Typical sections across subvertical mica slate and schist (pale brown) zones (a–c), with folded and boudinaged marble sheets (blue grey with white calcite veins), locally with (d) subhorizontal kinks and vertical tectonic lineations of mica (e) crenulation cleavage (black), and (f) quartz (white). For location a–c see Section 6.

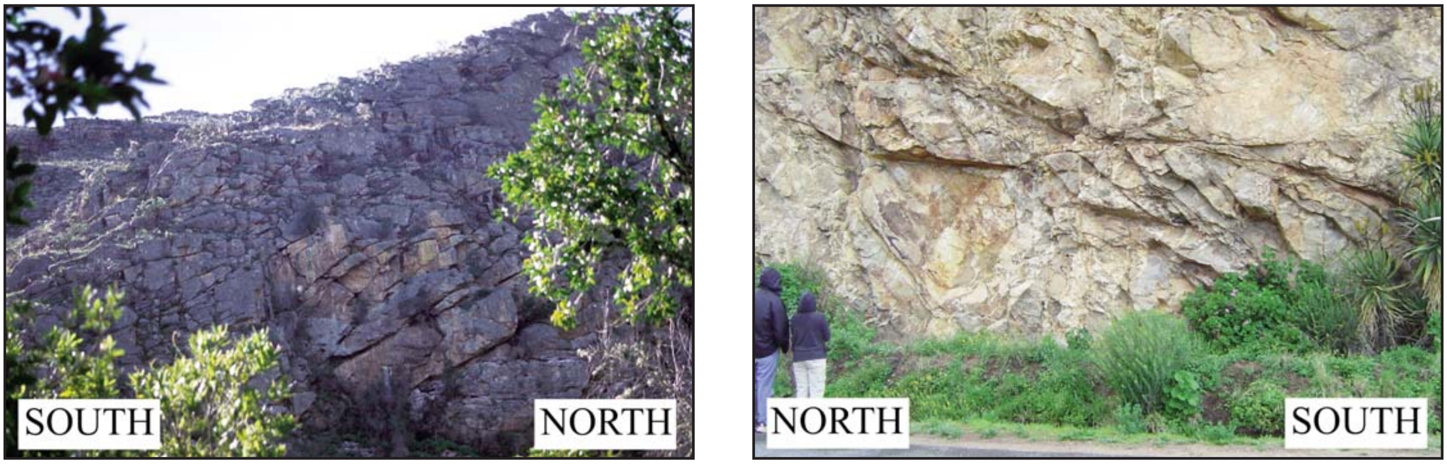


Figure 4E. TMG quartzites flanking the north and south boundaries of the Kango Complex. (Left) North boundary of complex, steep and shallow north-trending thrusts across the contact between the Kango and TMG rocks (Section 11). (Right) South boundary of complex brecciated and brittle thrusts in TMG quartzite at Schoemanspoort near Section 10.

4D). Thick sequences of K-feldspar-dominated arenite are common, often with large, angular and poorly sorted orthoclase and microcline. Albite-oligoclase plagioclase is less common and always small in grain size. Minor orthopyroxene also has a wide distribution. Zircon, apatite, rutile, epidote and tourmaline make up 95–100 % of the non-opaque heavy minerals, of which zircon is the most abundant. Selected zircon grains from major coarse, poorly sorted feldspar–quartz sandstones in the lowermost sections of the Nooitgedacht Formation, in places directly flanking the Cango Caves to the south (pale brown in Map 1), have been dated between ca. 1377 and 1090 Ma (Barnett et al. 1997; Naidoo et al. 2013).

Between these coarse arenite (and local slate) units of the Nooitgedacht and the Kombuis formations, are the thick sequences of massive Cango Caves carbonate layers and lenses (commonly referred to as limestone – e.g. Stocken 1954; Naidoo et al. 2013; Nel et al. 2018). These are dark grey, with numerous folded and boudinaged calcite–quartz veins (Section 1). The clastic nature of the limestone is evident from the ubiquitous presence of detrital limestone fragments and clasts, calcite grains, ooids and variable concentrations of quartz and feldspar grains in the more arenaceous carbonate rocks. In many places, carbonate sandstones and conglomerates, grading to large boulders, represent complex deposition processes (Sections 2-4 and 7).

The oldest preserved Cango strata comprise variable conglomerates and sandstones that contain poorly sorted pebbles of granitoid gneiss and pegmatite interlayered with unsorted carbonate and quartzite clasts that range from centimetres to several metres in size, commonly with local unconformities and disconformities (Section 3; see also Nel et al. 2018). The characteristic mineralogy and clast lithologies attest to limited transport from the eroded sources and conditions favourable to the preservation of the feldspar. This suggests erosion of a granitic terrane adjacent to a sea or lake with limited reworking, and/or cold, possibly subglacial conditions.

Thus, while the uppermost conglomerate beds across the Kango Complex (Kansa Group) are predominantly well-sorted quartzite with well-rounded granite boulders interbedded with cross-bedded sandstone, the top and bottom of the Cango carbonate sequences are characterized by poorly sorted carbonate conglomerate commonly with limestone boulders in excess of 1 m in diameter.

Mafic dykes are common across the entire Kango Complex, and in most cases are strongly cleaved or schistose (Fig. 5a). The geochemistry of the basaltic andesite has been reported elsewhere (e.g. Barnett et al. 1997; Van Staden et al. 2006; Van Staden 2011); in the western Cango region, they have been dated at ca. 512 ± 10 Ma (Haas 1998). Felsic dykes (Fig. 5b) have only been encountered in the lowermost sections of the Kango Caves Group (the Nooitgedacht Formation). The REE of the felsic dykes are similar to those of the mafic dykes (Fig. 5c), but their dates, presented here for the first time, are very much older (Section 7).

Tectonic contacts between and within the Kango sequences are common (Fig. 4E and Map 2), and it remains unclear how the different sequences are linked stratigraphically. Below, we first provide an example of a general deformed section across the Cango Caves, followed by detailed analyses across eleven other sections, from the oldest to youngest, which, when linked to published data and the structural analyses reveal that a new stratigraphy is required for the studied region. This we attempt at the end. The locations of all geosections described below are shown on Map 1.

Stratigraphy of Twelve Cross Sections Based on Lithology and Structural Data

Section 1. Foliated Marbles of the Cango Caves

Highly deformed carbonate rocks are exposed within the Cango Caves (Fig. 6), here referred to as Cango marbles, and along their contacts with 80–200 m thick pelitic schists.

Good exposures of deformed marble flank the entrance of the caves, along strike below the edge of the car park and along the partly exposed roofs within the caves (Fig. 7). Massive 'limestone' marble with calcite veins and boudins is tectonically foliated. Similar tectonic zones are common in parts of the Kango Caves Group across the entire studied region, but are often difficult to quantify, since the carbonate rocks are usually recrystallized, weathered, and poorly exposed. It is therefore not possible to measure accurately the tectonized sections of the Kango Caves Group (see also Stocken 1954); however deformed carbonate layers and conglomerates (Figs. 7 and 8) confirm extensive deformation throughout the Cango carbonate rocks, including those flanking, and interbedded in the Groenfontein Formation (Section 9).

Section 2. Conglomerates and Phyllites Along the Road to the Cango Caves

To the south, the Cango limestone is flanked by boulder conglomerates and phyllites of the Nooitgedacht Formation, more than 500 m across (Fig. 8). The contact is a fault zone with 80 m thick green fine-grained phyllite to schist locally with sandstone interbeds with some preserved crossbedding that indicates younging directions to the south. This road section cuts across thick bedded conglomerate and coarse sandstone, in total 40 m thick, younging north, in the opposite direction, highlighting a tectonic boundary. The conglomerate is clast-supported, with angular to sub-rounded pebbles of granite pegmatite, granite gneiss, with coarse blue quartz and white feldspar matrix, and rounded, poorly sorted boulders of carbonate between 0.1 and 3 m in diameter (Fig. 9A). These lithologies reveal the relative proximity of two distinct sources: first from coarse-grained granite and pegmatite intrusions, and second from carbonate platforms from which exotic limestone blocks were derived. The limestone boulders resemble 'megabreccia' beds of the Cow Head Group, western Newfoundland, deposited as talus sediments (e.g. Hiscott and James 1985; James and Stevens 1986). Such a process of rapid, catastrophic deposition indicates a high topography such as along continental slopes and submarine escarpments (Coniglio and Dix 1992; Ager 1992).

Well-exposed outcrops along the road reveal multiple unconformities and anticlinal structures plunging southwest

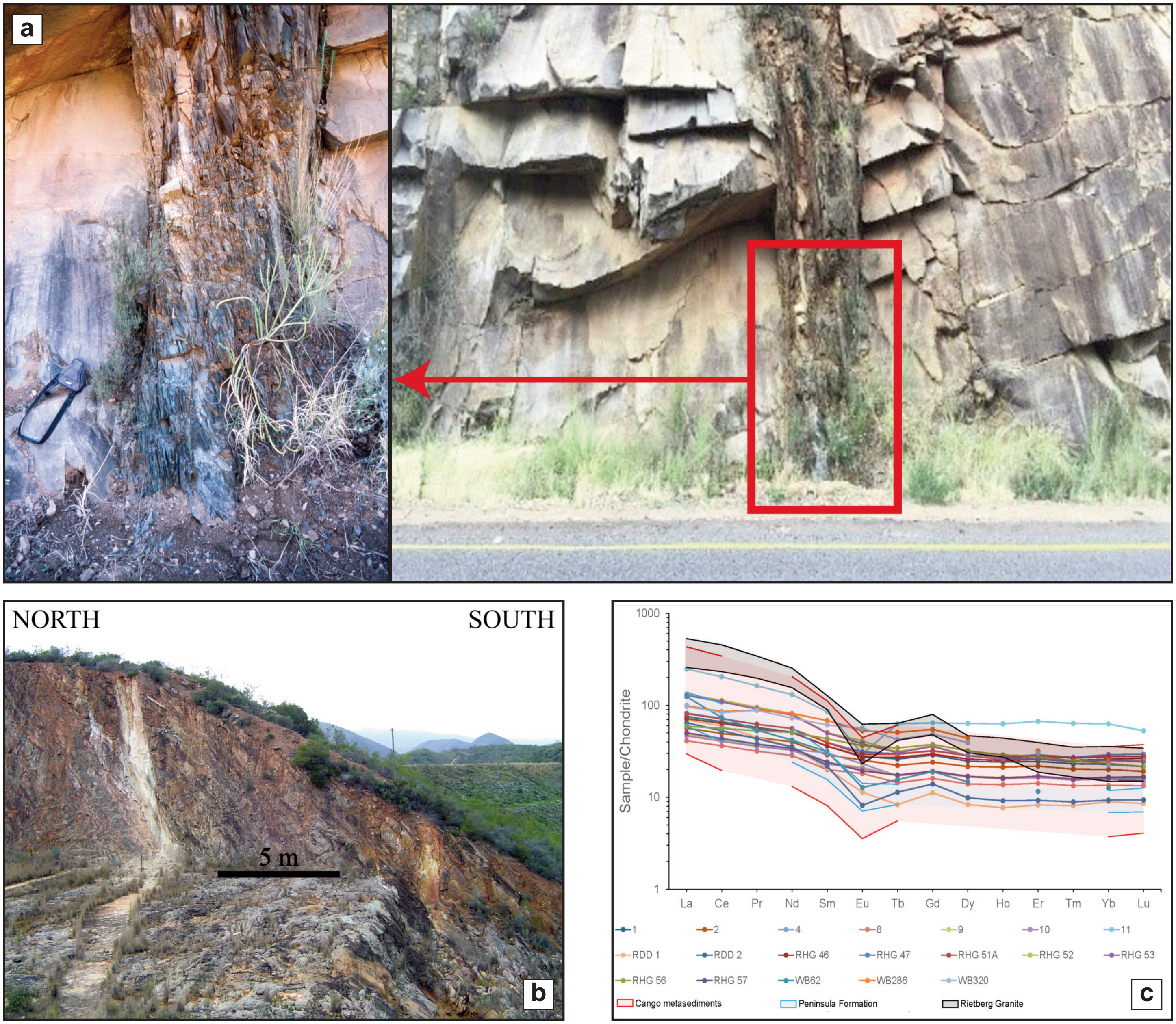


Figure 5. (a) Typical green schistose dolerite dyke (vertical) with extended quartz veins intruding poorly deformed quartz-dominated sandstone (subhorizontally bedded) of the Vaartwell Formation along the Schoemanspoort road (Section 10). Igneous zircon grains from this and similar dykes date between 550 and 450 Ma (see text); the geochemistry of the dykes is typical basaltic-andesitic. (b) White, fine-grained schistose and weathered silicic dykes intruding south-dipping sandstone of the lowest exposed sequence (Nooitgedacht Formation) of the Kango Caves Group. U–Pb-dated zircon grains are older than 1000 Ma; the geochemistry of these dykes is andesitic. (c) Normalized rare earth elements for rock samples of the Kango Complex compared to data from Macey et al. (2018; the Rietberg Granite dated at 1033–1086 Ma) and Naidoo et al. (2013; the Cango and Peninsula sedimentary rocks).

(N275). Boulder conglomerate (40 m thick) is clast- to matrix-supported, with angular to sub-rounded pebbles and large blocks of carbonate, feldspar, pegmatite and blue quartz (Figs. 8 and 9B). It is overlain by carbonate schist, phyllite and again boulder conglomerate but with larger blocks (1–3 m), although it is not clear if these beds are repeated.

The good outcrops exposed farther down along the road show several unconformities (Fig. 10). Although grading and cross-lamination of sandstone interbeds within the phyllite indicates younging directions to the south, it is not clear if the succession is repeated more than once. Southward the boulder conglomerate becomes thicker (80 m thick) with larger limestone boulders up to 3 m in diameter. Large quartz veins cut across this sequence (Fig. 8).

Section 3. Massive Sandstones, Clastic–Carbonate Rocks and Boulder Beds Between Groenfontein and Grootkraal

A 2 km long, north–south cross-section is described flanking the valley between Groenfontein and Grootkraal (Figs. 11 and

Figure 6. Westward view across the Cango Valley with generally poorly exposed limestone in the foreground, highlighting the well-exposed steep south-dipping (70–80°) interlayered sequences of Cango 'limestones' (pale grey carbonate rocks) and shales (green, and generally covered by vegetation) of the Kombuis Formation (Section 1, Map 1). The famous Cango Caves occur close to the contact between the southernmost carbonate layers and pelitic schist; here the carbonate rocks are highly deformed (see Figs. 7 and 8). Paleocaves and sinkholes are also preserved along the northern boundary of the carbonate with overlying turbidites of the Groenfontein Formation; for all cave locations see Map 2.

12). Linked to north-younging Cango massive limestones and carbonate conglomerates of the Kombuis Formation along its tectonic contact with the Groenfontein Formation, is a large syncline–anticline fold pair of coarse feldspathic sandstones, thick sequences of phyllite, and clastic-carbonate rocks with boulder beds (the Nooitgedacht Formation; Fig. 3).

These rocks are deformed along tight, axially subvertical folds (Figs. 13 and 14A), and it is not clear how much stratigraphic thickness is missing along the tectonic zone that separates the phyllites from the feldspathic sandstones, and particularly across the tectonically thinned carbonate layers flanking the southern part of the cross-section (Fig. 12). A change in bedding directions across a subvertical cleavage confirms large (0.5–1 km) anticlinal and synclinal structures.

To the south, more abundant green phyllites and massive carbonates terminate with 10 cm to 2 m-thick clastic-carbonate pebble beds that alternate with fine and coarse-grained limestone, with sharp laminations, cross-stratifications and relatively abundant soft-sediment deformation structures, characteristic of turbidites. All reveal younging directions to the south (Fig. 14B). Near Grootkraal Farm, this succession is 125 m thick, bounded by a subvertical slate shear zone (Fig. 13). Bedding becomes progressively thicker upward to the south and passes up into carbonate conglomerate beds (with subangular to well-rounded boulders), 0.5–5 m thick, separated by sandstone layers (Fig. 14C). Truncations at the bases of some of the beds (Fig. 14D) suggest that the general southward coarsening and thickening trend of this prograding sequence results from gravity flows. These are interpreted as oligomictic debrites (breccia flows) derived from slope failure, with the large clasts supported by the bulk density of the flow (e.g. Coniglio and Dix 1992).

The outcrop of these carbonate conglomerate sequences has been interpreted previously as a north-younging inverted paleo-valley (Nel et al. 2018; see their figure10). The different sedimentary structures described here are not consistent with this interpretation (Fig. 14B–D). This suggests similar depositional conditions, albeit more distal to the boulder conglomerates described along the road flanking the Cango Caves (compare to Fig. 8).

Section 4. Phyllites and clastic-carbonate rocks of Koos Raubenheimer Dam

Farther east, along the banks of Koos Raubenheimer Dam (Fig. 15), massive sequences of clastic-carbonate rocks and siltstones to mudstones of the Matjiesrivier Formation are well exposed especially during low rainfall years. The beds young and dip between 50 and 80° north.

Along the western section (Fig. 16A), subvertical conglomerate and coarse sandstone (115/80°N, overturned; 170 m thick) are sharply overlain by more than 100 m thick clastic limestones. The contact between the two sequences is folded

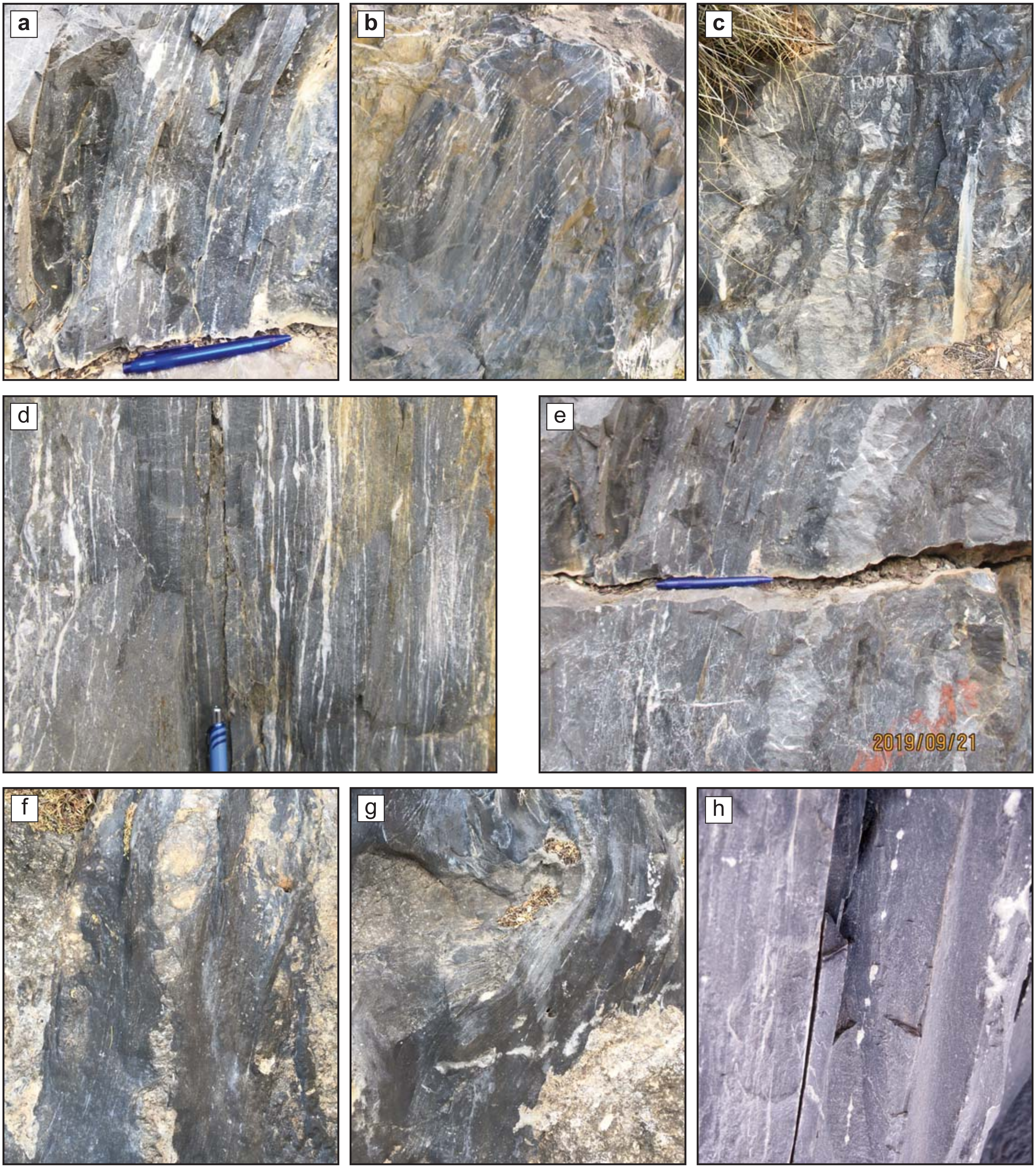


Figure 7. Foliated Cango Caves marbles with quartz–calcite veins and boudins of distinct carbonate members. Many sections like these occur throughout the Cango limestone units, separated by less deformed sequences. The deformed carbonate rocks are difficult to recognise in the Cango sections, but much of the limestone in the caves is part of these intensely deformed sections, and it remains uncertain how to stratigraphically separate the deformed and undeformed limestone/marble sequences. Top photos are from the car park below the entrance to the Cango Caves (Fig. 6); middle photos are from along the road section (Fig. 8); and bottom photos are from along the western Rauberheimer Dam (Section 4).

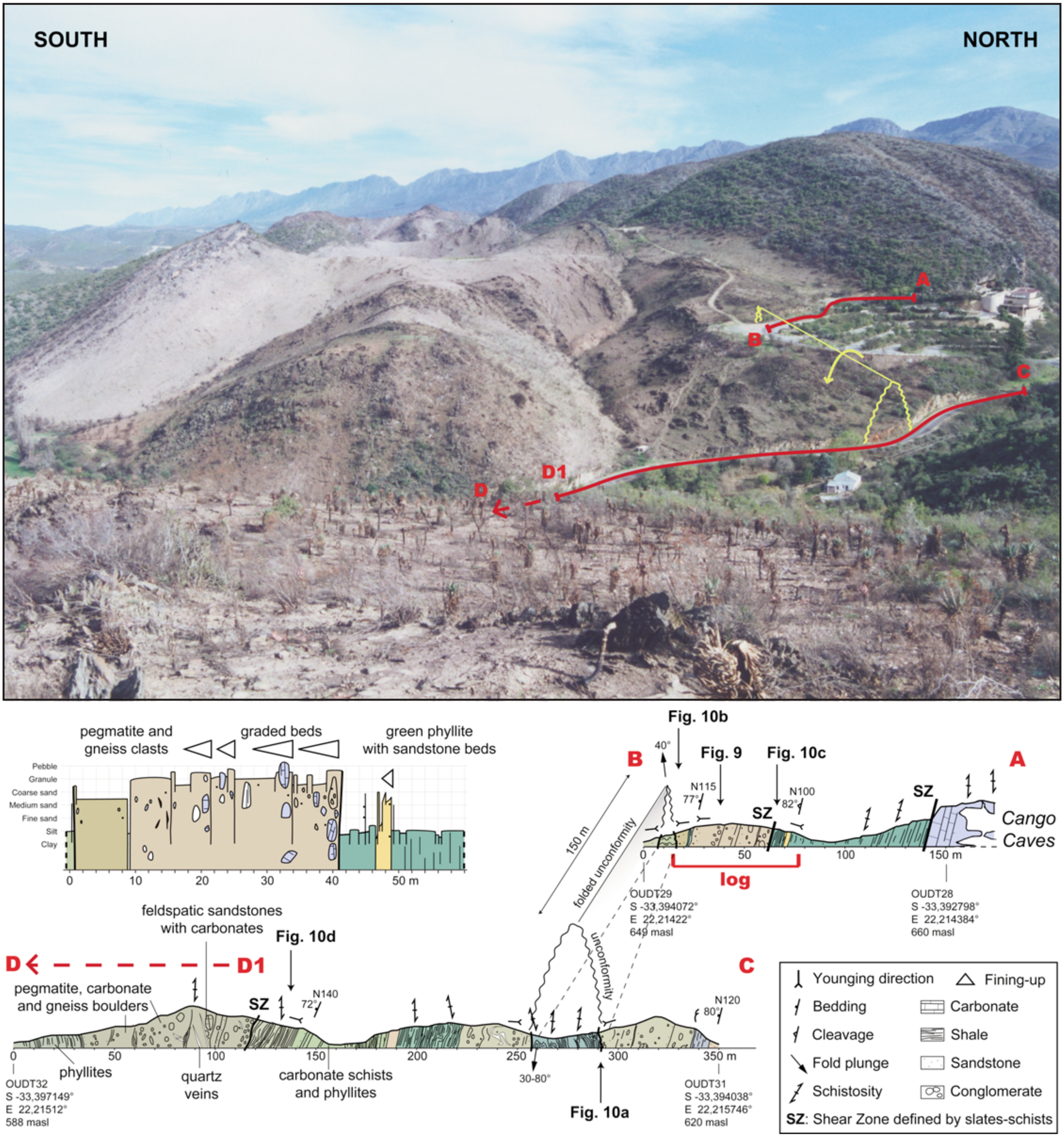


Figure 8. North–south cross-section with tectono-stratigraphy logged along the upper road (A–B; with the Cango Caves entrance building just to the right of A) and the main road to the Cango Caves car park (C–D); for location see Section 2, Map 1. Limestone boulder conglomerate and green phyllite are folded and sheared against the limestone–marble of the Cango Caves (the Kombuis Formation).

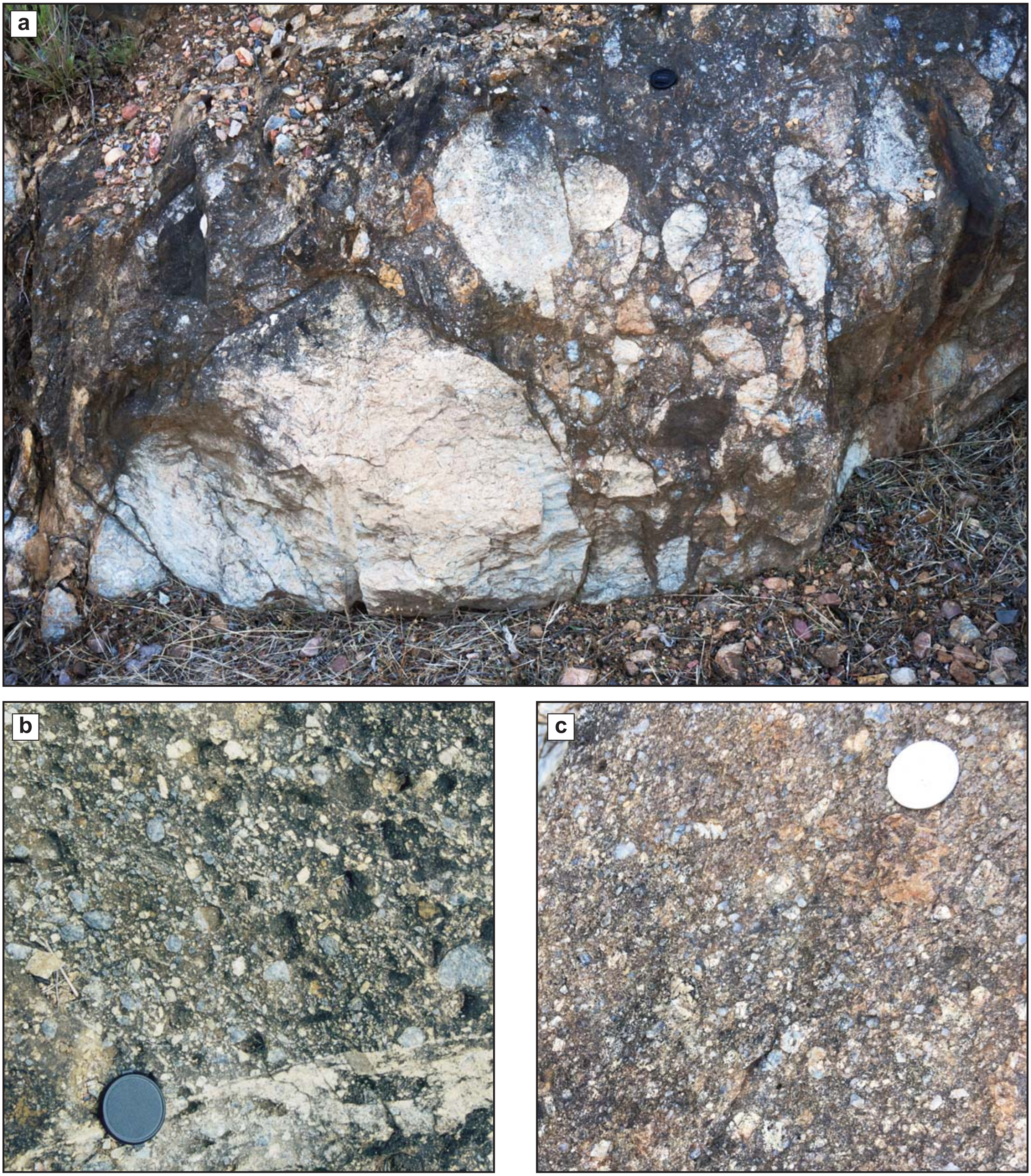


Figure 9A. (a) Graded bed of carbonate pebbles to boulders with angular to well-rounded clast- and matrix-supported pebbles of pegmatite and gneiss in feldspar–quartz matrix (Fig. 8 for location). (b–c) Typical coarse, poorly to well-sorted sandstone to grit with single white crystal K–Na plagioclase feldspars and blue quartz in the Nooitgedacht Formation. U–Pb geochronology of detrital zircons from the sandstone yielded Mesoproterozoic $^{206}Pb/^{238}U$ dates between 1200 and 1050 Ma (Barnett et al. 1997).

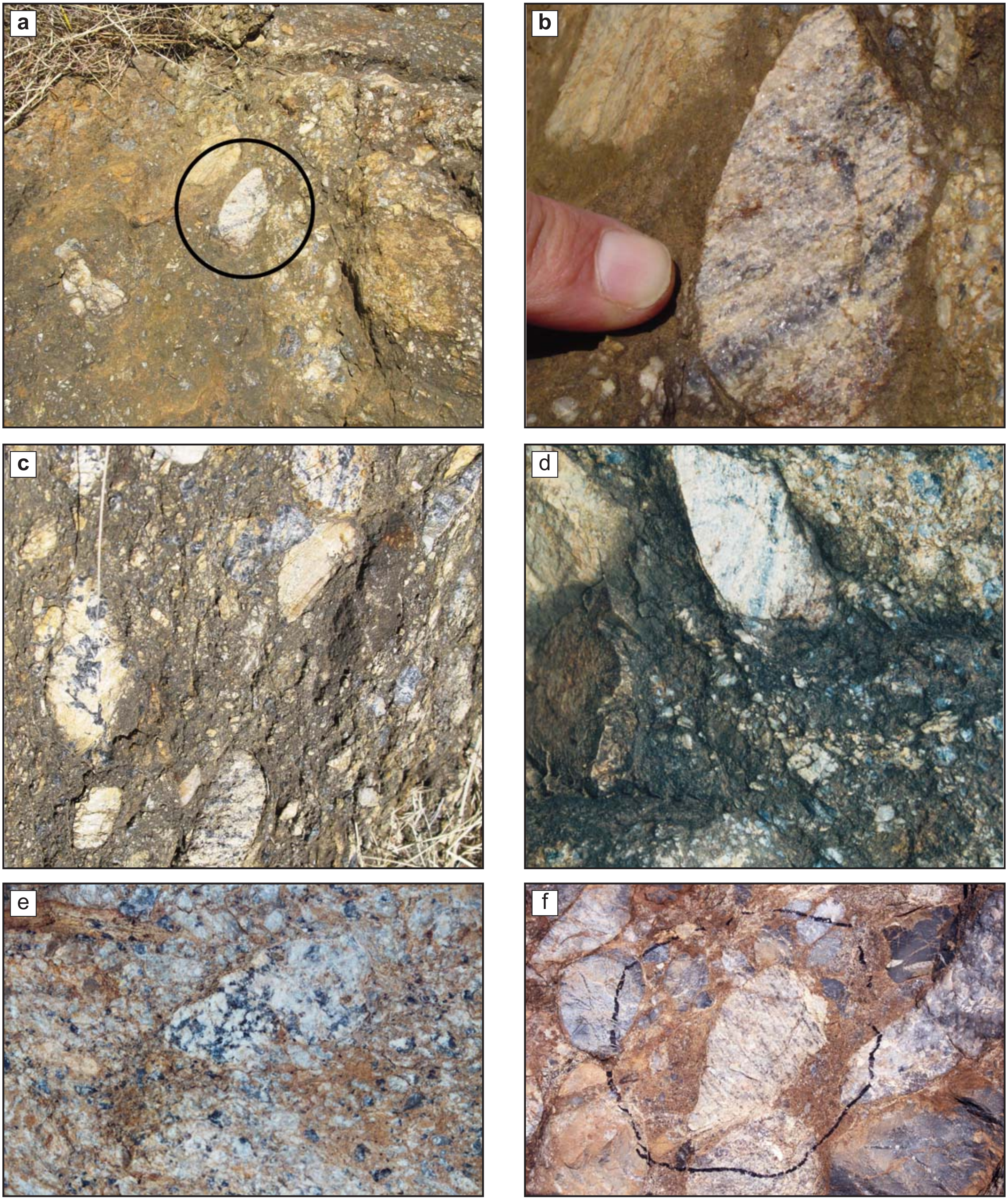


Figure 9B. Angular to well-rounded and matrix-supported small pebbles (3–7 cm long) of pegmatite and granite gneiss in feldspar–quartz matrix (Fig. 8 for location).

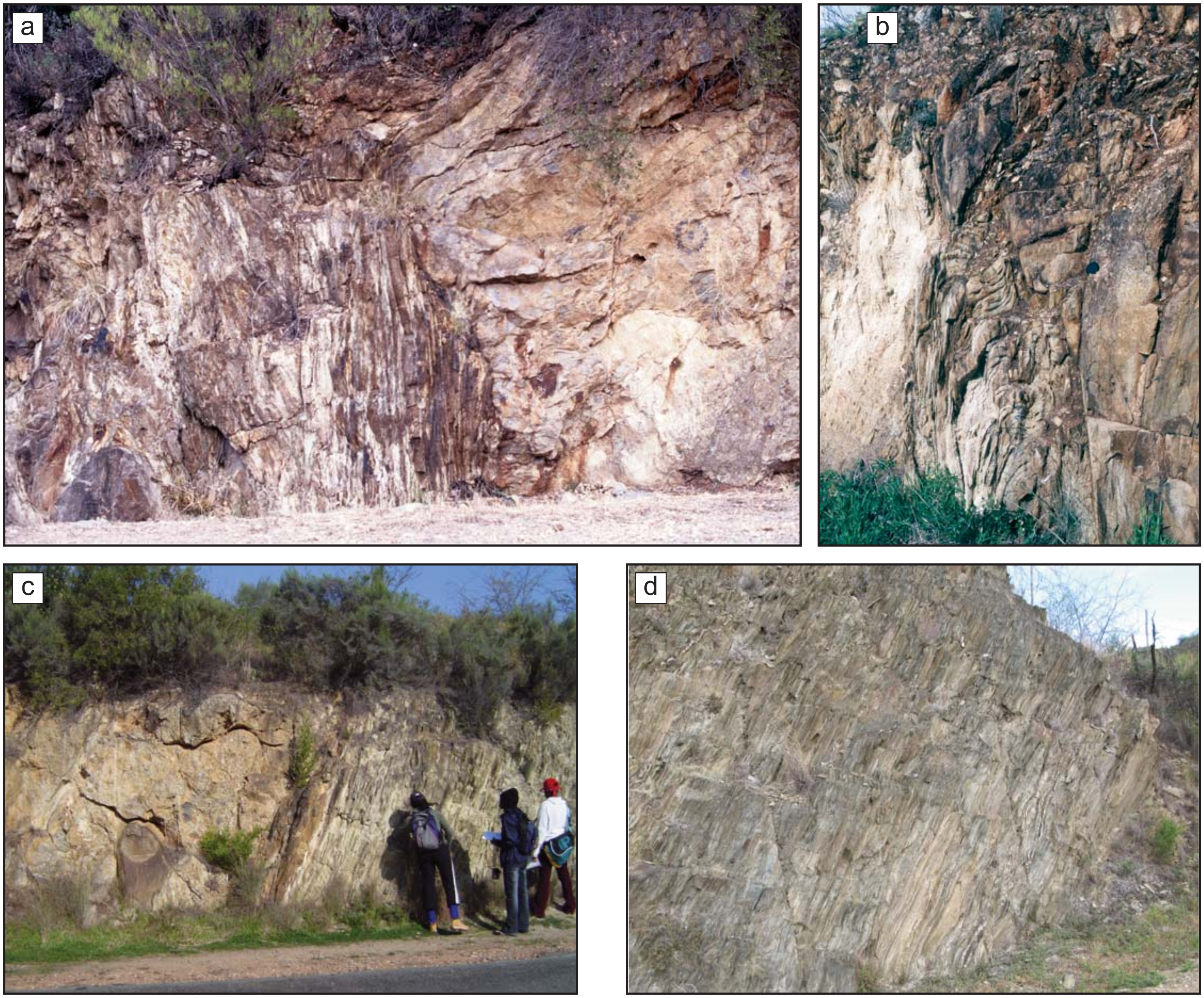


Figure 10. (a, bottom road, and b, top road) Unconformable contacts between thin bedded shale (left) and thick conglomerate–sandstone (right). (c) Tectonic contact between conglomerate–sandstone and phyllite, with (d) close-up of phyllite behind students. For locations a–c, see Figure 8.

and reprecipitated carbonate about 3 m thick. The lower conglomerate is composed of clast-supported small pebbles of feldspar and black quartz, grading into sandstone and shale, which suggests a younging direction to the north. Overlying sandstone comprises pebbly to very coarse-grained beds with shale interbeds that have a cleavage of direction N275.

The clastic-carbonate rocks are thinly to thickly bedded, between 0.3 and 3 m, with matrix-supported clasts showing normal and reverse grading and passing gradually into fine sandstone and shale to the north (Fig. 16A). The clasts are mostly small sub-angular limestone pebbles and granules of quartz, and occasionally limestone boulders. This characteristic diamictite facies indicates sediment gravity flow.

Along the eastern section the sequences are also near vertical (Fig. 16B). To the south, more than 55 m of dark grey sandstone is flanked by more deformed clastic-carbonate rocks and shales, in total 420 m thick. The lower part of this succession comprises 70 m of bedded limestone with matrix-supported clasts covered by 130 m of shale with intercalations of coarse sandstone and limestone. Shales show folding and a cleavage direction of N120. The upper part has alternating thin and thick beds of massive limestone with clasts and granules, characteristic of gravity flow and suspension deposits.

Correlations of the Kombuis carbonates across Sections 1, 2 and 3 illustrate a facies changes across ca. 10 km, with more distal slope deposits to the east-southeast (Fig. 17). These are characteristic carbonate slopes, which include different environments from shallow platform margins to the deep ocean basins, with a relatively steep continental slope (Coniglio and Dix 1992). Sediment transport by suspension settling, gravity

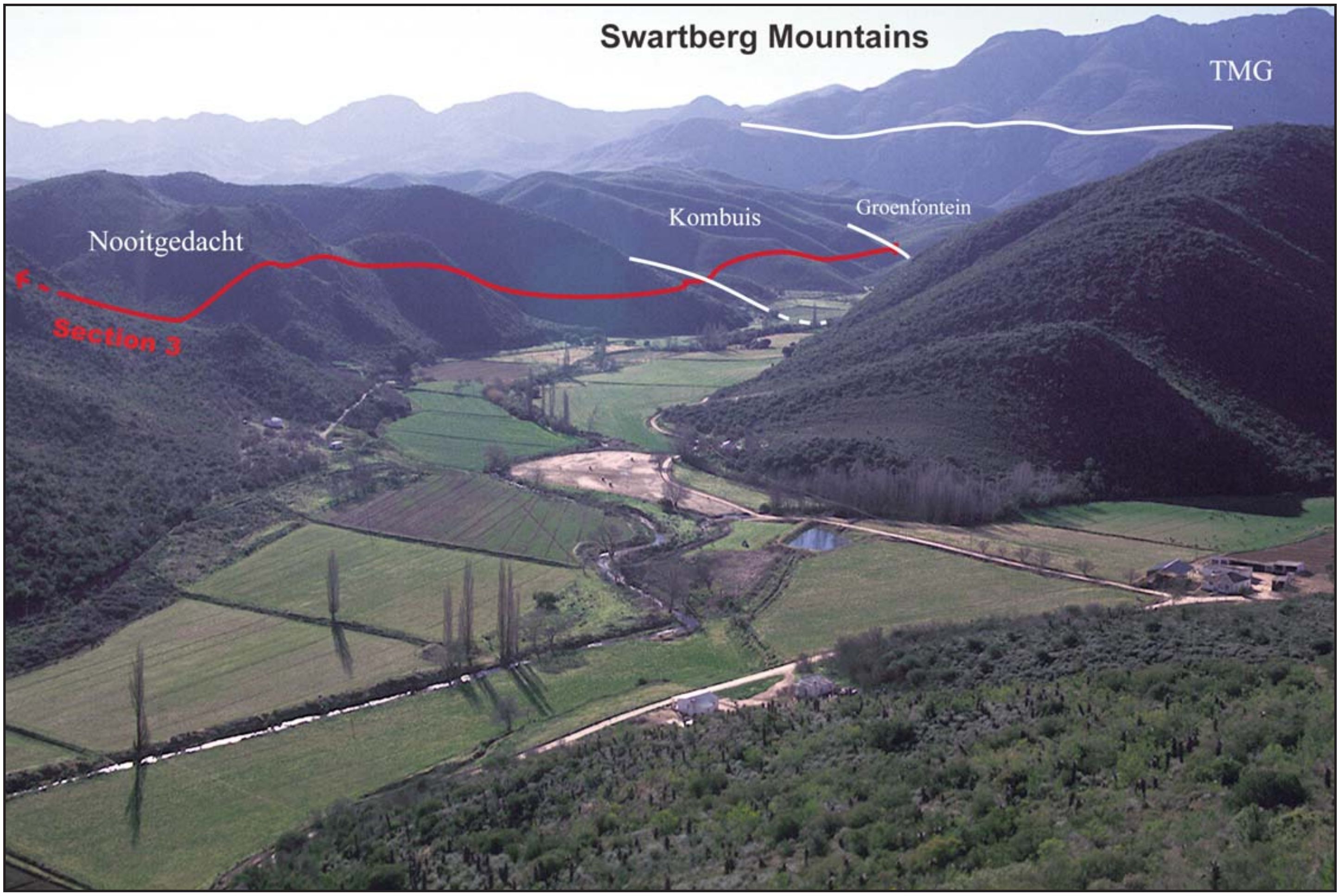


Figure 11. View north towards the Swartberg Mountains along the Tier Berg River showing mapped contacts (white lines) between the Nooitgedacht, Kombuis, Groenfontein and Peninsula formations. Stratigraphic section 3 is described in Figure 12 (Map 1 for location).

(resedimented) flow and submarine sliding often result in interbedded suspension deposits, shale and limestone, turbidites, debrites and contourites. Examples of such preserved stratigraphic records with carbonate boulder beds have been described in detail across the Cow Head Group in the Long Range Peninsula of Newfoundland (e.g. Hiscott and James 1985; James and Stevens 1986).

Section 5. Thrust Fault and Felsic Dykes Along Raubenheimer Dam Wall

Along the cut-off wall of the Raubenheimer Dam, south-dipping carbonate rocks and phyllites of the lower Nooitgedacht Formation are tectonically overlain by grey to orange, thickly bedded coarse quartzitic sandstone (grit) intruded by fine-grained felsic dykes (Fig. 18). The footwall comprises foliated carbonate rocks with extensional veins and interbedded very fine sandstone and shale. Locally preserved ripple cross-laminations show a younging direction to the south. The tectonic contact is filled with ca. 10–20 cm of schist with folded and duplicated calcite veins that reveal a north-trending thrust zone subparallel to the bedding (Fig. 19).

The new dates of two felsic dykes (Fig. 20) that cut the sandstone (and Cango limestones; see Section 6 below) of the lower Nooitgedacht Formation are similar in age to the ca. 1070 Ma Noritoid Suite in the Nababeep district, the Koperberg Suite and the Little Namaqualand Suite of the Khoisanland (Bushmanland) subprovince, and in general the Spektakel Suite (ca. 1100 Ma) and high-grade Namaqualand basement (e.g. Joubert 1986; see also Clifford et al. 1975, 1981; Waters 1990; Eglington 2006). These ages confirm for the first time a much older age for the lower sequences of the Kango Complex.

Section 6. Schists, Thrusts and Felsic Dykes Along the Main Road Near Grootkraal

Well-exposed subvertical sections (Fig. 21; separated by poor exposures) of phyllite (schist) and psammite with highly deformed limestone lenses (A – ca. 250 m; and separated to the south by 500 m from schist of Section 9), are separated by about 100 m from (B) 50 m of foliated limestone thrusted across phyllite and psammite. Farther inland, the poorly exposed carbonate rocks reveal in places deformed but well-preserved carbonate conglomerates (Fig. 4B) that confirm their link to the Kango Caves Group, and together with abundant silicic schists likely the Nooitgedacht Formation (Fig. 3). Between outcrops B and C (Fig. 21), the carbonate rocks are

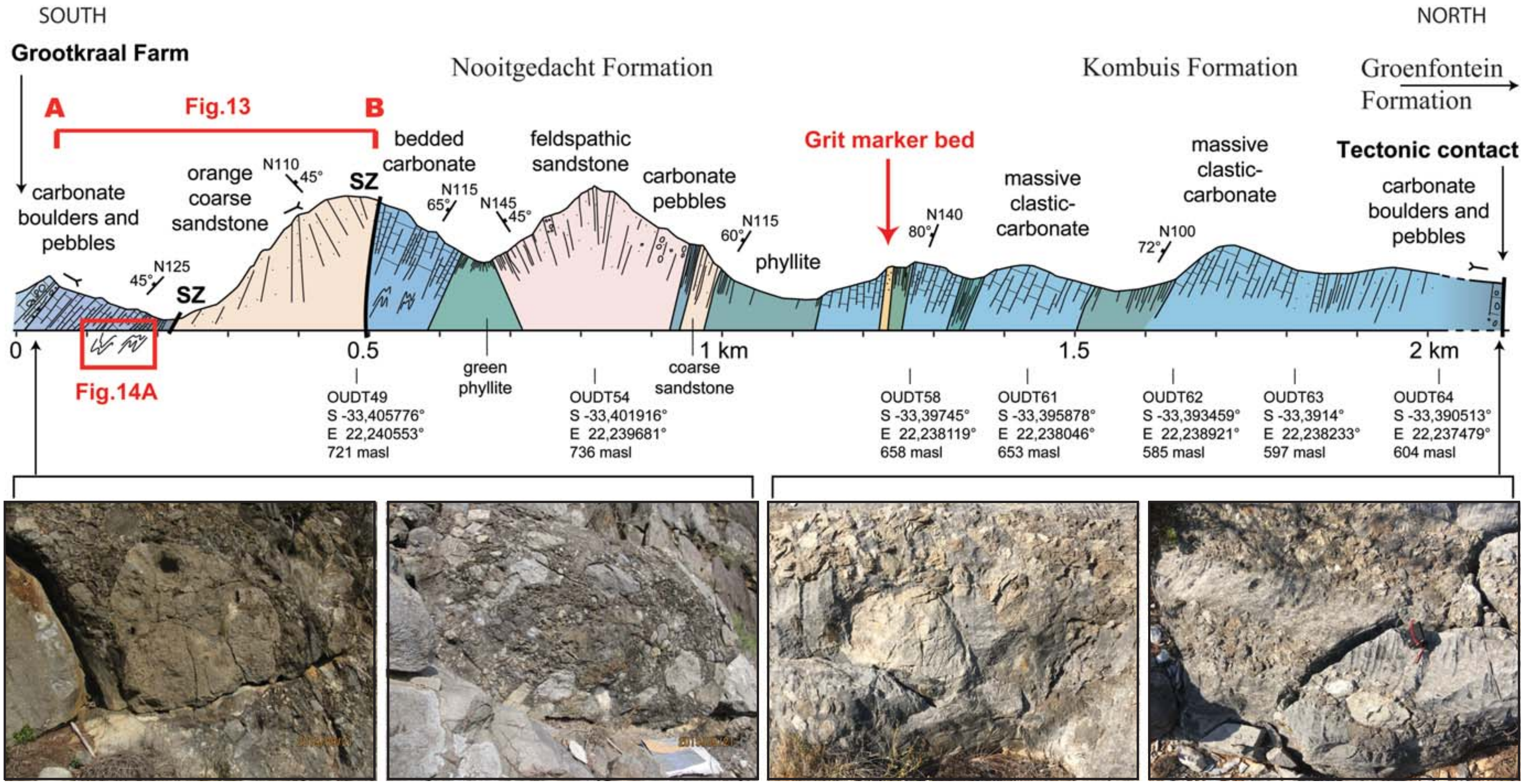


Figure 12. North–south cross section more than 2 km long between Grootkraal (south) and Groenfontein (north), showing the repetitions and contacts between limestones and shales of the Kombuis Formation and conglomerates and sandstones of the Nooitgedacht Formation (Section 3, Map 1). Highlighted in the photographs are similar limestone-conglomerate layers likely of the same upper Kombuis Formation. The massive clastic-carbonate sequences are tectonically overlain by sandstones and shales of the Groenfontein Formation that, in turn, flanks the TMG of the Swartberg Mountains to the north (Fig. 11). Section A–B (with carbonate boulder beds) is detailed in Figures 13 and 14.

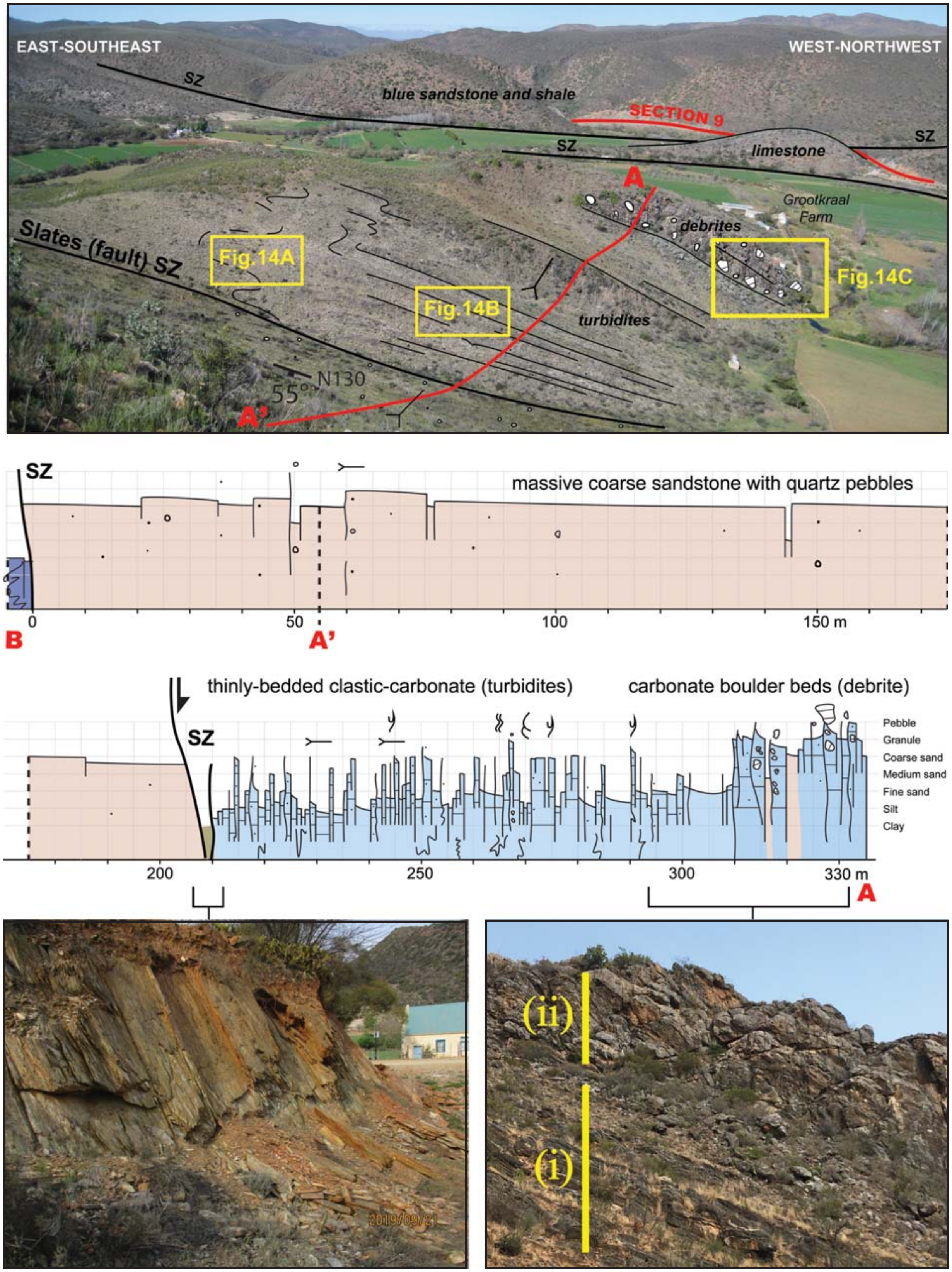


Figure 13. Section across Grootkraal Farm, 125 m thick clastic-carbonate rocks with sedimentary structures that indicate younging directions to the south, becoming thicker bedded upward and passing into carbonate boulder beds interpreted as turbidites and debrites (Fig. 12 for location). A 50 m thick schist zone (SZ, bottom left) marks the lower tectonic contact, and in turn is overlain by (bottom right) younging-upward sequences of carbonate turbidites (i) and carbonate boulder and sandstone beds (ii); for detailed outcrops see Figure 14A–D.

Figure 14A. Examples of steeply plunging folds within the layered clastic-carbonate rocks in the southern part of Section 3 (Fig. 12 for location). (a–b) Open folds without axial planar cleavage; (c) tight folds with variable axial planar shear zones (blue lines); and (d) open fold with folded tectonic calcite zones parallel to bedding that likely represent pre-fold shear zones (compare to Fig. 4A).

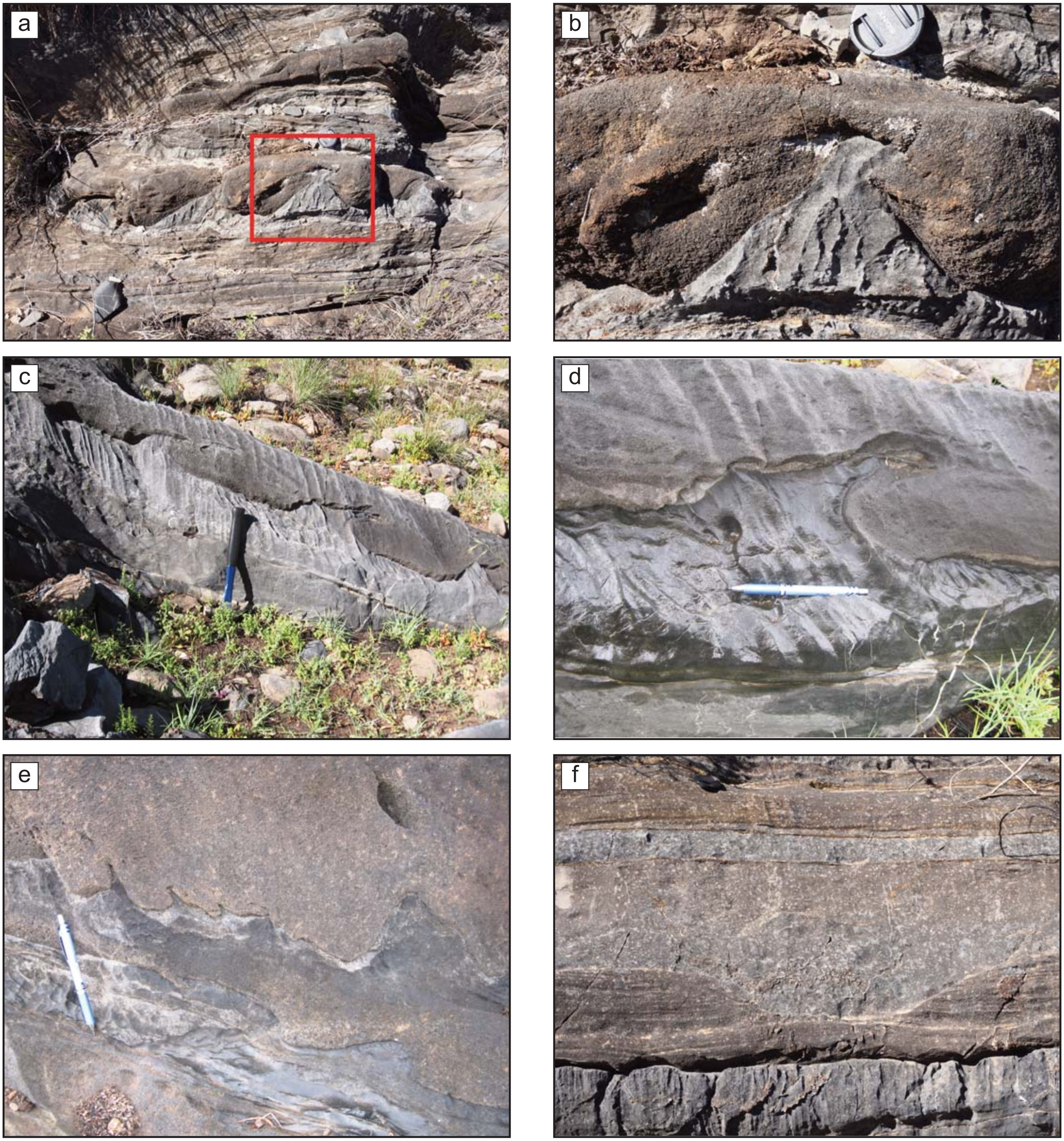


Figure 14B. (a–e) Soft sediment deformation (flame) structures within the limestone turbidites (brown = coarse-grained; grey = fine-grained); and (f) erosion channels (contourites). All structures confirm younging directions to the south (Fig. 13 for location).

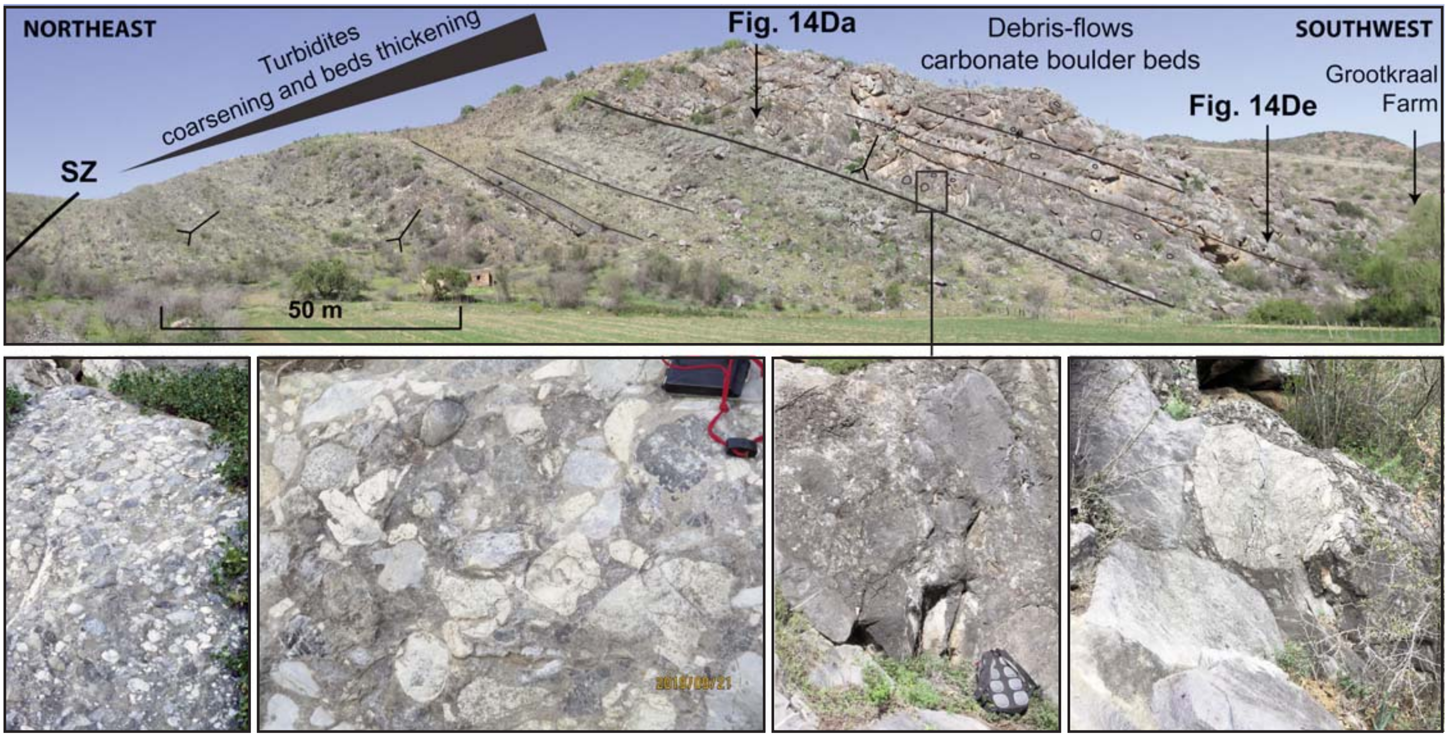


Figure 14C. Sequences of clastic-carbonate rocks are sharply overlain by thickly bedded boulder conglomerate and coarse quartzitic sandstone. The succession dips 40° to the north and contains erosion surfaces and large rounded to angular limestone boulders interpreted as debris flows.

less foliated and reveal open folding with psammitic layers. At outcrop C, these rocks are intruded by subvertical felsic dykes (Fig. 22A). Zircons from two of these dykes (d1 and d2) yielded a U–Pb date of ca. 1084 Ma (Fig. 22B).

Farther west along the road, this section is structurally overlain by a thick isoclinally folded carbonate-marble sequence (highlighted in Fig. 4C). In detail, this entire section represents part of a highly deformed fold limb of the Kango Caves Group (shortened by at least 60%; see Map 2), which makes it difficult to separate the Kombuis from the Nooitgedacht formations with confidence.

Section 7. Clastic-Carbonate Rocks at De Hoek Cave

Thick-bedded limestones within the Groenfontein Formation outcrop at De Hoek Cave (Fig. 23A). These are bluish grey, mud-supported carbonate rocks containing quartz granules and clasts that show both fining and coarsening-upward sequences (Fig. 23B). Rare erosion surfaces indicate a younging direction to the south. The logged section is on the northern limb of an anticlinal structure, unconformably overlying green shale with orange sandstone beds. It comprises 70 m thick fine-grained limestone overlain by 40 m thick clastic limestone that become thicker bedded and coarser upward. This succession suggests deposition by filling large channels and progradation.

Section 8. Interbedded Sandstones, Siltstones and Shales of Melville Dam

At Melville Dam (Fig. 24), interbedded sandstones, siltstones and shales more than 1 km across are repeated along east–west relatively tight folds plunging south. The sedimentary facies are green to orange, fine to very coarse-grained sandstone beds, 10 cm to 1 m in thickness, alternating with siltstone and shale. The fining upward successions of coarse sandstone with erosional bases, passing upward into ripple cross-laminated siltstone and shale are characteristic of turbidites. Preserved groove marks indicate a northwest–southeast transport direction.

Section 9. Thrust Fault and Cross-bedded Sandstones Along the Main Road Near Kombuis

Flanking the main road near Kombuis (Fig. 25), a major shear zone (Boomplaas Thrust) linked to 70 m of highly schistose phyllite of the Groenfontein Formation and 70 m of interlayered limestone/marble and phyllite of the Kombuis Formation, dips 65–80° south along this fully exposed section. To the north, this schist zone, unexposed for 30 m, links to zones of highly deformed marble boudins in schistose phyllite (described in Section 6). Southward, the shear zone is tectonically overlain by 260 m thick grey to blue cleaved sandstone, siltstone and greywacke of the Uitvlugt Formation (Fig. 26a) where, across the upper 50 m, the cleavage cuts across bedding of a well-preserved anticline linked southward for 200 m to separated parts of a highly fragmented synform along schistose phyllite (Fig. 26c).

The sandstone beds are overturned, comprising relatively abundant syn-depositional erosional features that indicate younging directions to the north (Fig. 25). The sedimentary facies include undular and large-scale cross-stratifications, 2–10 m in width, with mud drapes and rip-up clasts, which indi-

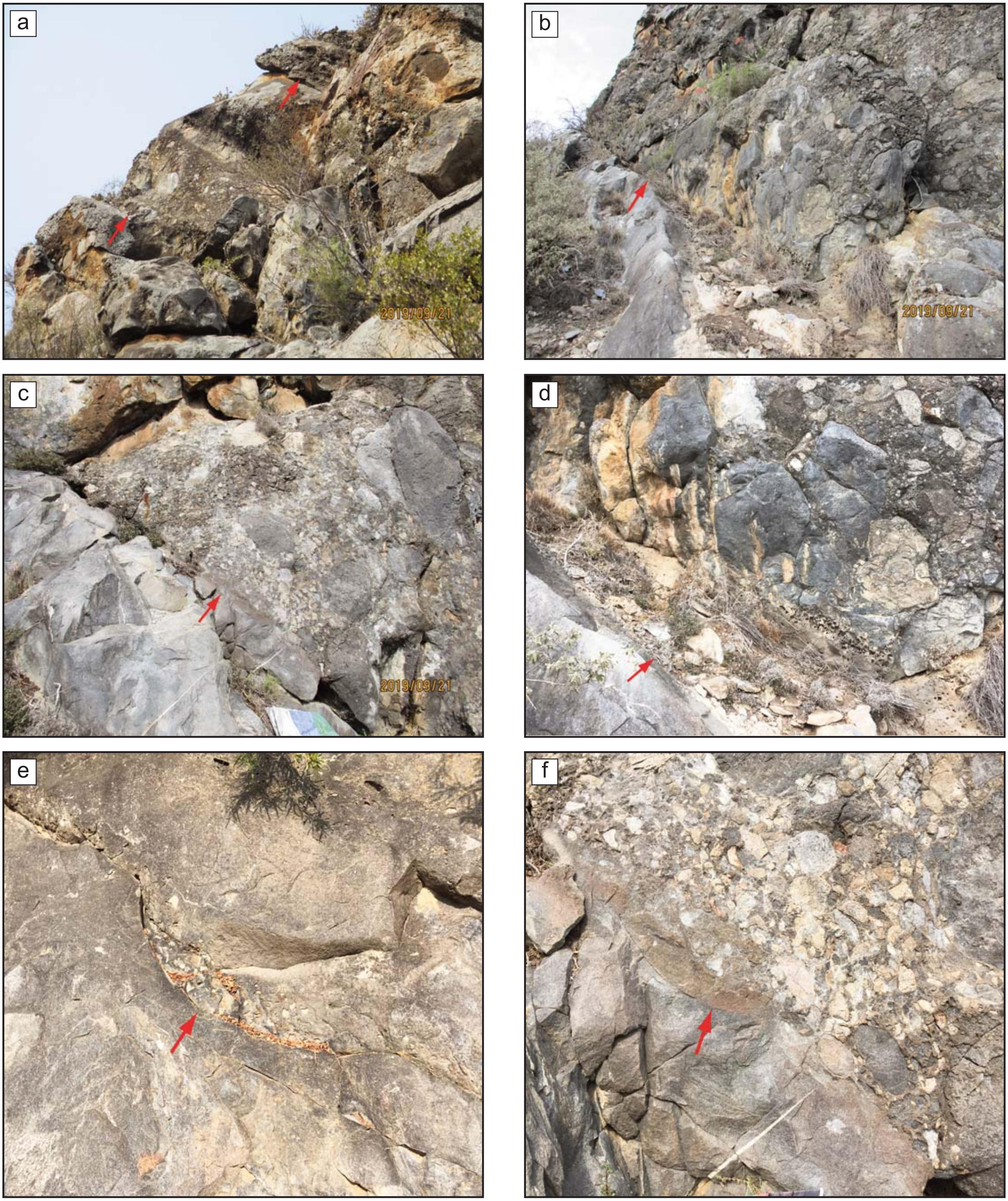


Figure 14D. Erosive contacts (red arrows pointing up) within the carbonate boulder beds indicating younging directions to the south (Fig. 14C for location).

Figure 15. General north-facing view across the lake of Koos Raubenheimer Dam (Section 4, Map 1), showing the location of detailed cross-sections along the western and eastern banks in Figures 16A and 16B, respectively.

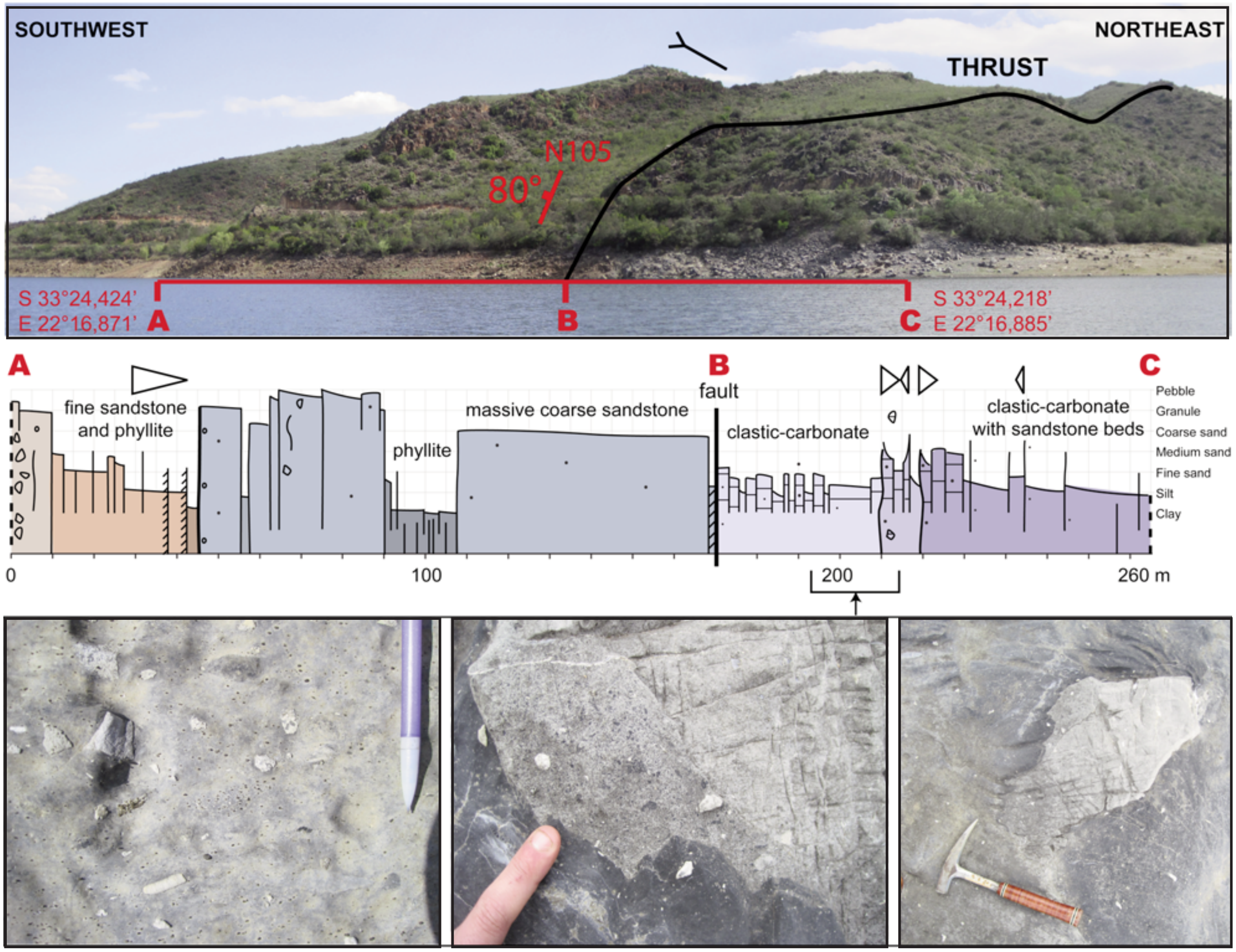


Figure 16A. Northwest–southeast cross-section and sedimentological log along the western bank of Koos Raubenheimer Dam (Fig. 15 for location). Conglomerate, sandstone and shale of the Nooitgedacht Formation are covered by clastic-carbonate rocks and shales of the Kombuis Formation.

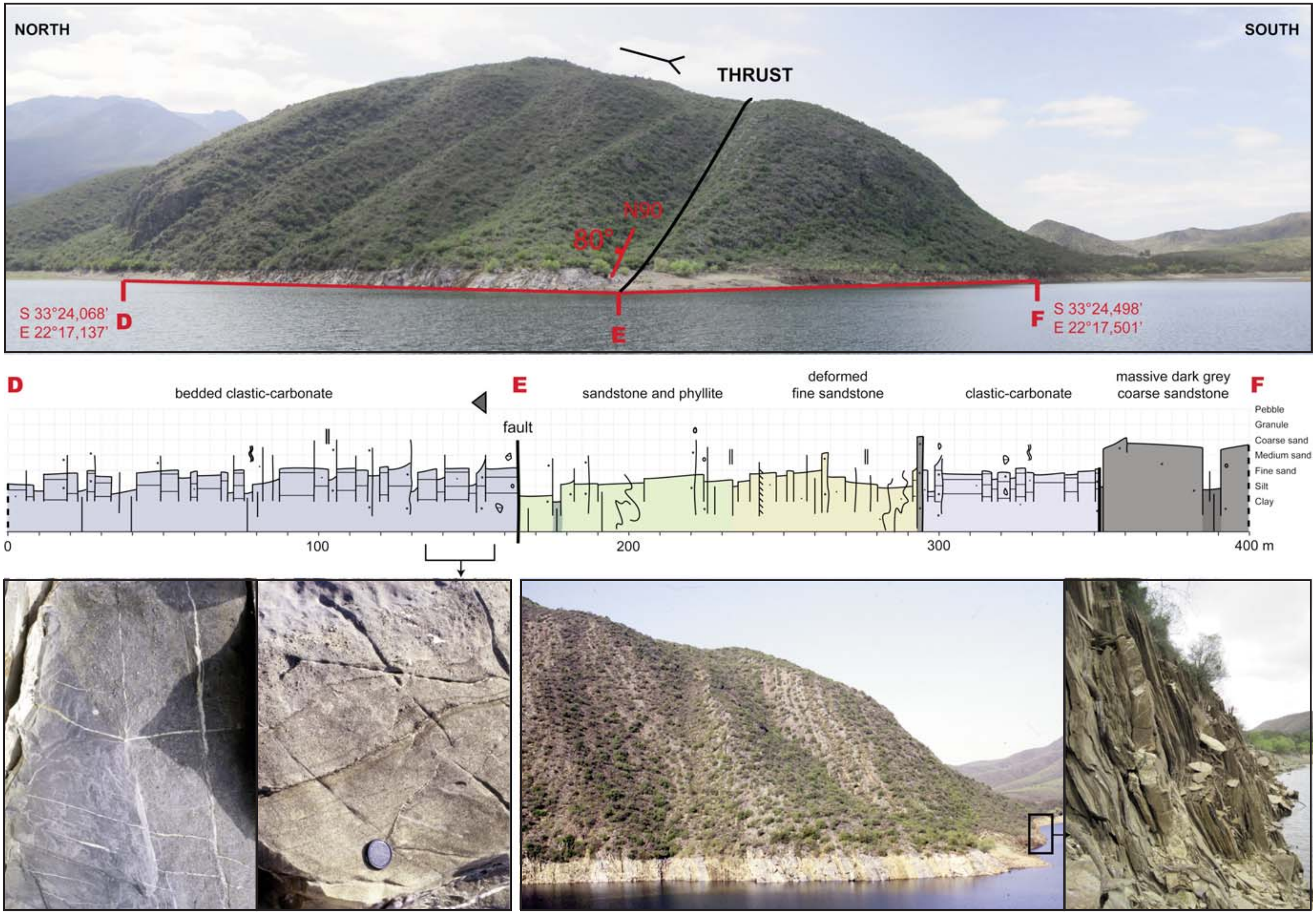


Figure 16B. Section of limestones and shales of the Kombuis Formation along the eastern bank of Koos Raubenheimer Dam (Fig. 15 for location). Sequences of coarse sandstone and phyllite with bedding-parallel cleavage and schistosity alternate with clastic-carbonate rocks and bedded limestones, which in places preserve sedimentary diamictite and graded clastic matrixes (bottom left). Bedding-parallel cleavage in slate sometimes crosscuts sandstone beds to reveal direction of sub-isoclinal fold closures (bottom right).

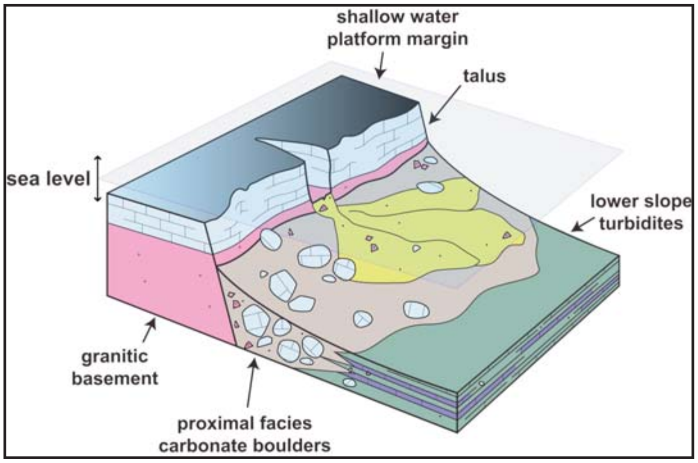


Figure 17. Schematic facies model of a submarine escarpment cut by a river section that deposited granite pegmatite and feldspathic sandstone/grit, limestone boulders and diamictite of the Kango Caves Group linked to variable sea-level changes. These carbonate sequences resemble the Lower Paleozoic marine sequences in Newfoundland, deposited across the Grenvillian basement of the Long Range Peninsula and from there eastward as far as Fleur de Lys (e.g. Figures 32–34 in James and Stevens 1986).

cate shallow marine deposition (Fig. 26b). These are underlain over ca. 2 km by similar, but less well-exposed subvertical sandstones and shales, cut by numerous internal shear zones and subvertical thrusts with fragmented phyllites (e.g. Fig. 26e).

The abundant bidirectional cross-bedding and flaser beds with laminated mud in the quartzite indicate rapidly changing low- and high-energy currents in an intertidal paleo-environment, such as for example sand flats in estuaries. Notably, no fossils or bioturbations have been observed anywhere in this section.

Section 10. Conglomerates and Sandstones Along Schoemanspoort

This north–south section (> 500 m across), previously called Reitkloof (Map 1), is best exposed along the main road to Oudtshoorn flanking the Grobbelaars River near Ou Tol (Old Toll House). Southward from the Toll House entrance, the section comprises well-cleaved cross-bedded arkoses and blue quartzitic sandstones with pebbles and cobbles of the Vaartwell Formation (Fig. 27). The clasts are mainly of sandstone (intraclasts) and well-rounded granite pebbles between 5 and 30 cm in diameter. The shale/sandstone pebbles and cobbles are mostly flattened along the cleavage, while the granite boulders generally preserve their original shapes. The subhorizontal bedding shows open folds cut by a strong east–west striking subvertical cleavage that makes the identification of bedding planes challenging in many places. In coarse-grained sandstone, younging directions from cross-stratifications are to the north.

The section is intruded by several mafic dykes, now amphibolite, with vertical schistosity, commonly with deformed quartz veins (Fig. 5a), and similar to those dated at ca. 512 Ma in the eastern region of the Kango Complex (Haas 1998; Fig. 2b).

This quartzitic sequence is equivalent to the Kansa Group conglomerate that unconformably overlies the Groenfontein Formation of the Goegamma Group, and it is here interpreted as a molasse deposit (Fig. 3). The basal contact is well exposed in the mountain section about 200 m higher (Barnett et al. 1997) where U–Pb detrital zircon dates reveal a Cambrian age for the conglomerate (< 518 Ma), consistent with another detrital zircon date of ca. 485 Ma obtained from the Uitvlugt Formation (Naidoo et al. 2013). The age of the granite boulders is consistent with the age of the Saldinian (including Table Mountain) granite bodies (e.g. Scheepers and Armstrong 2002; Kirsters 2016; Miller et al. 2016).

Section 11. Subvertical Unconformity Between the Kango and TMG Rocks

TMG quartzite is coarse to fine-grained with quartz pebble

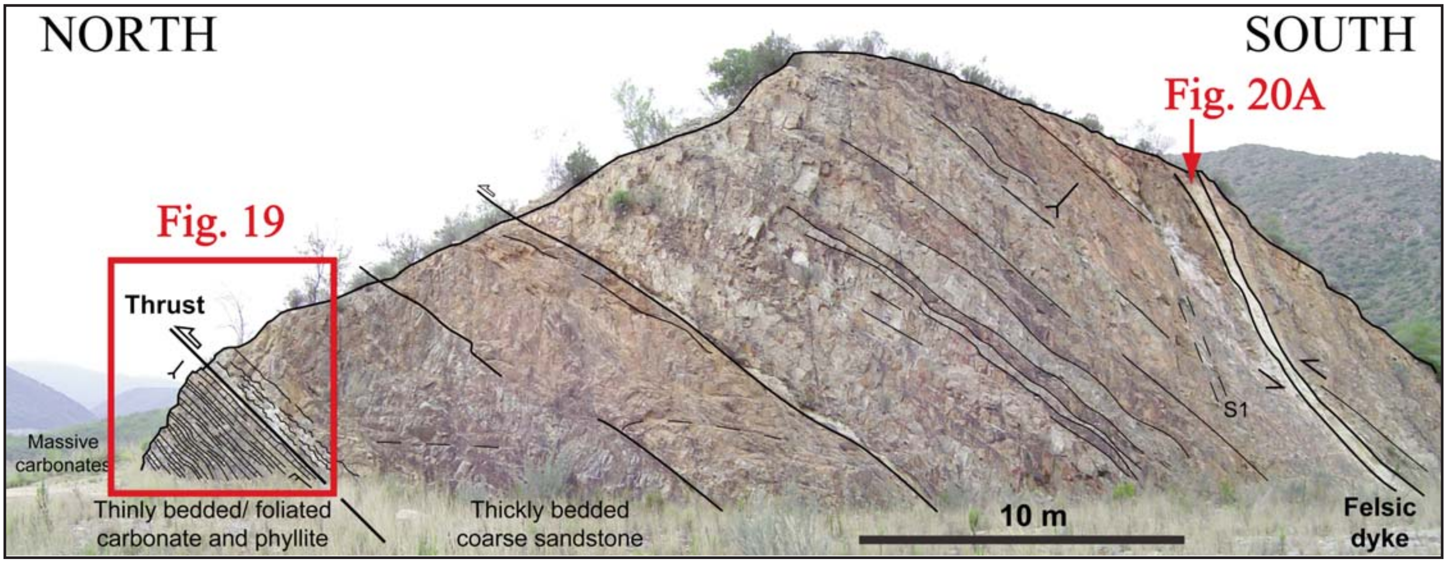


Figure 18. Thrust contact between clastic-carbonate rocks and coarse quartz sandstone dipping south, intruded by felsic dykes (Section 5, Map 1). Figure 20 presents the new geochronology.

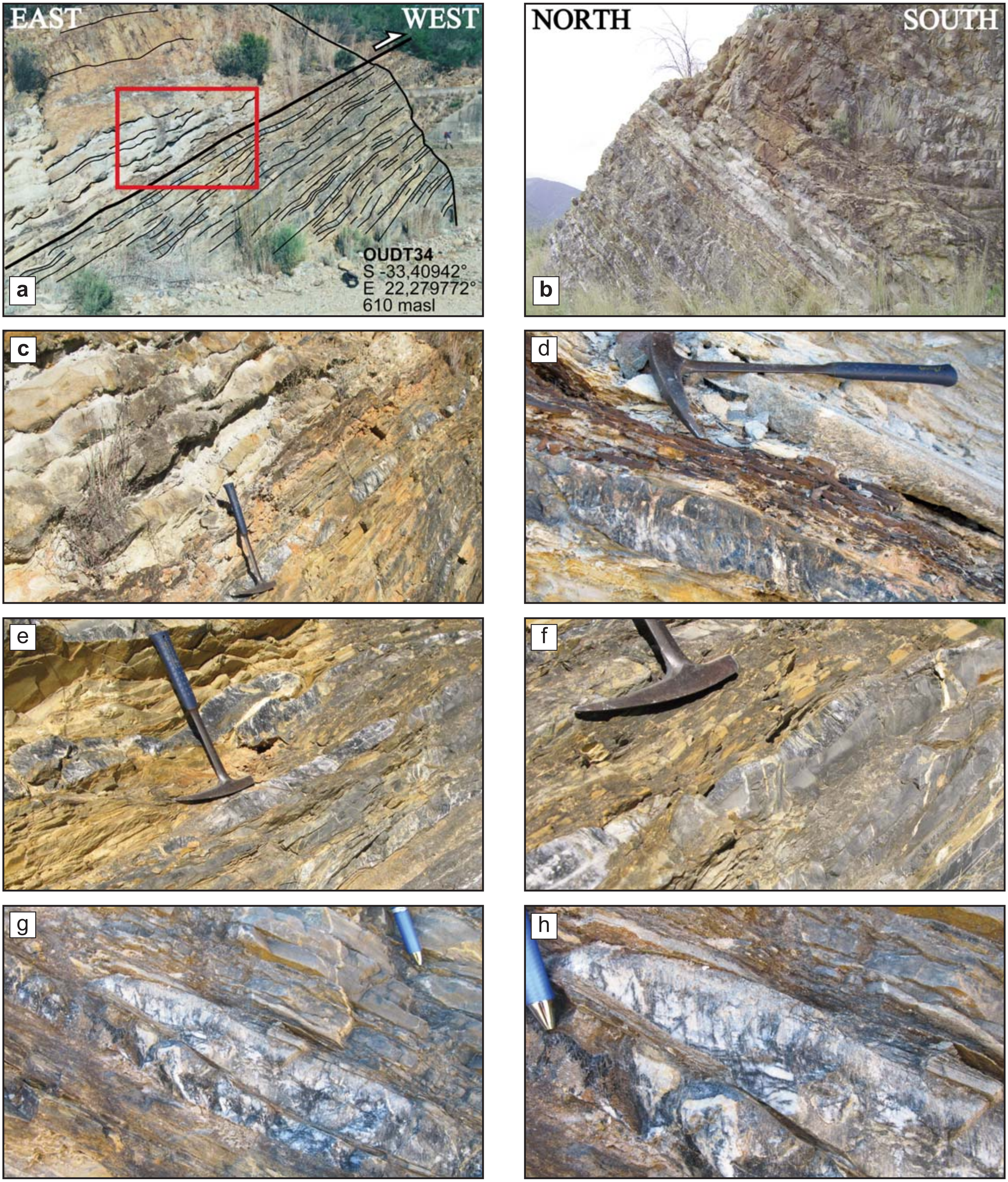


Figure 19. Along the thrust fault, thin limestone beds preserve extension veins that are duplicated – this is a complex thrust zone with episodic extensional carbonate veins (Fig. 18 for location).

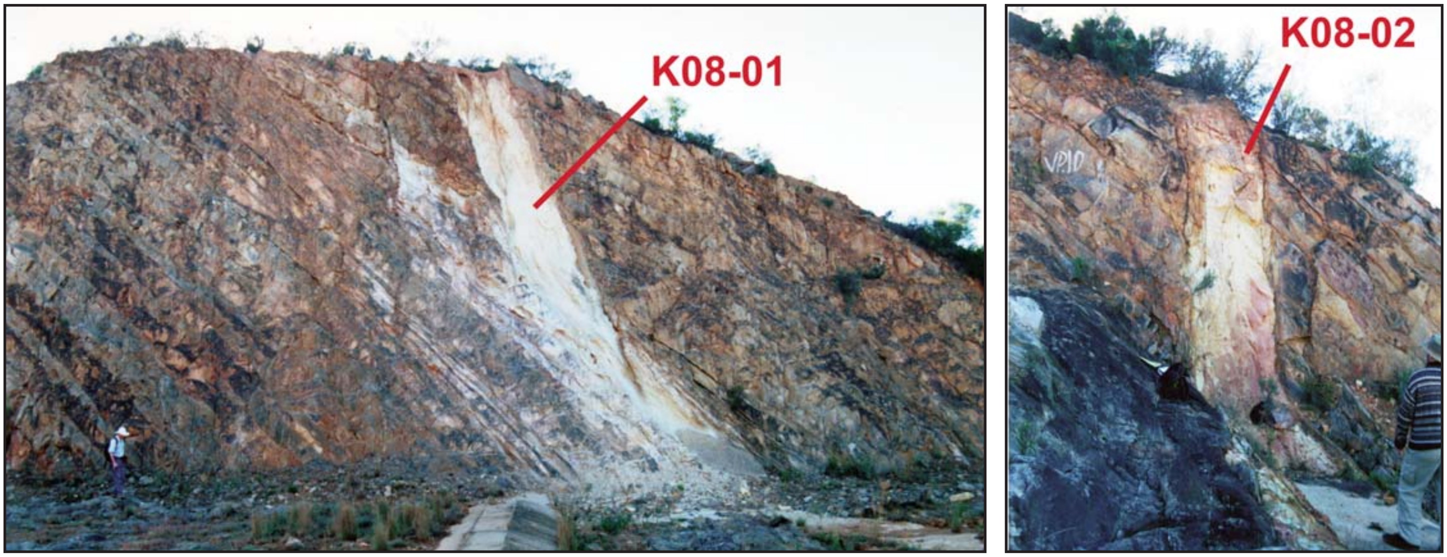


Figure 20A. South-dipping quartz sandstone (grey-red) of the Nooitgedacht Formation intruded by two steep dipping felsic dykes (white to pale brown) along the cut-off wall of the Koos Raubenheimer Dam (Fig. 18 for location).

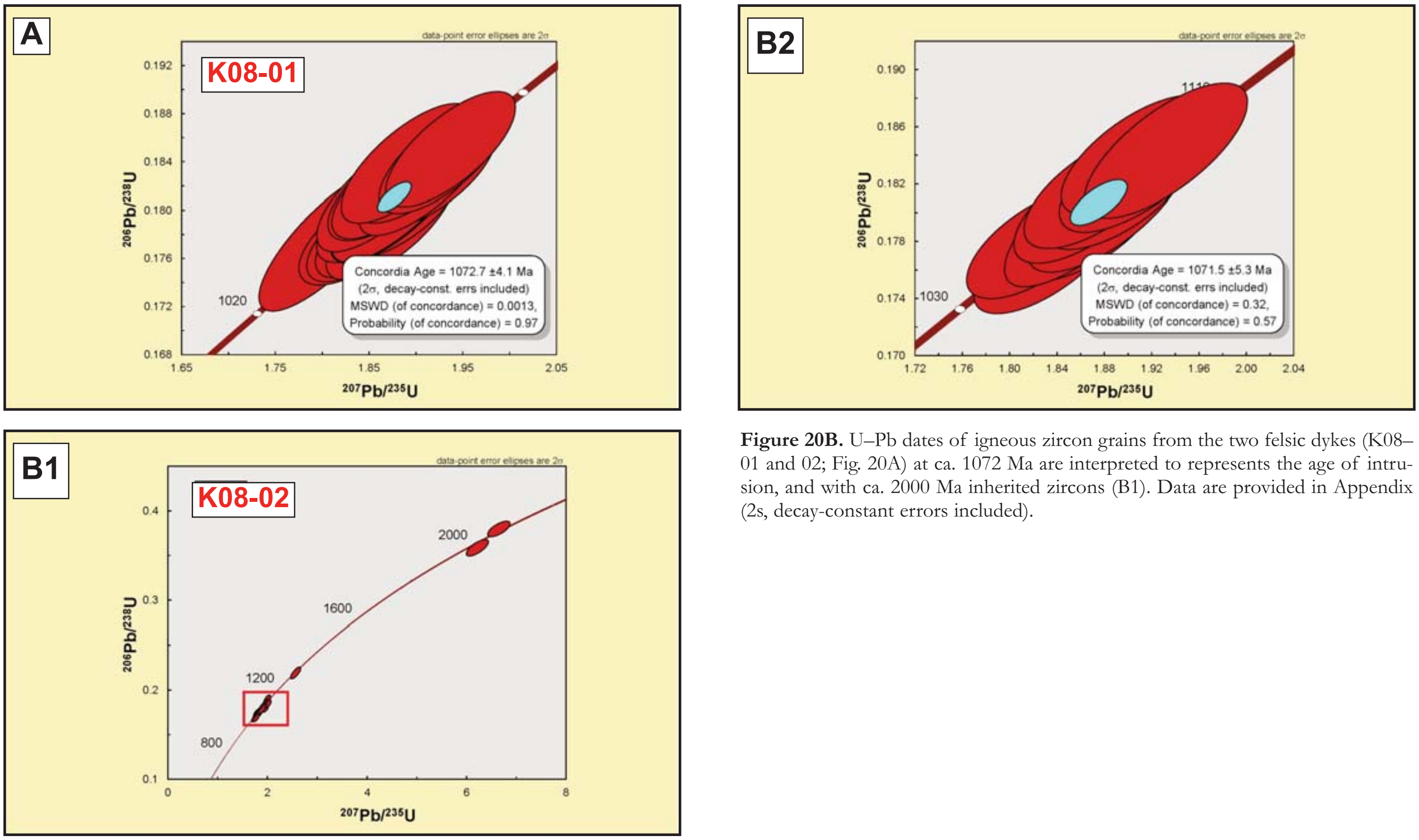


Figure 20B. U–Pb dates of igneous zircon grains from the two felsic dykes (K08–01 and 02; Fig. 20A) at ca. 1072 Ma are interpreted to represents the age of intrusion, and with ca. 2000 Ma inherited zircons (B1). Data are provided in Appendix (2s, decay-constant errors included).

conglomerates and dips from subhorizontal to steeply north (overturned) above the Kango sequences. Deformed unconformities are well preserved in local exposures (Map 2). In most sections, the TMG directly overlies schistose greywackes and shales of the Groenfontein Formation. However, in a small folded section of the studied area (Fig. 28a), Groenfontein greywacke is unconformably overlain by schistose conglomerates, sandstones and shales of the Schoongezigt (Gezindskraal) Formation, which in turn are unconformably overlain by quartzites and conglomerates of the TMG. This feature outcrops best in an open to close fold exposure, confirming that the main deformation across the Kango Complex is of post-TMG age, and thus likely linked to the Cape Fold Belt orogeny at ca. 252 Ma.

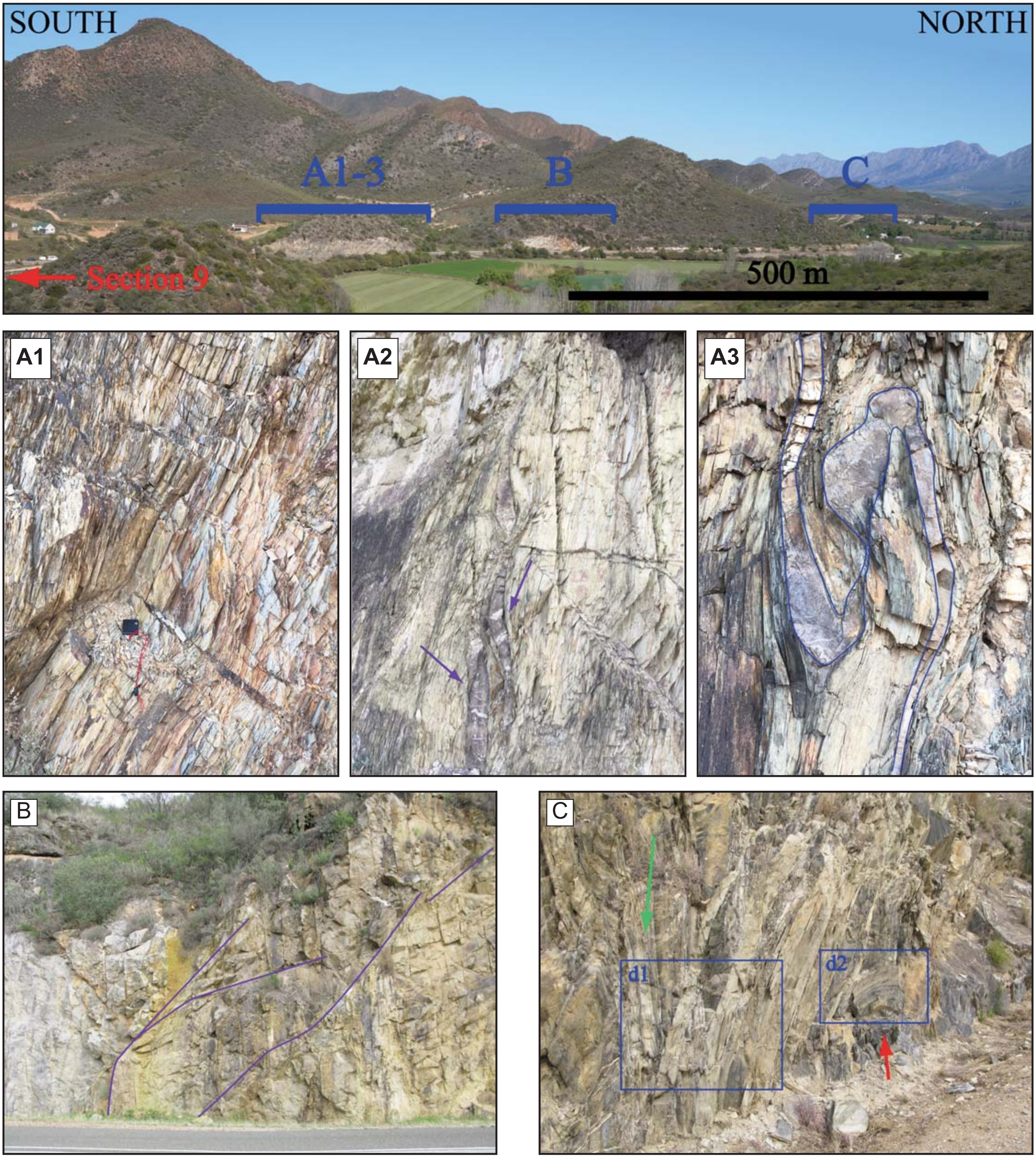


Figure 21. Section 6 of phyllites–psammites and foliated carbonate rocks of the Kango Caves Group; for location see Map 1. (A1) Phyllitic schist (pale yellow) with thin dismembered marble lenses, (A2) with limestone marble boudins and with isoclinally folded limestone lenses (blue-grey with white carbonate veins), and (A3) typical thin slate unit (dark grey with white quartz veins) duplicated within a thrust zone separating massive sandstone beds (pale grey). (B) Thrust between carbonate section (left) and phyllites–sandstones with thin grey carbonate limestone units (right and small thrusts within this unit). (C) Open fold of limestone (dark grey, red arrow) and subvertical limb of sandstone (green arrow), cut by steep dipping felsic dykes (d1 and d2 = highlighted in Fig. 22A).

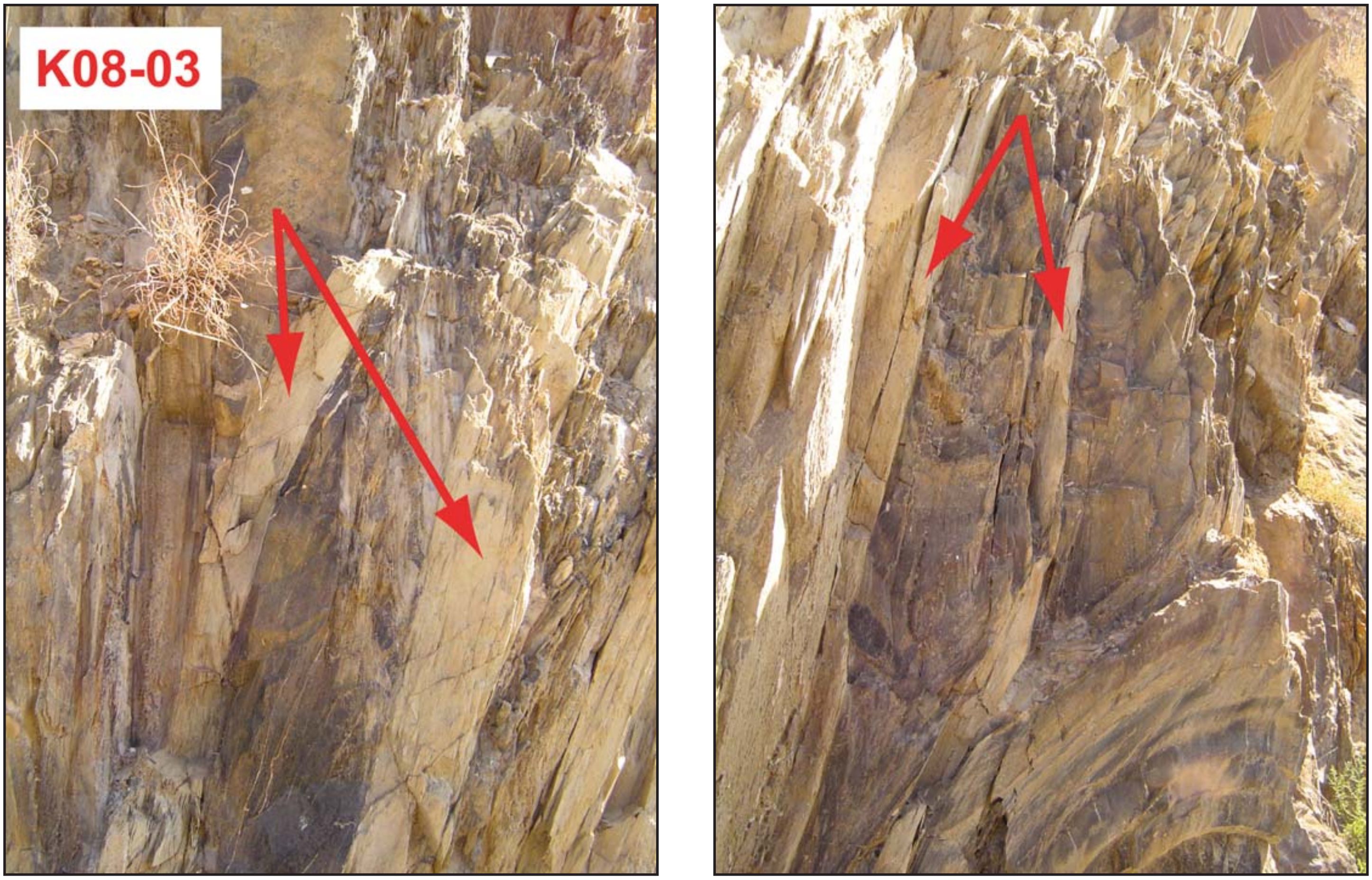


Figure 22A. Thin subvertical felsic dykes (red arrows) with parallel cleavage that is also axial planar to intruded subhorizontal open folded limestone (dark grey) and subvertical psammite beds (pale yellow), exposed 30 m below a major subvertical thrust zone (Fig. 4C).

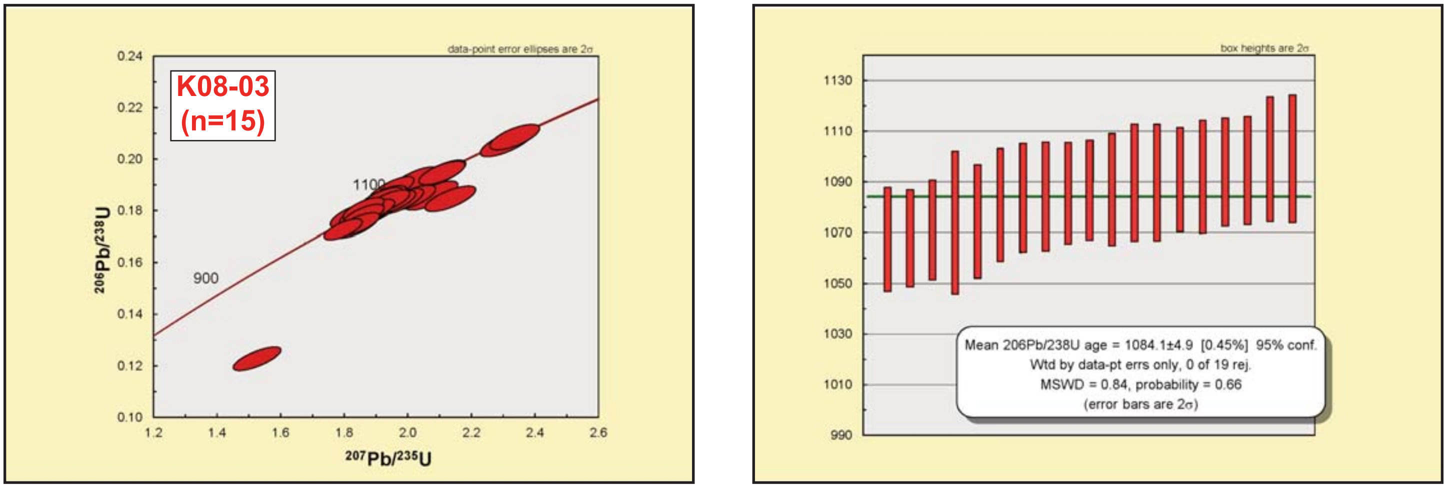


Figure 22B. U–Pb dates of igneous zircon grains from thin felsic dykes cutting a sequence of thin-bedded sandstone and limestone/marble of the Nooitgedacht Formation (Fig. 21C). The average U–Pb date of these felsic dykes (K08-03; Fig. 22A) is ca. 1084 Ma, which is 10 m.y. older than that of the Raubenheimer dykes, and very similar to the age of granitoids of the Spektakel Suite of the Khoisanland sub-province (e.g. Reid and Barton 1983; Joubert 1986; Reid et al. 1987). Data are provided in Appendix (2s, decay constant errors included).

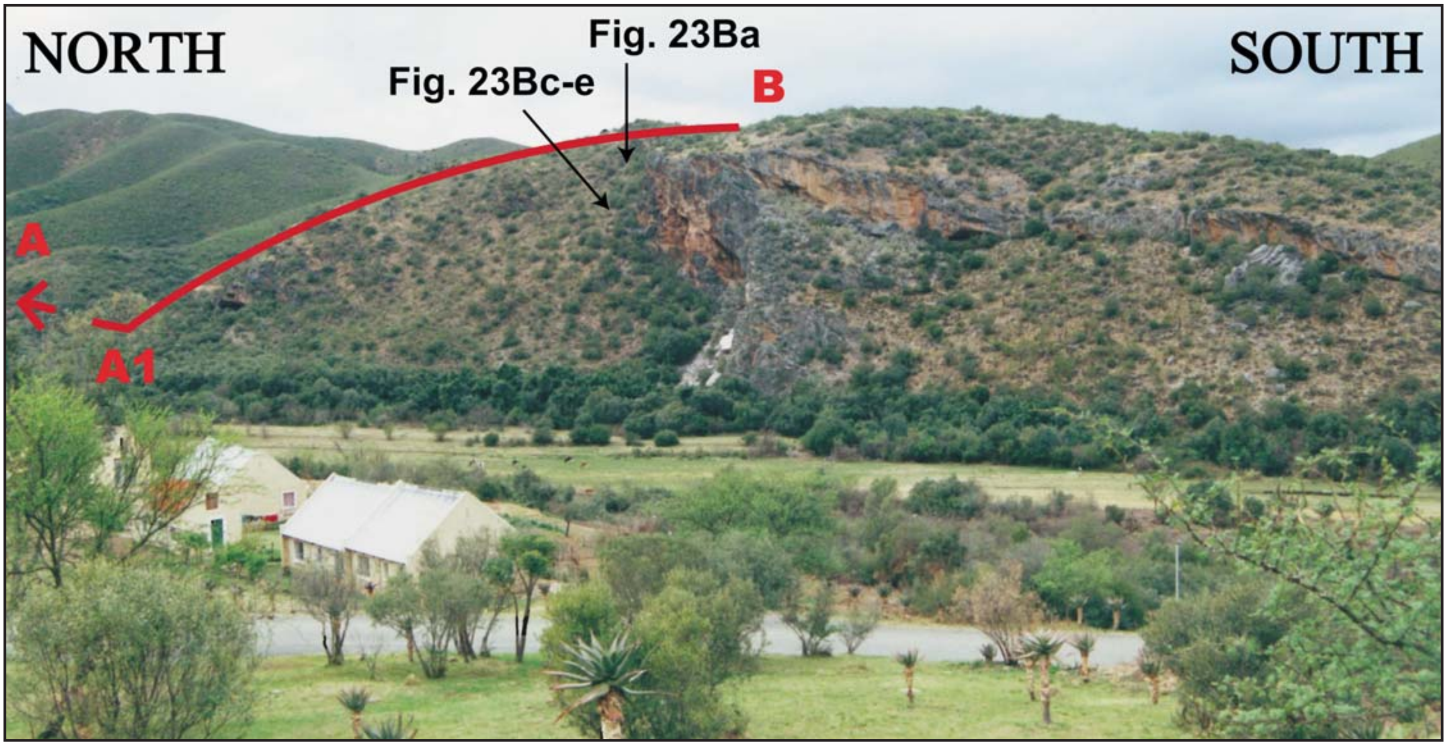


Figure 23A. Clastic limestone (orange weathering) about 100 m thick, exposed at De Hoek Cave near the Resort (Section 7, Map 1).

Frequently, highly schistose zones within the TMG, parallel to its bedding, are well exposed close to the contact with the Kango rocks (Fig. 28c–h), and shallow north-facing and folded thrusts are well exposed within the TMG well above the contact (Fig. 4E, and see below). Steeply dipping, axial planar cleavage is well developed in open folded shale of the Goegamma Group, and reveals a near parallel bedding between the two groups (Fig. 28b).

Section 12. Subhorizontal Unconformity Between the Kango and TMG Rocks

Stretching some 2 km south from the subvertical dipping contact between the Kango and TMG rocks along the Swartberg Range, two sections of subhorizontal bedded quartzite of the TMG outcrop unconformably across the Groenfontein shales and sandstones (Fig. 29). The Groenfontein Formation has a subvertical cleavage or schistosity linked to open well-spaced subvertical fractures in the overlying quartzite. The bedding orientations of shales across these outcrops are part of open folded subhorizontal sequences.

This subhorizontal section of TMG covering the Kango Complex is only very locally preserved, but the TMG outcrops across the entire study area in the west (Fig. 30). Here, the shallow dipping contact across the southern margin is overlain by a thrust duplex of TMG quartzite, with a total early subhorizontal shortening of about 75%. This is similar to thrust zones across the subvertical, but poorly outcropping TMG quartzite flanking the southern margin of the eastern Kango Complex (Map 2).

GEOMORPHOLOGY

Cretaceous to Present Erosion Rates

Rounded boulders of TMG quartzite cover remnants of the old flat regional topography preserved at ca. 1000–700 m asl, above the Kango sequences (Fig. 31). The onset of subsequent deeper river erosion implies that climate variation created an opportunity to open caves from the top of these flat surfaces along the subvertical contacts of limestone-marble with pelitic schist and sandstone of the Nooitgedacht Formation, linked to small rivers that eroded down to about 600 m asl (Decker et al. 2013). Similar caves occur along the contact of the Kango Caves Group conglomerate with the Groenfontein pelite–psammite units (for all caves location see Map 2).

Erosion rates changed considerably from ca. 100–200 m/m.y. during the Cretaceous (140–80 Ma), based on apatite fission track analyses (AFTA) on deep borehole samples just north of the Swartberg Mountains, to less than ca. 10–20 m/m.y. in the Cenozoic around 60–30 Ma; and, less than ca. 3–6 m/m.y. over the last 5 m.y., based on measurements of three river systems in the study area (Fig. 2b). Thus, the deep valleys across the Kango rocks are not due to the slow erosion during the relatively dry recent climate (e.g. Flowers and Schoene 2010; Scharf et al. 2013; Kounov et al. 2015; Evans 2015 and references therein). The origin of the Cango Caves may therefore link to high precipitation times before 60 Ma, and the formation of stalagmites during significantly reduced precipitation periods, as confirmed by their oldest known age of about 200 ka (de Wit et al. unpublished).

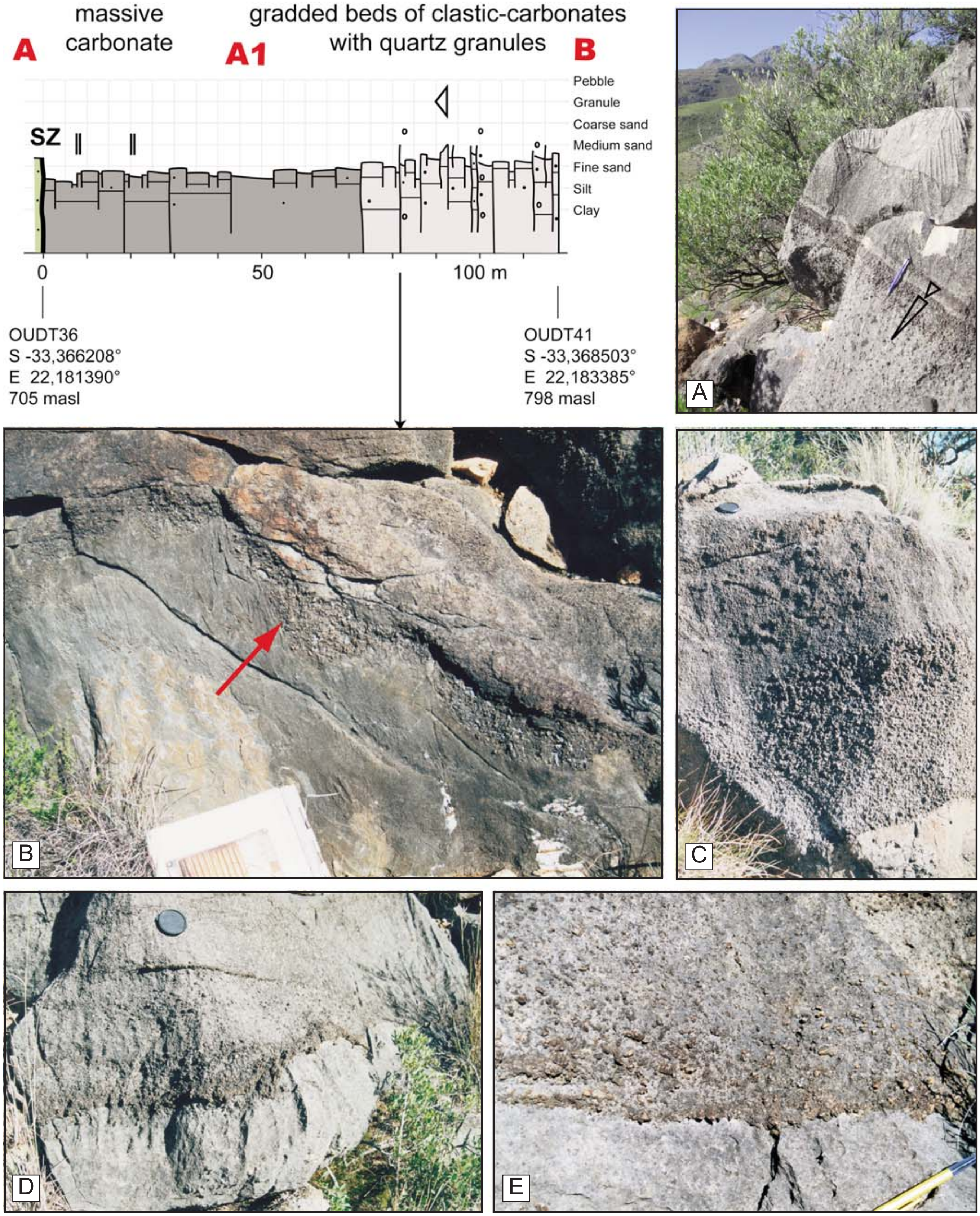


Figure 23B. The sedimentary log highlights a 120 m thick succession (Fig. 23A) that preserves both fining-up and coarsening-up graded beds of limestone (grey) with granule to gravel-sized quartz (brown). Erosion surfaces (red arrow pointing up) indicate younging to the south.

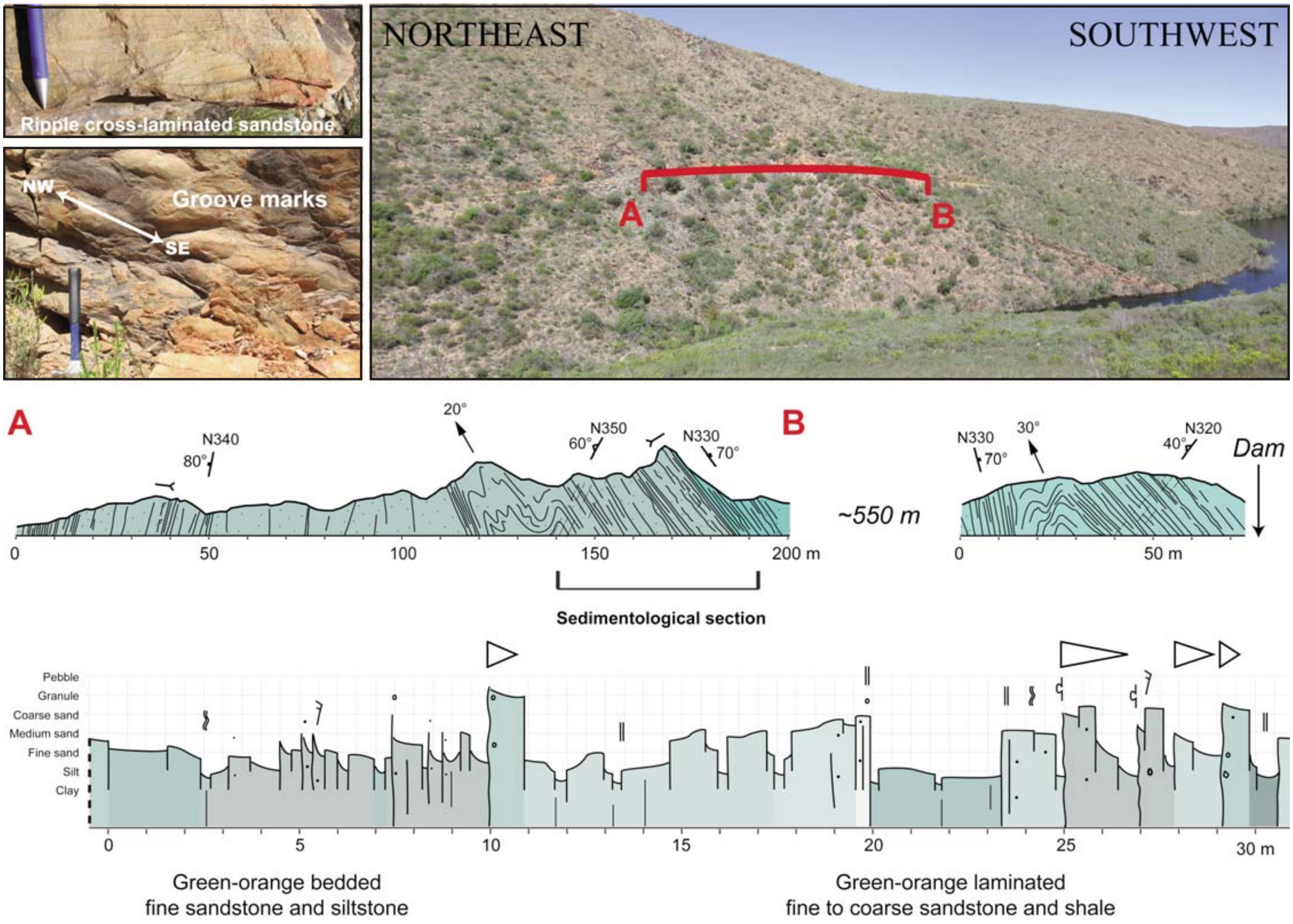


Figure 24. Northeast–southwest cross-sections and sedimentary log along the banks of the Melville Dam (Section 8, Map 1). Green and orange, fine to very coarse-grained sandstone, siltstone and shale of the Groenfontein Formation are characteristic of turbidites and show north-verging folds.

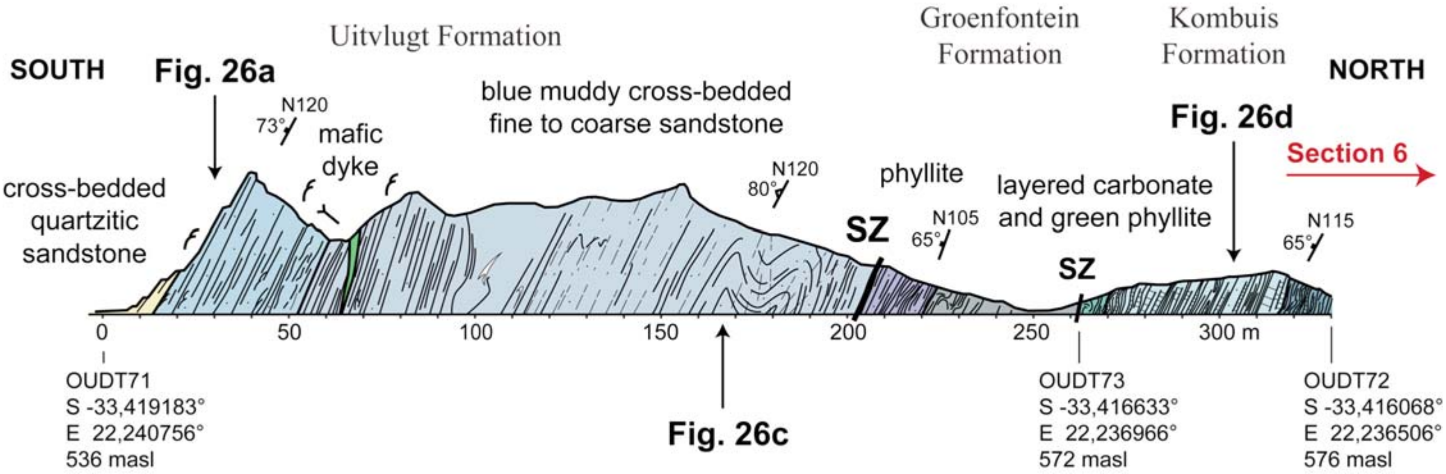


Figure 25. North-south cross-section more than 300 m long along the main road near Kombuis (Section 9, Map 1).

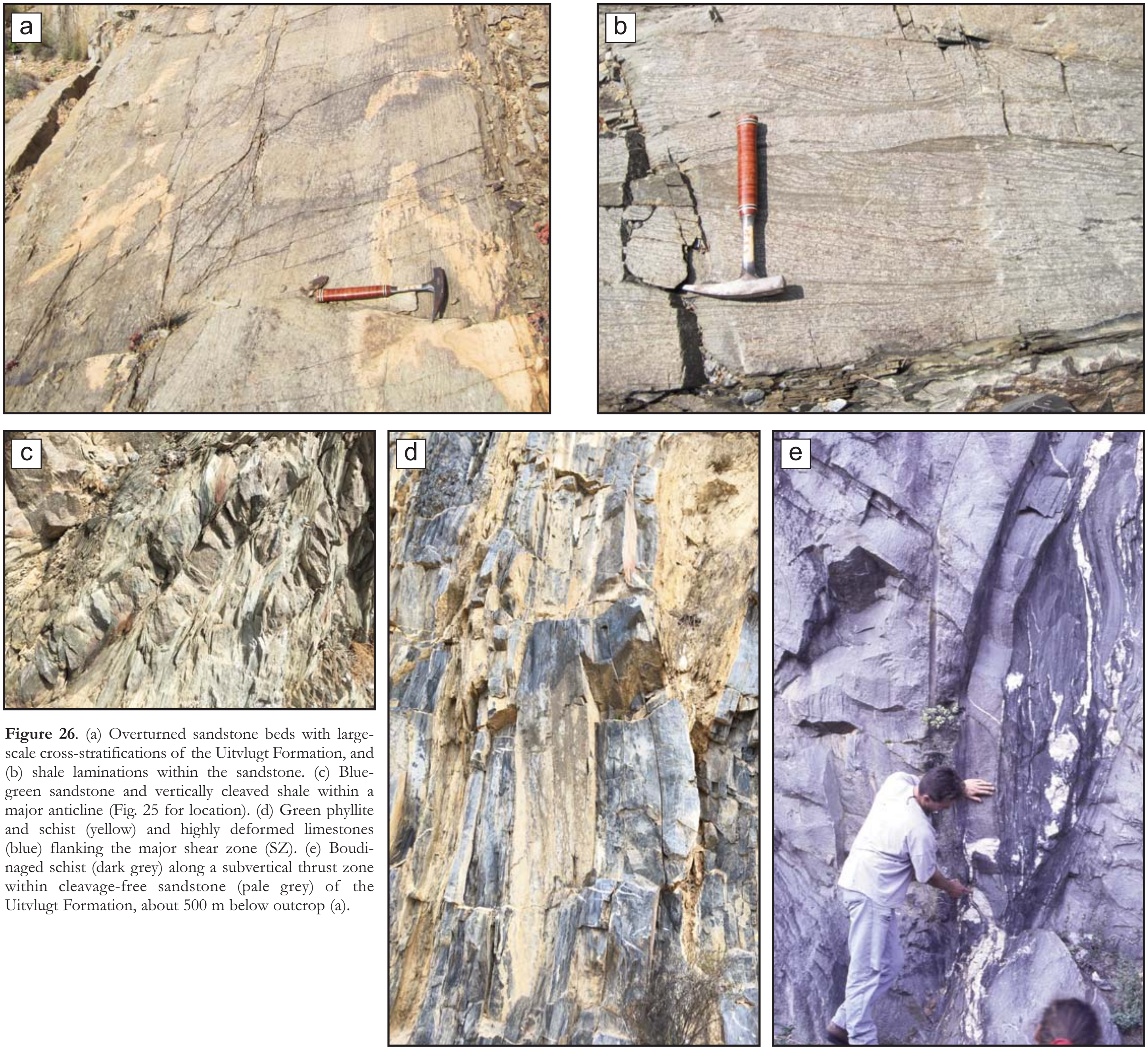


Figure 26. (a) Overturned sandstone beds with large-scale cross-stratifications of the Uitvlugt Formation, and (b) shale laminations within the sandstone. (c) Blue-green sandstone and vertically cleaved shale within a major anticline (Fig. 25 for location). (d) Green phyllite and schist (yellow) and highly deformed limestones (blue) flanking the major shear zone (SZ). (e) Boudinaged schist (dark grey) along a subvertical thrust zone within cleavage-free sandstone (pale grey) of the Uitvlugt Formation, about 500 m below outcrop (a).

Caves Flanking the Contact of Limestones with Greywackes

Karst topography and linked caves near the contact between the carbonate rocks of the Kombuis Formation and the pelite–psammite units of the Groenfontein Formation have been described by many field geologists; and while the paleodeposition system along this contact has been debated, all described the contact as an unconformity (e.g. Le Roux 1977, 1983, 1997; Le Roux and Gresse 1983; Gaucher and Germs 2006; Praekelt et al. 2008; Nel et al. 2018).

The best preserved evidence of such an unconformity is within the major fold closure exposed in the centre of the studied area where the unconformity surface dips steeply (Map 2). By contrast, the contact between these two formations along the fold limbs is cleaved and highly deformed along vertical shear zones, and most of the direct relationship between schistose shales and carbonate rocks is poorly visible and eroded, with the carbonate rocks being slightly more elevated at present (Fig. 32a).

The tectonic contact is commonly flanked by a section of carbonate conglomerate near the top of the Kombuis Formation along which at least five sinkhole localities are well-preserved (Fig. 6). Only one of these sinkholes is open deep below surface, and often explored by cavers who assume it to be linked to the Cango Caves via subsurface groundwater systems. All others are filled with sand and, at least at surface, with

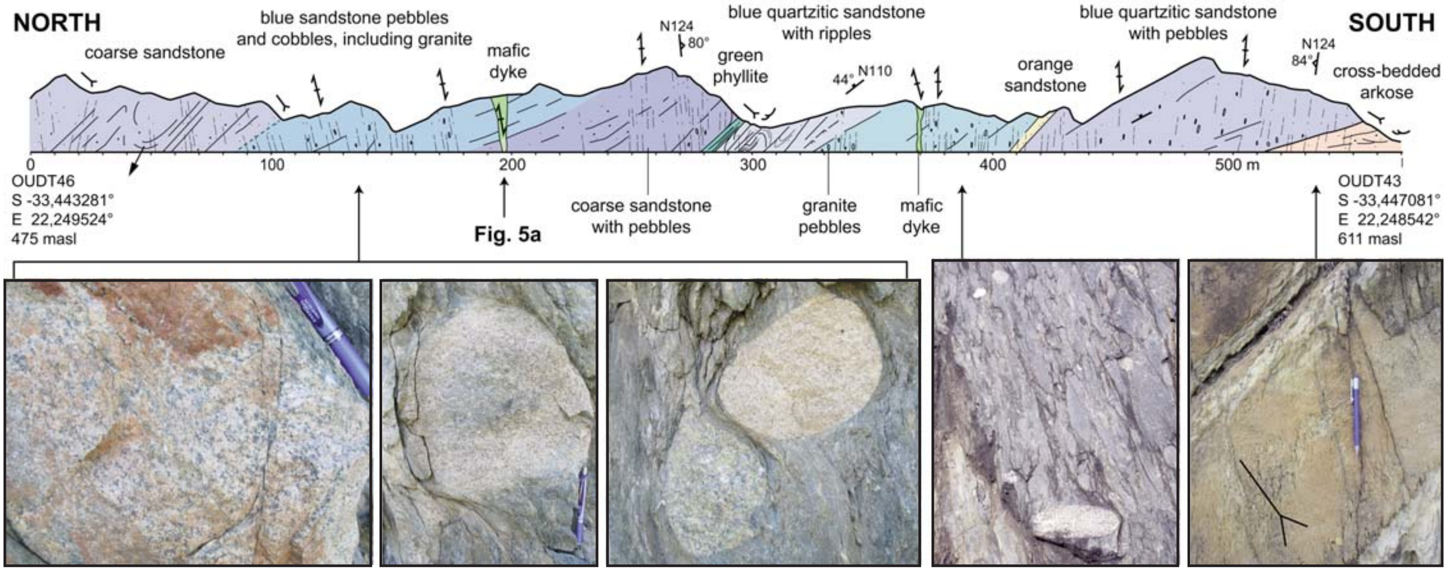


Figure 27. North–south cross-section of variably deformed/foliated conglomerates and psammites (sandstone) near Schoemanspoort (Section 10, Map 1). Well-rounded granite pebbles and cobbles remain resistant against the subvertical phyllite of the greenish blue pelitic psammite (left), compared to highly elongate sediment boulders (second right). In less deformed sections, graded sandstone beds with cross-stratification (right) confirm upward grading and define local open folds axis. These sequences are older than the 512 Ma basic dykes, and the granite blocks are likely linked to the Cape/Saldanian batholiths exposed along the western and southern coasts (Fig. 2a and cross-sections below).

quartzite boulders and pebbles, fragments of carbonate rock, and in places covered by iron precipitate (Fig. 32b–d).

We interpret these karst structures as relatively recent sinkholes likely filled during the early erosion of TMG quartzite, perhaps linked to glaciation–deglaciation of the Swartberg Mountains. By contrast, Praekelt et al. (2008) interpreted these sinkholes as paleokarst structures and paleovalleys filled with Neoproterozoic glacial deposits along the unconformity on top of the Kombuis carbonates, and fossilized by the Groenfontein turbidites. This interpretation is based on purported Late Ediacaran architarchs across the surface sinkholes mentioned above, and the fact that this paleokarst topography reveals development of subaerial unconformities (Gaucher and Germs 2006; Praekelt et al. 2008; Naidoo et al. 2013; Nel et al. 2018). While the biological affinities of architarchs cannot be determined with certainty, they may have been previously linked to stromatolites along the contacts between shale and carbonate. It is also possible that these are recently eroded stalagmites and carbonate precipitates, which are at present abundantly preserved in and around the Cango Caves.

Until more detailed analyses of these artefacts are provided, they remain in the realm of pseudo-fossils, especially as the (now deformed) unconformity contact between these sequences predates the deposition of the Goegamma Group (> 670 Ma; Fig. 33). Similarly, the existence of Neoproterozoic microfossils at the Cango Caves is unlikely, since the limestone is highly deformed (Fig. 7) and intruded by Mesoproterozoic felsic dykes (Fig. 22).

SYNTHESIS OF KANGO STRATIGRAPHY AND LANDSCAPES

Below we summarize the stratigraphy and landscape evolution across our study area (Fig. 33), and use these data to construct simple models for the deposition and erosion history (Figs. 34 and 35).

The complete section across the central Kango Complex, close to the Cango Caves (Map 1), has a stratigraphic thickness of some 10 km that covers a time span of 700–800 m.y. The section contains at least 50% phyllite, suggesting a thickness of at least 20–30 km before tectonic compression. However, folding into a near isoclinal system across this section halves the stratigraphic thickness to some 10–15 km, which appears reasonable if somewhat simplified without evaluating changes linked to the many thrust systems that have affected the area.

Many dated detrital zircons between 2.0 and 0.9 Ga recorded in the Kango sequences are likely derived from Mesoproterozoic basement that directly underlies this series (Fig. 2a). The (non-exposed) basement in the southern extremity of Africa is not Pan-African in age, as widely assumed, but most likely Namaquan (Grenvillian in age), ranging between 1.3 and 1.0 Ga (Hartnady 1969; Eglington and Armstrong 2003; McCourt et al. 2006; Lindeque et al. 2007; Stankiewicz et al. 2007; Linol and de Wit 2016).

Recent seismic and magnetic sections across the Cape–Karoo topography, including the present studied region, reveal relatively flat Namaquan basement between 5 and 10 km below surface. It is likely therefore that sediment was deposited in local basins after rapid erosion of the Namaquan sequences across western South Africa that were metamorphosed at relatively low-pressure granulite facies, followed by intrusion of late felsic magmatism at ca. 1.0 Ga (e.g. Waters 1986, 1990; Cornell et al. 2006; Cornell and Pettersson 2007).

The closest dates to compare with the age of the felsic dykes dated in this study are those from the Mesoproterozoic Kliphoek and Garies granites, which have dates of ca. 1078 ± 5 Ma (de Beer and Macey 2016a, b). These ages are within

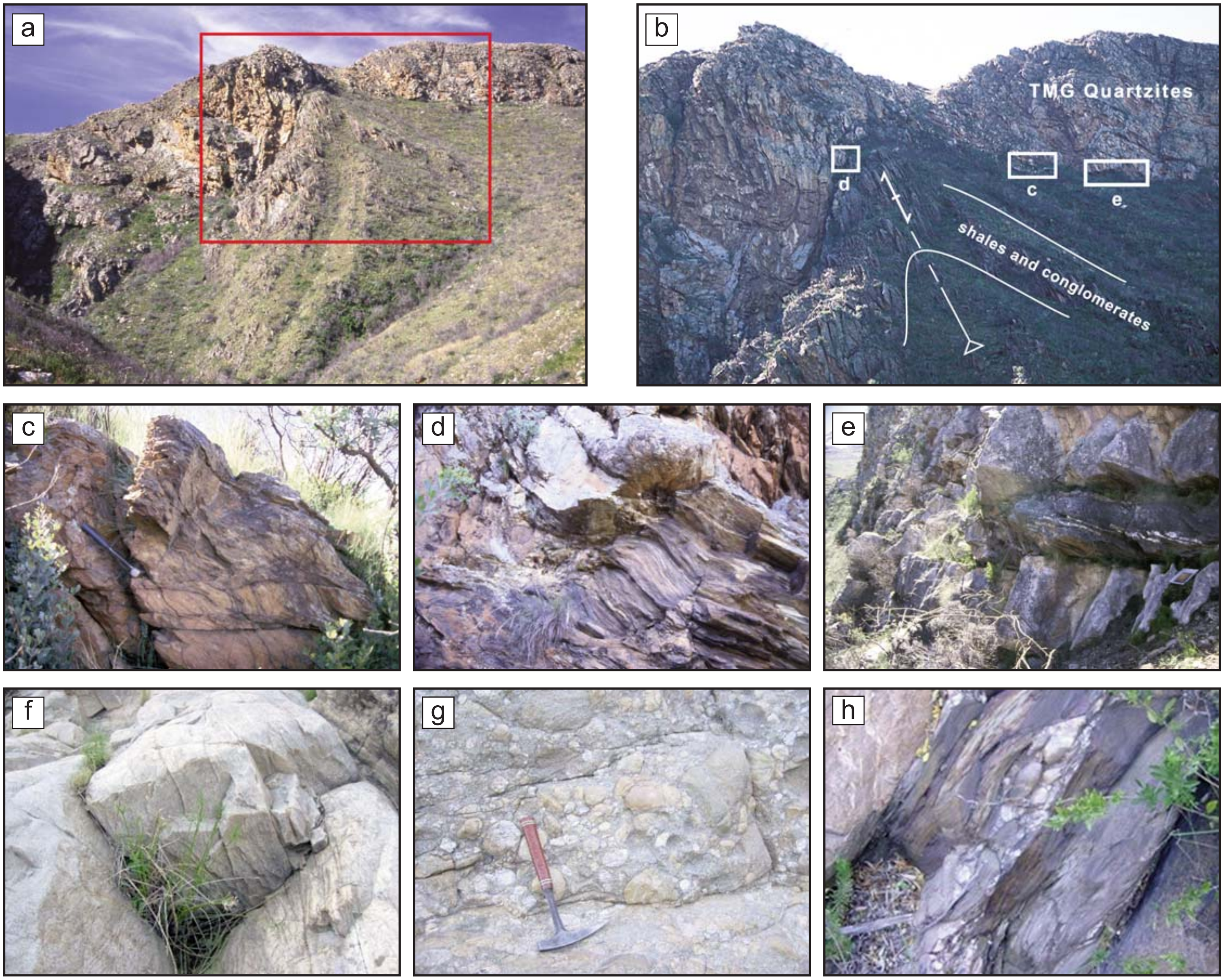


Figure 28. (a) Folded unconformity between the Goegamma Group and TMG quartzite (Section 11, Map 1), showing (b) the subvertical cleavage where slates of the Schoongezigt Formation are axial planar to a relatively shallow north-plunging open fold. Across this contact, TMG quartzite is cut by widely spaced axial planar fractures. (c) Steeply dipping schistosity across subhorizontal bedding of Schoongezigt pelite and psammite, (d) directly below the unconformity and (e) separated by a tectonic shear zone from the subhorizontal TMG. (f) Typical TMG quartzite, (g) conglomerate, sometimes (h) in bedding parallel shear zones, along the Kango–TMG contact at the northern margin of the Kango Complex.

error of the dated felsic dykes intruding the lower sections of the Kango Caves Group (ca. 1084 ± 5 Ma; Fig. 22). They also link closely to detrital zircon dates in the Kansa Group (ca. 1030–1080 Ma; Barnett et al. 1996; Naidoo et al. 2013). By contrast, intrusion of the ca. 512 Ma old mafic dykes were likely linked to uplift following local Pan-African deformation, often referred to as the Saldanian orogeny (e.g. Scheepers and Armstrong 2002; Gresse et al. 2009), linked along the western margin of South Africa to the East Brasilian orogens in South America (de Wit et al. 2008), and which may thus be responsible for the allochthonous and molasse deposition of the Kansa Group.

Geo-rates – ‘More Gaps Than Records’

A 10–15 km thick stratigraphic thickness covering this 700 m.y. time period reveals an average thickness of deposition between 1 and 2 m/m.y., and thus a rate of some 1–2 mm/ka, nearly 30–40 times less than the accumulation rates of limestone under the Bahamas (4–6 cm/ka; Newell 1967; Ager 1992) and 10 times less than modern sediment preservation rates on the floor of the Indian Ocean (Fig. 35). Given the thickness of many carbonate turbidites and diamictite units in the studied area, this seems extraordinarily low. While many identified unconformities and disconformities across bedding planes represent significant time gaps, more time must therefore be missing across the Kango stratigraphy due to non-deposition and erosion.

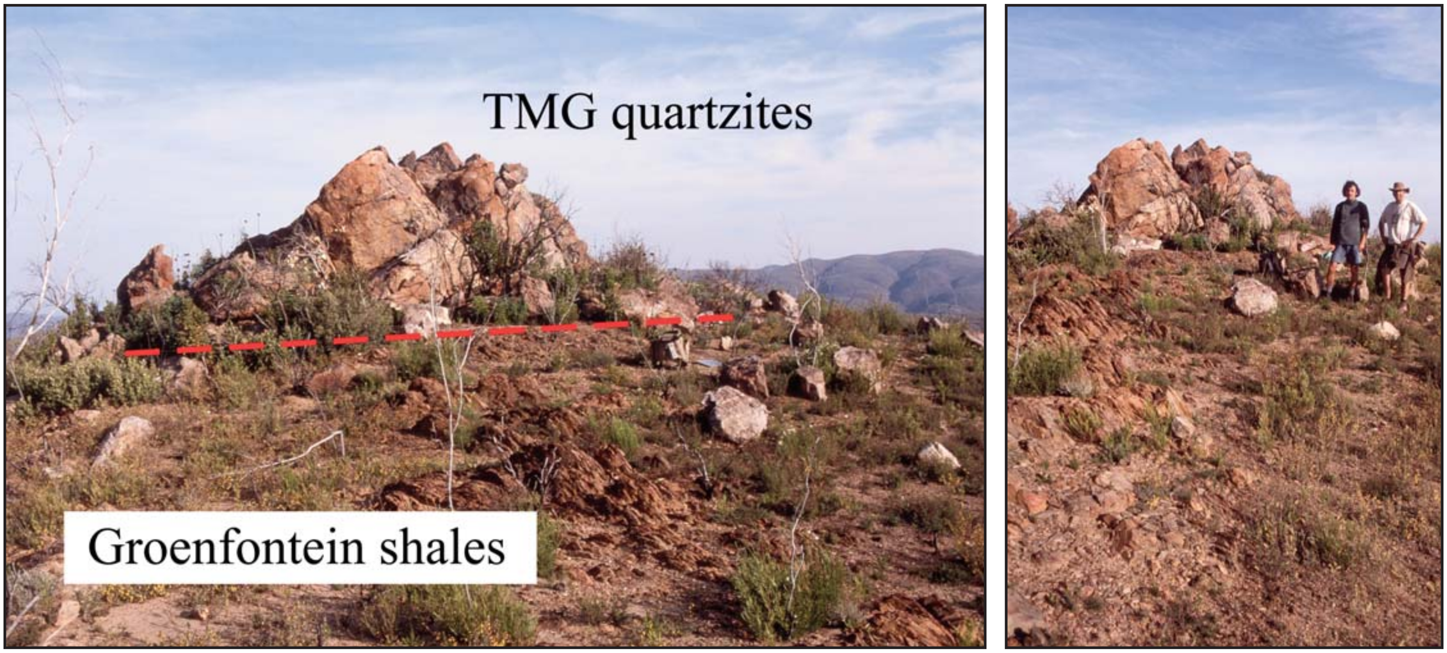


Figure 29. Subhorizontal contact between the Groenfontein Formation turbidites and TMG quartzite, cut by subvertical cleavage and joints, respectively (Section 12, Map 1); for scale students Jacek Stankiewicz (left) and John Decker (right) who first discovered these outcrops in 2004.

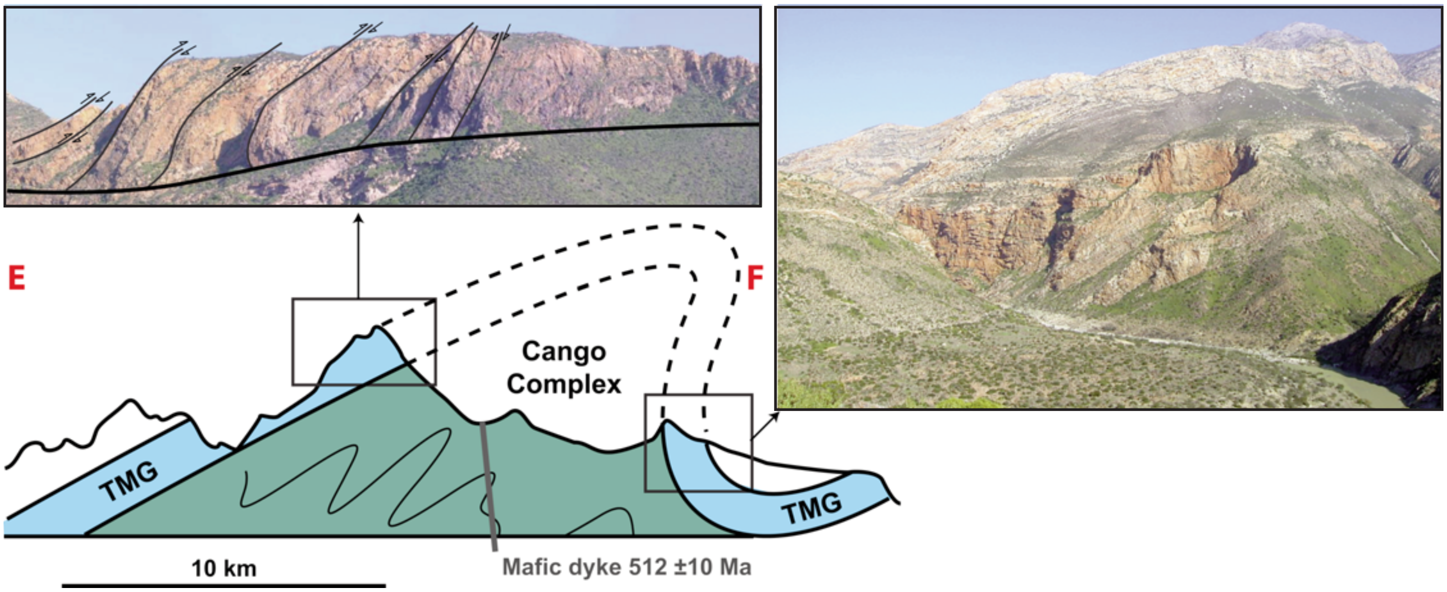


Figure 30. Schematic section across the western Cango region (Fig. 2b for location), showing a (pre-fold) accretionary thrust zone that tectonically separates TMG quartzite from Groenfontein turbidites (top left); and along an overturned section of the TMG, well-exposed along the Gamka River in the Hell (top right). Frequent conglomerate sections of the TMG preserve unconformable contacts. The dolerite dyke dated at 512 Ma links to a series of intrusive gabbro bodies in this area of the Kango Complex (Haas, 1998).

The Kango Complex represents an inescapable example of long gaps with only occasional records of sedimentation (cf. Ager 1992). It needs much created micro-stratigraphy nit-picking, linked to new geochronology techniques, to quantify these hiatuses and how they represent regional erosion processes linked to the Namaquan and Pan-African mobile belt orogens and the Kalahari epeirogeny (Dewey et al. 2006; de Wit 2007).

Since its present stalagmites date back at least 200 ka, Ager's famous idealized diagram of the condensed sequences preserved in solution hollows of Jurassic limestone (Fig. 32; Ager 1992) also fits the Cango Caves and their linked subsurface river systems well. In this case, condensed sequences within the caves may link back more than 300 Ma to the Carboniferous (Fig. 33).

Figure 31. Topography across the Cango Valley with relatively well-preserved open paleo-river sections flanking the Swartberg Mountains and eroding at ca. 0.5 to 1.5 m/m.y. over the last 5 m.y. (see below). The 1000 m asl topography in foreground (left) is covered by rounded quartzite boulders, in places with eroded impact textures (right), confirming their likely fossil link to Cretaceous paleo-river sections preserved at this high elevation.

TECTONO-STRATIGRAPHIC LINKS – LOCAL TO GLOBAL

From Kango to Table Mountain – Orogeny and Epeirogeny

While there are no granite plutons exposed across the Kango region, U–Pb zircon dates from some granite boulders of the Kansa Group are ca. 518 ± 9 Ma (Barnett et al. 1997). Granite boulders from the base of the Sardinia Bay Formation in the Eastern Cape (Gamtoos Complex) also have a Cambrian age with dates at ca. 530 ± 5 Ma (Miller et al. 2016; Fig. 2b). Both are similar to the U–Pb zircon dates obtained from the Neoproterozoic–Lower Paleozoic granite intrusions of the Western Cape at 560–500 Ma (Gresse et al. 2009), and in the southern Cape (543 Ma, flanking George and Victoria Bay; Scheepers and Armstrong 2002). Therefore, the Cape Granite Suite is most likely to have been a source for the sediment (Fig. 27).

Specifically, the granite of Table Mountain in Cape Town, dated at ca. 540 Ma (U–Pb zircon date; Scheepers and Armstrong 2002), unconformably underlies the baseline of TMG quartzite (Figs. 36 and 37). Based on U–Pb dated detrital zircons, this unconformity is younger here than ca. 520 Ma (Armstrong et al. 1998); and perhaps younger than 504 Ma based on the other U–Pb detrital zircon dates from TMG in the Swartberg Mountains found directly above the Kango sequences (Fig. 33).

Final emplacement of the Table Mountain granite took place from ca. 15–18 km (5 kbar) at 750°C, intruding the subvertical Malmesbury greywackes some 10–20 km below surface (Armstrong et al. 1998; Villaros et al. 2009; Harris and Vogeli 2010). Thus, this granite must have been uplifted and eroded by at least 15 km within 17–20 m.y. Along the seashore, the intruded Malmesbury Group is dated with detrital zircons at about 560 Ma, which is broadly similar to the greywackes of the Groenfontein Formation (the Geogamma Group, < 620 Ma; Fig. 37).

While there are no Ar/Ar dates from rocks or minerals across the Kango Complex, such dates from the Cape Granite and its micas, calculated between 1996–2004 by Derek York and his colleagues in Canada (University of Toronto), provide a more detailed history of the cooling, multiple uplift, and erosion rates with relevance to the Kango Complex (Fig. 36).

The first dates at ca. 537 ± 0.3 Ma (MSWD of 0.79) are interpreted as the primary age of cooling of the samples through the muscovite and biotite closure temperatures. The very close agreement of ages from both minerals implies rapid cooling of the sample between their respective closure temperatures. These ages compare well with the U–Pb zircon date of ca. 540 ± 4 Ma obtained from the same outcrop (Armstrong et al. 1998) and reveal onset of cooling (uplift) within less than 3 m.y. and erosion of > 15 km within 20 m.y., reaching a relatively low apparent temperature of 440°C, well below the crystallization temperature of the Cape Granite and about 50–100°C below the closure temperature of quartz–feldspar (Harris and Vogeli 2010).

The second dates at ca. 354.1 ± 0.3 Ma (MSWD of 0.84) apparently represent a reheating episode, sufficient to completely reset the K-feldspar, to affect over 20% of the biotite's K–Ar budget, while affecting only 1.3% of the muscovite K–Ar budget, in agreement with the sequence of closure temperatures from highest (muscovite) through biotite to lowest (K-feldspar). The weighted mean age of this overprint is dominated by a precise high-temperature isochron date of the K-feldspar (Fig. 36). We interpret this age as a resetting of the Table Mountain granite/Malmesbury greywacke contact, and by inference the Kango Complex, during Carboniferous glaciation of the Dwyka Ice Age, which likely was covered by an up to 3–5 km thick Antarctic-like ice dome at 350 Ma and that had completely melted by ca. 300 Ma (e.g. Schulz et al. 2018). Thereafter, little is known about the subsequent erosion rates across Table Mountain, which today are less than 20 m/m.y. (Erlanger et al. 2012).

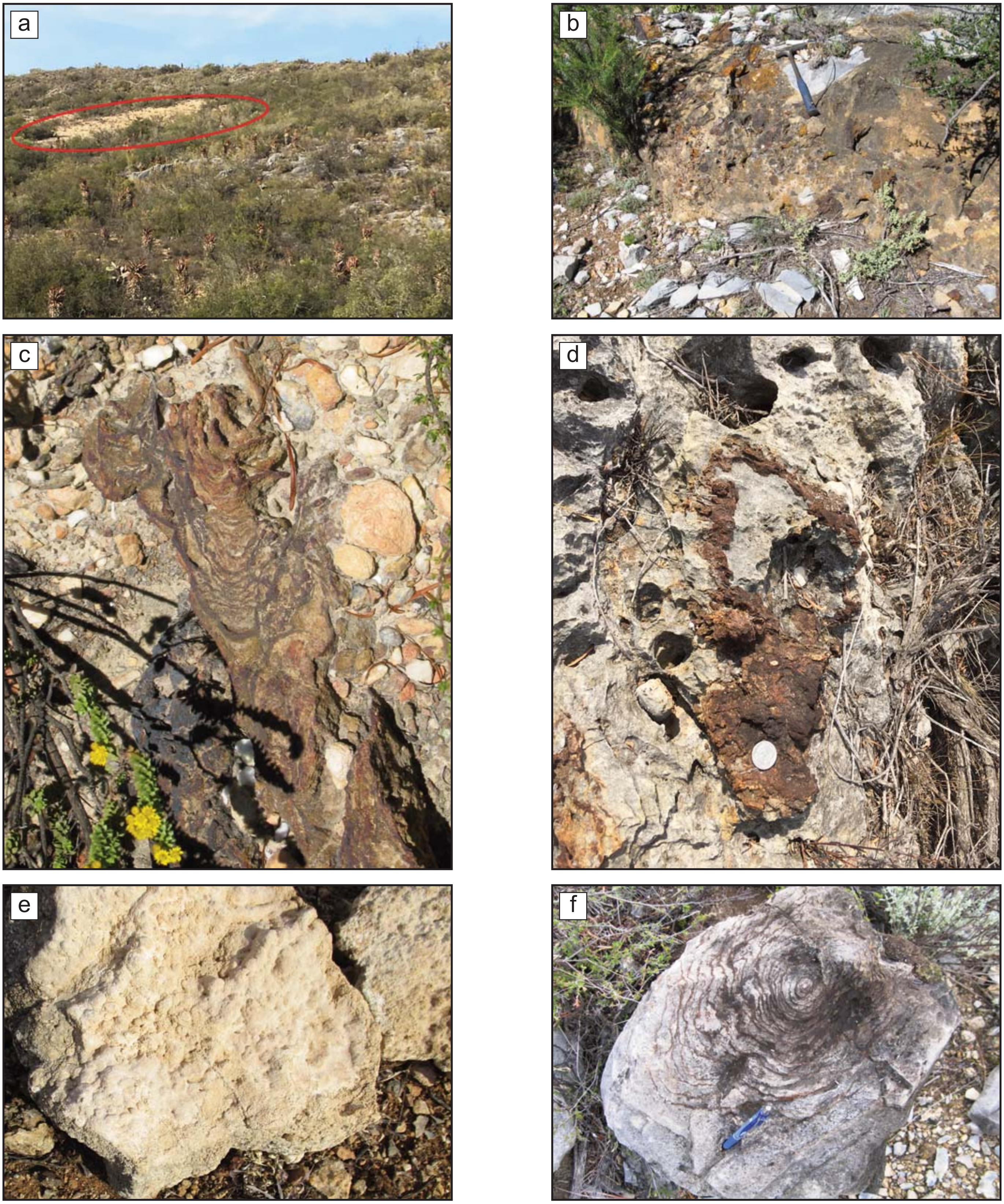


Figure 32. (a) Circular section of a 150 m wide paleo-cave (red ellipse) filled with yellow sand and conglomerate within the upper section of the Kombuis Formation (grey outcrops). (b) Cave-filled sandstone with clasts overlain by carbonate fragments (blue-grey) derived locally from the Kombuis carbonate rocks. (c) Iron precipitate (brown) covering the Cave sandstone and conglomerate. (d) Iron precipitate covering carbonate flanking the paleo-cave contact. (e) Carbonate precipitates (pale yellow) and (f) paleo-stalagmite(?) section (grey) flanking the contact with the Kombuis carbonate rocks.

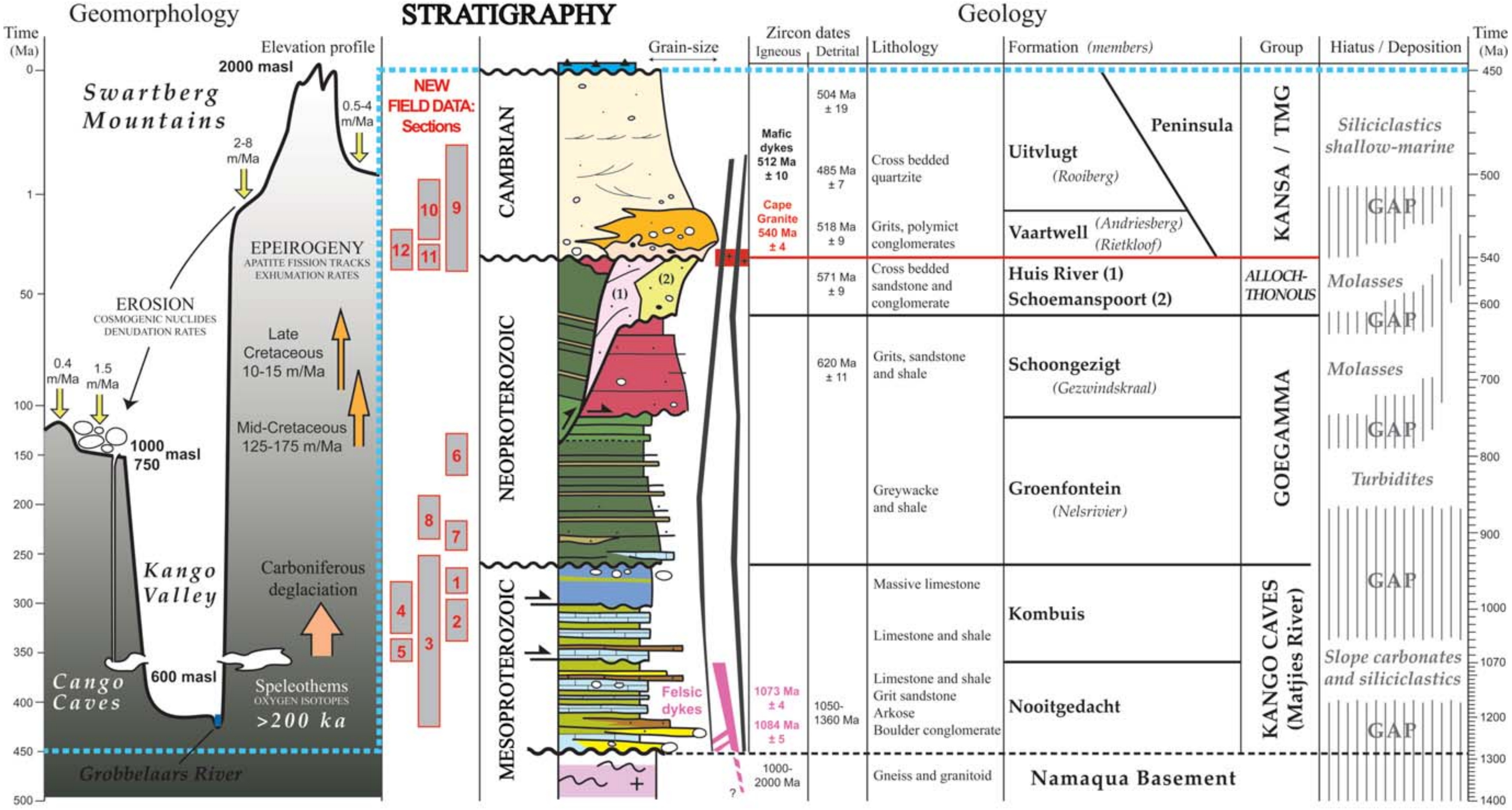


Figure 33. Revised stratigraphy of the Kango geology highlighting missing time gaps (hiatuses) linked to erosion/non-deposition events between 1300 and 450 Ma, based on U–Pb zircon data (right); and its surface geomorphology based on various isotope analyses and thermochronology (left). The stratigraphic gaps are likely of greater thickness than shown here due to poorly quantified data but based on a present average thickness of 10 km, sedimentation rates were extremely low (1.4 m/m.y.). Note that there is a poorly quantified stratigraphic overlap between the Upper Kango (Kansa Group) and TMG sequences. The geomorphology gaps are linked to unquantified erosion rates during deglaciation (twice, at 450 and 300 Ma; Linol and de Wit 2016) followed by high Cretaceous erosion rates of ca. 100–175 m/m.y. based on fission track analyses from boreholes through TMG/Karoo/Namaqua basement (Tinker et al. 2008; Brown et al. 2014), which decreased by the mid-Cenozoic to relatively low rates (< 10 m/m.y.), based on cosmogenic nuclides studies (Decker et al. 2011; Scharf et al. 2013; Kounov et al. 2015) and (U–Th)/He surface dating (Stanley et al. 2013), and in line with general low erosion rates across southern Africa today (de Wit 2007; Flowers and Schoene 2010; Decker et al. 2013; Evans 2015). Present subsurface erosion rates are also low, based on isotope analyses of stalagmites preserved in the Cango Caves (de Wit et al. unpublished).

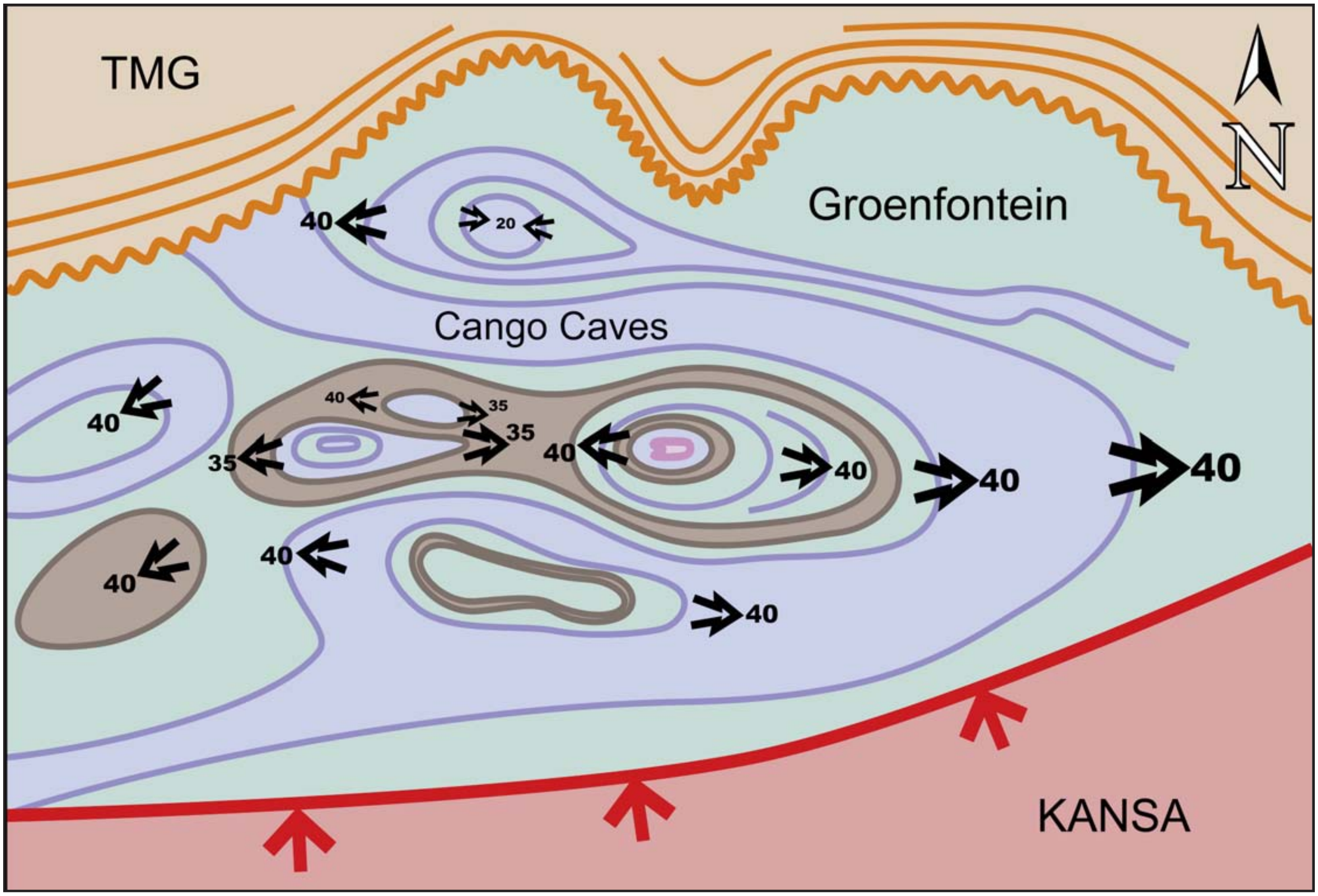


Figure 34. Simplified pre-Kansa/TMG restoration in the central part of the study area (by 50% at right angle across the cleavage/schistosity and along the fold closures) reveals a number of 8–12 km wide, 20–40° dipping domes and basins across Namaquan/Grenvillian basement. These sequences were covered by molasse-like sandstones and conglomerates of the Kansa Group and the overlapping conglomerates and quartzites of the TMG, deposited during end-Pan African times (Fig. 33).

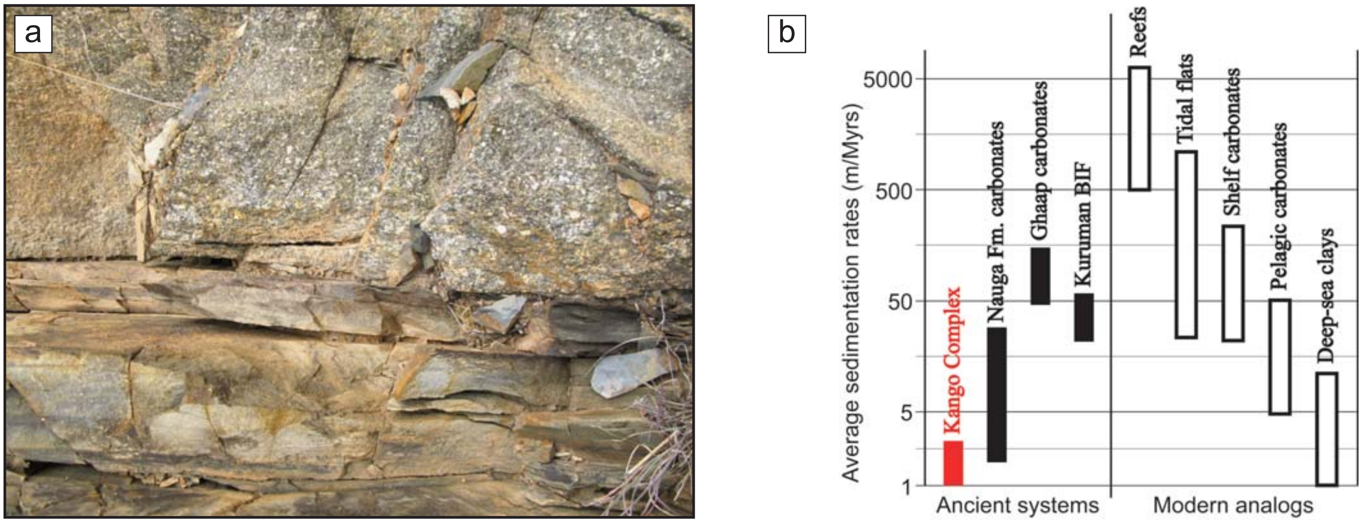


Figure 35. (a) Typical contact between parallel-bedded mudstone and feldspathic grit across the Kango Complex (Section 2). At present, there are no geochronological data that can quantify non-depositional/erosion breaks ('missing time') across these surfaces, which likely represent significant pauses in sedimentation and erosion, given the more than 700 m.y. period recorded across the total 10 km thick stratigraphy. (b) Average deposition rates across variable sedimentary systems; the average accumulation rate of the Kango system is about 1.5 m/m.y. (highlighted in red), comparable only to the lowest sedimentation rates across modern deep oceans (modified from Altermann and Nelson 1998).

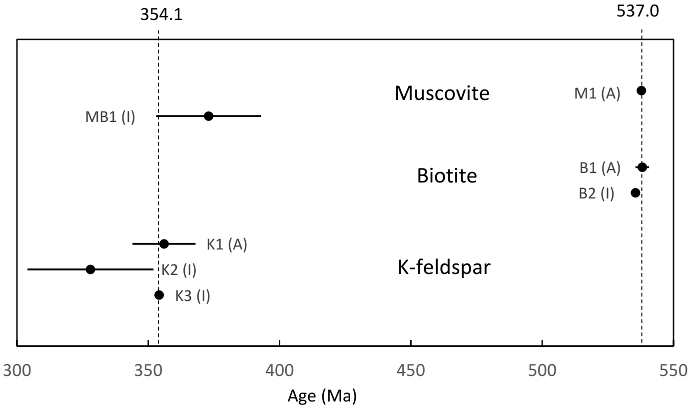


Figure 36. Detailed ^{40}Ar/^{39}Ar step heating results on single grains of biotite (11 steps), muscovite (16 steps) and K-feldspar (59 steps) from a whole-rock sample of the same Cape Granite reveal uplift/erosion during two distinct episodes.

Across West Namaqualand

Farther north, many U–Pb zircon dates of the Namaqua Natal Mobile Belt reveal igneous and metamorphic ages near the end of the Mesoproterozoic, between ca. 1230 and 1025 Ma (Friese et al. 1996; Thomas et al. 1996; Barnett et al. 1997; McCourt et al. 2006; Cornell et al. 2006; Minnaar et al. 2017; Moen and Cornell 2017; Macey et al. 2018).

The closest regional stratigraphic equivalents of the Kango sequences are rocks exposed in West Namaqua and within the Saldania Belt near Cape Town (Fig. 38). The Namaquan basement is dated between about 2.0 and 1.0 Ga, including some late tectonic intrusions dated at ca. 1030–1100 Ma, and surrounding feldspathic quartzites (the Bitterfontein Subgroup; Joubert 1986), which are similar to those described and dated in this study of the Kango Complex. To compare with the Goegamma and Kansa groups the tectono-stratigraphy of the other time equivalent, Precambrian–Lower Paleozoic sequences across the Saldania Belt remains poorly resolved. This is due to limited field mapping, which prevents precise correlations for example with the Malmesbury Group (Fölling and Frimmel 2002; Frimmel 2018; Zimmermann 2018).

From Gondwana to Rodinia

Large uncertainties exist in the global paleogeographic reconstructions between about 1300 and 500 Ma, during deposition of the Kango sequences (e.g. Cawood et al. 2016; Merdith et al. 2017). However, possible connections during the Mesoproterozoic Namaquan–Grenvillian orogenies, and again during the Late Paleozoic Variscan–Gondwanan orogenies, suggest similar tectonic basin evolution in southern Africa and in northern America (Fig. 39).

The oldest sequences of limestone and feldspar-rich sandstone of the Kango Complex (including the Cango Caves limestone) were intruded by ca. 1070–1080 Ma old felsic dykes (Fig. 33). These earliest clastic sedimentary rocks are linked to rapid uplift and erosion of relatively low-pressure Namaqua granites and charnockites during their extensional unroofing flanking the Grenvillian Mountains system. While such basement rocks are not exposed in the Cango region, relatively abundant granite and pegmatite pebbles preserved in the lowest sequences suggest a close connection to a flat Namaquan basement that hosted shallow marine platforms which were the sources of carbonate slope conglomerates, breccias and turbidites linked to sea-level changes and extensional tectonics along a continental margin perhaps analogous to that proposed for the Paleozoic Cow Head–Fleur de Lys sequences in Newfoundland.

The Kango Caves Group limestone is unconformably overlain by the Goegamma Group comprising sandy turbidites and laminated siltstones deposited between 900 and 700 Ma and linked to molasse-like sandstones and conglomerates in front of Pan-African mountain belts by ca. 620 Ma (Fig. 39). These sequences were all disconformably overlain between 530 and 500 Ma by shallow marine sandstones of the Kansa and Table Mountain groups, with conglomerates that contain granite boulders post-dating intrusion and erosion of granite down to sea level across the Western Cape at ca. 520 Ma, ahead of the onset of glaciation across southern Gondwana during the Early Paleozoic.

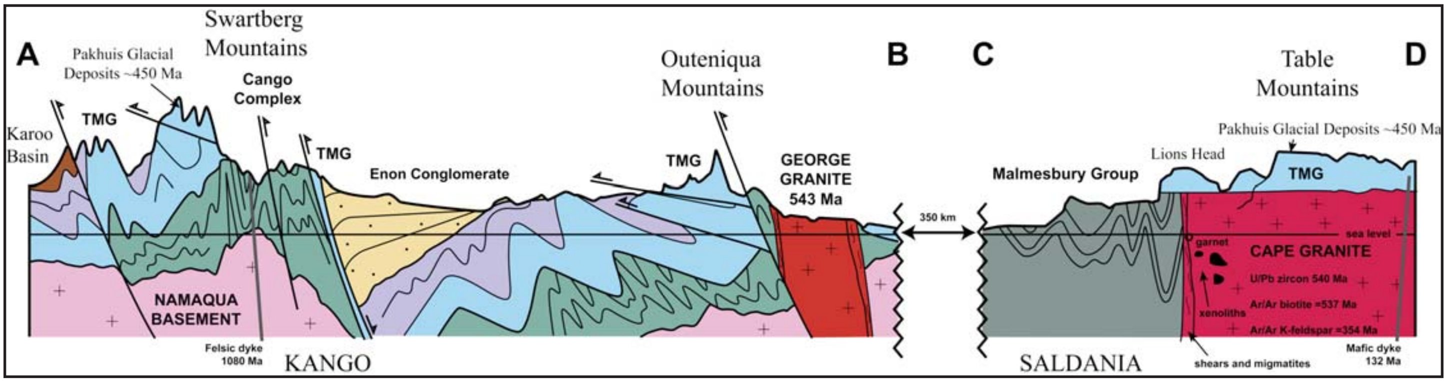


Figure 37. Schematic cross-sections of the Swartberg and Table mountains, highlighting chronostratigraphic differences between the Table Mountain Group (TMG) and its underlying sequences (Fig. 2a for location). In both areas the youngest dated detrital zircon grains from quartzites of the TMG that unconformably overlie granites and metasedimentary rocks range between 520 and 504 Ma, revealing a stratigraphic time gap of 20 to 100 m.y. between the Goegamma–Malmesbury and the Table Mountain groups. However, the precise ages of these sequences are poorly constrained: between 950 and 610 Ma (for the Malmesbury – Scheepers 1995; Harris and Vogeli 2010); and between 1000 and 570 Ma (for the Goegamma – Naidoo et al. 2013), respectively. No Archean zircon grains derived from the Kaapvaal Craton have been reported yet in the Kango and Saldania sequences as they have across the TMG (Scheepers and Armstrong 2002; Naidoo et al. 2013). There are still many outstanding data needed to test these possible links, including along the south coast near George (e.g. Gresse et al. 2009; Kirsters 2016; Kirsters and Belcher 2018).

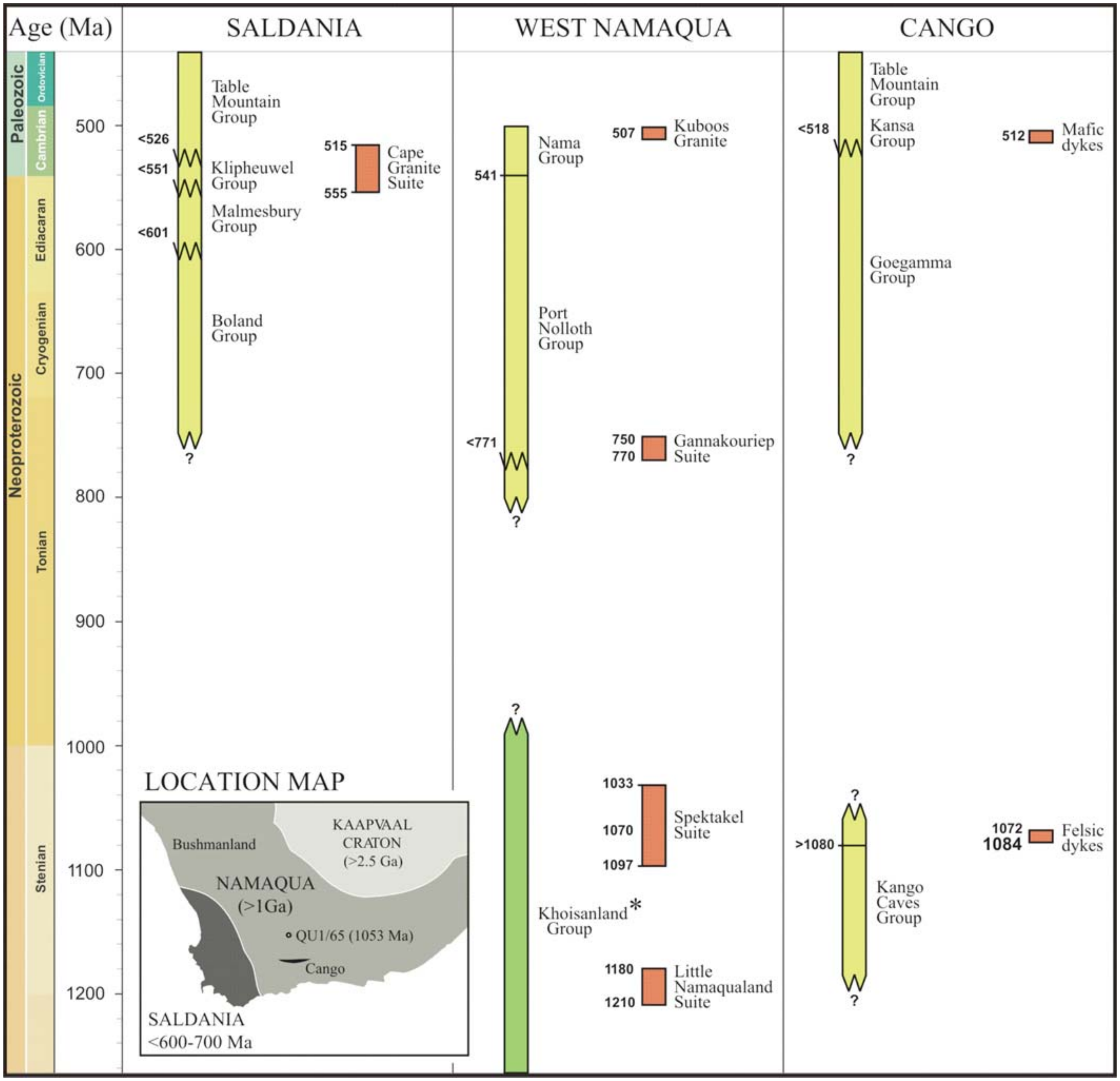


Figure 38. Stratigraphic table comparing sedimentary (yellow), high-grade low-pressure metamorphic (green), and intrusive (red) rock records from Namaqualand and Swartland with the Kango Complex, compiled from Joubert (1986), Barnett et al. (1997), Scheepers and Armstrong (2002), Eglington and Armstrong (2003), Frimmel et al. (2013), Frimmel (2018), and this study (right); see inset for location. Most maximum ages of sedimentation are uncertain due to limited field constraints, but most likely the Kango Caves Group correlates with similar quartzite–schist sequences (e.g. the Bitterfontein SubGroup) of the Khoisanland Group*.
* renamed after the colonial Bushmanland.

The Kango rocks thus trace the orogenic histories of Grenville and Appalachia across Canada to epeirogeny across South Africa, preserving a globally unique stratigraphic section that encapsulates this long history of changes from Rodinia to Africa.

CONCLUSION

The new geological map and detailed descriptions of sedimentary and deformational structures of a central-eastern section of the Cango region of southern South Africa improve our understanding of the regional stratigraphy. Together with new U–Pb zircon dates of dykes and the existing geochronology, geophysics, geomorphology, cosmogenic nuclides and thermochronology, and global geodynamic models, this review provides a solid foundation for further field investigations.

The Kango Complex preserves a ca. 8–10 km lithostratigraphic record with a significant number of disconformities between 1200 and 500 Ma, with an average preservation rate

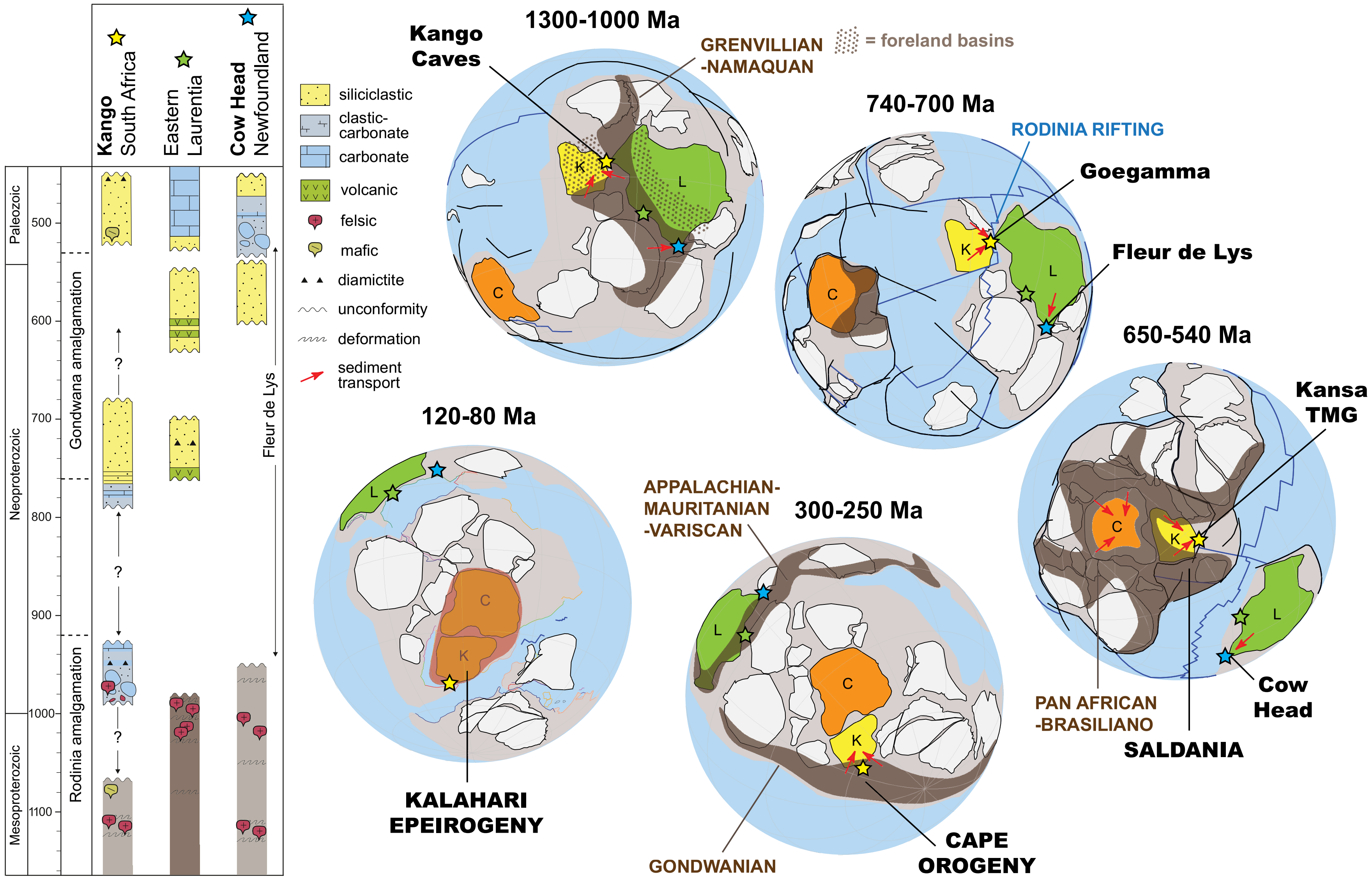


Figure 39. Simplified history between 1300 and 80 Ma of sedimentation and erosion preserved across the Kango sequences linked to global evolution of Rodinia to Africa via Pangea and Gondwana, highlighting rapid erosion of Grenvillian-linked Namaquan foreland and onset of deposition of carbonate conglomerates similar to the famous Lower Paleozoic Cow Head deposits of Newfoundland some 600 m.y. later (Supercontinent reconstruction in Gplates is modified from Merdith et al. 2017); C= Congo Shield; K= Kalahari Shield; L= Laurentian Shield.

of about 1.5 m/m.y., and thereafter overlapping in time with the Table Mountain Group (TMG) to at least 486 Ma. Between 450 and 350 Ma, these Kango and TMG sequences vertically subsided variably by up to 4 km below Antarctic-size ice sheets that yielded Pakhuis and Dwyka glacial deposits across southern Gondwana. After deglaciation by 300 Ma, and the Cape orogeny (252 Ma), the Kango Complex was uplifted vertically and eroded by ca. 3–5 km at rates between 100 and 200 m/m.y. during the Jurassic–Early Cretaceous, decreasing to less than 10 m/m.y. today. These variable rates left a complex paleosurface and subsurface geomorphology across the Cango region, including different plateau elevations, valleys, canyons and caves.

Based on the low rates of sedimentation and erosion, the Kango Complex is a prime example of a long stratigraphic record with, apparently, more "Gaps than Records" (e.g. Ager 1973, 1992), but based on little age data. This recording deserves more testing through more innovative geo-timing (e.g. Bowring et al. 2006). The varied landscapes across the Cango region offer an excellent opportunity for new transdisciplinary sciences to try and close these gaps.

ACKNOWLEDGEMENTS

Andrew Hynes visited the Cango with Maarten de Wit in 2002 and provided inspirational suggestions, including potential links with Grenvillian and Appalachian sequences in Canada. It has taken nearly 15 years to document this, in part because we all know his expectations. Even earlier, Arthur Fuller (AF) first drove Maarten through the Cango following his arrival at University of Cape Town (UCT), making sure that he would follow up Arthur's field sedimentology there for more than 20 years, but which he never published; and thanks to Lester King for similar inspirations about the Cango geomorphology during a Gondwana workshop in 1979 at the Bernard Price Institute at Wits University. This would also not have happened without the visions of Louis Nicolaysen (LN). AF and LN were remarkable geologists, if somewhat elusive persons who completed their PhDs in Princeton University where AF got to know Albert Einstein, and where LN designed how best to display Rb–Sr isotope data. Some of the early Kango whole-rock samples were dated by this method in the 1980s by Hugh Allsopp, and subsequently by U–Pb, following a decade of multi-disciplinary co-operation among earth scientists from six South African universities, and its Geological Survey, during the Inter Union Commission of Geodynamics of the IUGS and IUGG (Nicolayson 1983).

By 1995, Richard Armstrong dated the first zircon grains collected by honours student Wayne Barnett. Then during a following decade, Derek York completed the Table Mountain Ar–Ar analyses by 2006 following his sabbatical year in Cape Town in 1996. In 2004, the new U–Pb zircon dates of felsic dykes were completed by Kerstin Drost. Maarten owes them all a deep apology for letting this all remain in his proverbial drawers for so long.

We thank all undergraduate students of UCT (1996–2014) and Nelson Mandela University (2014–present) for their hard mapping during field classes, and all Masters/PhD researchers that acted as field guides during these annual weeks to get away from their own routines. There are too many students (> 100) to mention individually, but they will remember their slogs in rain, snow and sunshine; and during their report writing. We also thank the managers of the Cango Caves and De Hoek Resort for putting up with these rowdy students for all those years.

Maarten, who left us during the finalization of this work, has inspired many young South Africans with the examples of the Kango. We would like to thank him for sharing his passion for field mapping and his enthusiasm in taking this transdisciplinary research forward.

This is AEON contribution 197 and Iphakade publication number 247.

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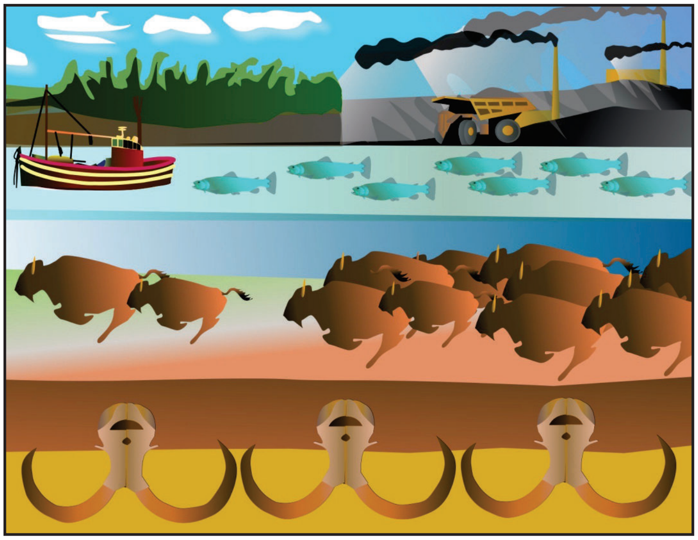
For access to the de Wit et al. (2020) Supplementary Material: *Appendix: U–Pb dated zircon grains from selected felsic dykes of the lower Kango Complex (Sections 5 and 6, Map 1)*, and U–Pb data tables and plots for samples K08-01, -02, and -03, please visit the GAC's open source GC Data Repository for the Andrew Hynes Series: Tectonic Processes at: https://gac.ca/gc-data-repository/.

Andrew investigating the geology of Greece during his PhD studies and much later in a celebratory trip with his supervisor Alan Smith.

COMMENTARY



Anthropocene: Transdisciplinary Shorthand for Human Disruption of the Earth System

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SUMMARY

Increasingly, deliberations to potentially add the Anthropocene to the Geological Time Scale in recognition of humanity's environmental impacts and stratigraphic record are attracting interest from non-geological disciplines and the news media. The 35 member Anthropocene Working Group, a constituent body of the International Commission on Stratigraphy, recently concluded that the worldwide fallout of radionuclides from atomic bomb testing in the mid-20th century best defines the base of the Anthropocene. With a search for the optimal 'golden spike' locality in progress as a key step toward any ratification by the International Union of Geological Sciences, there are widely held views outside of geological circles that the Anthropocene is already designated as an epoch. Regardless of its eventual formal or informal standing, this article opines that the term Anthropocene has become valuable shorthand for recognizing humanity as the dominant species which, in a geological nanosecond, has extensively detached itself from the Earth System, endangering the future of both. Accordingly, this article urges the entire geological profession to engage with the work of the Anthropocene Working Group and, as the originator of the term, to coalesce its activities with those of other disciplines concerned with environmental health and linked human health challenges.

RÉSUMÉ

De plus en plus, les délibérations visant à éventuellement ajouter l'Anthropocène à l'échelle du temps géologique en reconnaissance des impacts environnementaux de l'humanité et des données stratigraphiques suscitent l'intérêt des disciplines non géologiques et des médias. Les 35 membres du Groupe de travail sur l'Anthropocène, un organe constitutif de la Commission internationale de stratigraphie, ont récemment conclu que les retombées mondiales des radionucléides résultant des essais de bombes atomiques au milieu du XXe siècle définissent le mieux la base de l'Anthropocène. Avec la recherche de la localité de référence optimale du « clou d'or » en cours comme étape clé vers toute ratification par l'Union internationale des sciences géologiques, il existe des opinions largement partagées en dehors des cercles géologiques selon lesquelles l'Anthropocène est déjà désigné comme une époque. Indépendamment de sa position finale formelle ou informelle, cet article estime que le terme Anthropocène est devenu un raccourci précieux pour reconnaître l'humanité comme l'espèce dominante qui, dans une nanoseconde géologique, s'est largement dissocié du système terrestre, mettant en danger l'avenir des deux. Par conséquent, cet article exhorte l'ensemble de la profession géologique à s'engager dans les travaux du Groupe de travail sur l'Anthropocène et, en tant que créateur du terme, à fusionner ses activités avec celles d'autres disciplines concernées par la santé environnementale et les défis liés à la santé humaine.

LOOKING BACK

The term Anthropocene was launched 20 years ago with anxious viewpoints that "*the effects of humans on the global environment have escalated*" and that "*a daunting task lies ahead for scientists and engineers to guide society towards environmentally sustainable management*" (Crutzen and Stoermer 2000; Crutzen 2002). Between

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2006 and 2008, the Geological Society of London and Geological Society of America reported their initial considerations, as recalled by Zalasiewicz et al. (2017), and the term began to attract interest from non-geological disciplines (Robin and Steffen 2007). In 2009 the International Commission on Stratigraphy, a constituent body of the International Union of Geological Sciences, commissioned an Anthropocene Working Group (AWG) to explore this possible new unit of time. Its chair wondered what it will turn out to be: "*An age or epoch? Will it develop into a period or even an era? Or (heaven help us if that happens) an eon?*" (Zalasiewicz 2008).

In 2010 the chair and three members of the AWG declared: "*The Anthropocene represents a new phase in both humankind and of the Earth, when natural forces and human forces became intertwined, so that the fate of one determines the fate of the other*" (Zalasiewicz et al. 2010). The term then entered the public realm with magazine features and editorial opinions (e.g. The Economist 2011; The New York Times 2011). In 2013–14, Elsevier and Sage launched *The Anthropocene* and *The Anthropocene Review* as journals and in 2016 Future Earth launched *Anthropocene, Innovation in the Human Age* as a public subscription magazine. The New York Times Magazine (Rich 2018) devoted an entire issue to revisiting 1979–1989 when the causes and dangers of climate change became broadly understood. Oxford University Press added the Anthropocene to its handbook collection of summarized topics (Ellis 2018), and Elsevier published the *Encyclopedia of the Anthropocene* (Dellasala and Goldstein 2018).

At its spring 2019 meeting, the 34-member AWG reached binding 97% and 88% votes to regard the Anthropocene as a chronostratigraphic unit with the mid-20th century as its base, noting that the worldwide fallout of radionuclides from atomic bomb testing is "*the sharpest and most globally synchronous"* signal *"that may form a primary marker*" (Anthropocene Working Group 2019). As became clear at the dawn of the 21st century, the mid-20th century was also when global population, industrial activity, and humanity's adverse impacts on itself and the Earth System began to increase markedly (Steffen et al. 2005). A major step in the history of the Anthropocene concept occurred on 16 January 2015:

> "*Today, we (the International Geosphere-Biosphere Programme and Stockholm Resilience Centre) publish a dashboard of 24 indicators which depict the dramatic acceleration in human enterprise and the impacts on the Earth system over the last two centuries ... What is apparent is the synchronous acceleration of trends from the 1950s to the present day – over a single human lifetime – with little sign of abatement ... These trends are known as the Great Acceleration*" (Broadgate 2015; International Geosphere-Biosphere Programme 2015).

When the Anthropocene Working Group anticipated that the Anthropocene would be defined by a standard Global Boundary Stratotype Section and Point (i.e. "a golden spike"), it also noted its use in "*a non-chronostratigraphic context as an informal term to denote a broader interpretation of anthropogenic impact on the planet that is markedly diachronous.*" Relevant investigations include the role of early humans in the extinction of Pleistocene megafauna (Malhi et al. 2016; Plotnick and Koy 2020) and the surging environmental control of the biosphere by humanity, particularly since the 16th century (Lewis and Maslin 2018). Other examples are a review of evidence for human modification of rivers beginning around 15,000 years ago (Gibling 2018) and a collaboration of archaeologists who detected land-use transformations by hunter-gatherers, farmers and pastoralists earlier than reconstructions commonly used by geologists (Stephens et al. 2019). The archaeosphere is a proposed label for the surface part of the geosphere with "*an abrupt surface at the base of* [these] *deposits variously called 'artificial ground', 'anthropogenic ground' or 'archaeological stratigraphy*" (Edgeworth et al. 2015).

WIDENING CONTEXT

Broadgate (2015) noted: "*When Paul Crutzen first proposed the idea of the Anthropocene, he suggested it probably began as the Industrial Revolution kicked off around 1800*". Steffen et al. (2015) clarified: "*Of all the candidates for a start date for the Anthropocene, the beginning of the Great Acceleration is by far the most convincing from an Earth System science perspective … It is only beyond the mid-20th century that there is clear evidence for fundamental shifts in the state and functioning of the Earth System that are beyond the range of variability of the Holocene, and driven by human activities and not by natural variability.*" Reflecting the human dimension of the Anthropocene discussion, Steffen et al. (2018) stated: "*While recognizing that different societies around the world have contributed differently and unequally to pressures on the Earth System and will have various capabilities to alter future trajectories, the sum total of human impacts on the system need to be taken into account for analyzing future trajectories of the Earth System.*"

In 2014, the University of Wisconsin–Madison hosted an international workshop of activists, artists, humanists, and scientists to consider what kinds of museum objects would illuminate relationships between humans and non-humans (Robin 2018a). Nixon (2017) wondered: "*How can we most effectively curate and narrate the Anthropocene, an idea that can seem, by turns, dauntingly compendious and elusively abstract?*" The term has also become a frame of reference in the environmental humanities (Castree 2014), philosophical discourse about the direction of humanity (Scranton 2015), political perspectives on the changing relationship between humanity and nature (Purdy 2015), the evolution of purpose in museums (Möllers et al. 2015; Koster 2019), and the latest threshold in the development of the Universe (Christian 2019).

As the following examples demonstrate, the Anthropocene has captured the attention of disciplines beyond the Earth Sciences and climatology. A former New York Times science reporter assessed the term as "*common shorthand for this turbulent, momentous, unpredictable, hopeless, hopeful time — duration and scope unknown*" (Revkin 2016). A researcher in geography and environmental studies viewed it as

> "*a key theme in contemporary speculations about the meaning of the present and the possibilities for the future … how the Anthropocene is interpreted, and who gets to invoke which framing of the*

> *new human age … matters greatly for both the planet and for particular parts of humanity … [this] requires careful evaluation for how geology has recently become so important in global politics, and how scholars from various disciplines might now usefully contribute to the discussion"* (Dalby 2016).

"*A heady mix of science, philosophy, and politics linked to our deepest fears and utopian visions*" is how Yale University Press introduced an outlook on the Anthropocene by two Earth scientists (Lewis and Maslin 2018). Revisiting the visionary outlook of the explorer Alexander von Humboldt (1769–1859), Jackson (2019) surmised: "*The Anthropocene discussion focuses attention on a fundamentally Humboldtian observation: humanity and nature are deeply intertwined … nature would persist in the absence of humanity, but humanity cannot exist without nature.*" A humanities scholar (Schaberg 2019) offered this assessment: "*Debated, denied, unheard of, encompassing, the Anthropocene is a vexed topic and requires interdisciplinary imagination.*" At the College of the Atlantic in Bar Harbor, the first US college to go carbon-neutral and where all students study human ecology, a geologist and anthropologist co-teach an intermediate-level course titled *The Anthropocene*.

TAKING STOCK

Reflecting on a prediction by astronomer Fred Hoyle in 1948 that the first photographs of the Earth from space would alter the course of history (Bartusiak 2018), it might reasonably be concluded that all that is encompassed by the Anthropocene term amounts to the most consequential alteration. Twenty-one years after Hoyle's foresight, NASA's Apollo 11 mission to the Moon gave an estimated television audience of 600 million — 20% of the world population — new perspectives about the entire Earth and human ingenuity (Hsu 2019). At the first Earth Day in 1970, an estimated 20 million participants demonstrated the power of civic action to spur environmental stewardship. In 1992, 2017 and 2019, large and diverse groups of concerned scientists, including many Nobel laureates, issued increasingly publicized warnings about the escalating rates of climate change and related environmental impacts (e.g. Ripple et al. 2019).

Technological progress that has enabled exploration of interplanetary space has not been matched by environmental stewardship on Earth. A pessimistic commentary by Roberts (2020) refers to "*a civilization estranged from Earth*". This planet's health in an Anthropocene context was the focus of a joint commission by the medical journal Lancet and the Rockefeller Foundation "*based on the understanding that human health and human civilization depend on flourishing natural systems and the wise use of those natural systems*" (Whitmee et al. 2015). The coronavirus pandemic in 2020 has hastened the need for a seamless approach to the virosphere which refers to the world of viral diversity within the biosphere (Zimmer 2020).

With geology traditionally focused on the distant past, the focus on the Anthropocene to date has largely been on its chronological and stratigraphic dimensions. This emphasis likely explains why geologists seldom add their perspectives on teachable moments surrounding news stories about the modern natural world, such as the extinction of a species, peak oil, seismic events attributed to hydraulic fracturing, transoceanic tsunamis, rising frequencies of climate records, coastal subsidence and inundation, and the ubiquity of plastic waste. In particular, potential tipping points during periods of accelerated warming are strong opportunities for raising public awareness. Recent examples are updated investigations of sea-level rise (Kulp and Strauss 2019), the Florida-sized Thwaites Glacier in eastern Antarctica (Aguilera 2019), the Greenland ice sheet (Davis 2020), and, as an illustration of the field of glacial archaeology, the significance of artefacts along a medieval Viking trail in Norway exposed by receding ice (Pilø et al. 2020). Clearly, authoritative statements on climate change by associations of geoscientists (e.g. The Geological Society 2013; Geological Society of America 2015) are desirable steps, but projecting these into the public realm requires the geosciences to develop better marketing expertise to spread these important messages. Anthropology, "*the discipline most clearly devoted to the human condition over time and space*", set a high bar for its framing of climate change in a 137-page task force report (Fiske et al. 2014).

A quarter-century ago, an academician jointly appointed in geology and philosophy anticipated that future geoscientific investigations would require new types of reasoning (Frodeman 1995). In 2003 in Banff, the International Geosphere-Biosphere Programme considered how the Earth System and human societies could be viewed together. The results included a new project named Integrated History and Future of People on Earth (Costanza et al. 2012) which, five years ago, was consolidated under the Future Earth framework.

All things considered, a pragmatic statement on the importance of the Anthropocene would be that it recognizes humanity as the dominant species which, in a geological nanosecond, has extensively detached itself from the Earth System, endangering the future of both. The daunting whole picture of impacts involves awareness of the natural versus altered states of all 'shells' comprising the Earth System (Table 1). Underscoring the case made by Koster (2011) for an unprecedented topical relevance of the geosciences are *The Anthropocene Project* (Burtynsky et al. 2018) which is a multimedia experience about anthropogenic impacts on the Earth's surface, interest by mainstream news in how the Anthropocene has evolved as a scientific inquiry (Davison 2019), and a visual chronicle of the Anthropocene (Steinmetz and Revkin 2020).

LOOKING FORWARD

As the profession specialized in the scientific study of the Earth and the originator of the Anthropocene concept, geoscientists can become a leading force for public awareness — in the words of Crutzen (2002), "*to guide society*" — in these increasingly perilous times by rallying around the AWG's consensus. This task is urgent because the prevalent news about changing climates, rising sea-level and extreme weather is only one part of a more complex situation which the Anthropocene concept encompasses. As an example, worldwide loss of biodiversity has prompted consideration of a target of keeping species extinctions below twenty per year "*to galvanize both political will and public support*" (Rounsevell et al. 2020).

Table 1. Summary of anthropogenic impacts on each 'shell' of the Earth System.

Atmosphere

- Includes the troposphere, the lowermost layer up to the elevation where jet planes fly and in which all weather systems and habitats for air-breathing life and photosynthesis exist.
- Anthropogenic impacts include reduced air quality due to pollution, warming due to burning of fossil fuels, ozone layer damage due to aerosols, extreme weather causing floods, wildfires and droughts, and altered averages of season length, temperature and precipitation patterns.

Hydrosphere

- All oceans and seas that contain 96.5% of the world's water and cover 71% of its surface, and all freshwater in lakes, rivers, and groundwater from which all drinking water (aside from desalination products) is derived.
- Anthropogenic impacts include widespread pollution, ocean warming causing hurricane intensification and reduction of Arctic and Antarctic sea ice, ecosystem shifts, river flow disruptions, coral reef bleaching, ubiquitous plastic debris, and sea-level rise mainly due to melting ice sheets, icecaps and glaciers, locally exacerbated by coastal subsidence.

Cryosphere

- All frozen areas of the Earth's surface, including ice-sheets, icecaps, glaciers, and tundra.
- The Antarctica ice sheet and Greenland icecap contain the equivalents of approx. 60m and 6m of worldwide sea-level rise, respectively.
- Anthropogenic impacts include melting of permafrost with methane emissions and accelerated melting of glacial ice which is often a vital source to river flow and water for piedmont communities and agriculture.

Biosphere

- All life-supporting habitats on, just below and above land and ocean surfaces.
- Includes the virosphere, the world of virus diversity such as Covid-19.
- Extensively inhabited and affected by humanity (the Earth's dominant species) and these impacts have grown with the Great Acceleration since the mid-20th century.
- Anthropogenic impacts include pollution, disruptions of ecosystems, overfishing, and sharply reduced biodiversity in all major faunal and floral groups, including extinctions.

Lithosphere

- Crustal layer, 5 to 65 km thick, in which plate tectonics operates, volcanic activity and earthquakes originate, and from where fossil fuels and mineral resources are extracted.
- Includes the pedosphere: the thin outermost layer of agriculture-enabling soil where rock and sediment are altered by linked physical, chemical, and organic processes.
- Includes the archaeosphere: proposed term for the altered, highly varied, surface layer of the lithosphere containing evidence of human activities and impacts.
- Anthropogenic impacts include disposal of radioactive waste, groundwater pollution, aquifer alteration, impacts from hydraulic fracturing of rocks for recovery of hydrocarbons, and the predicted imminence of 'peak soil' and 'peak oil'.

The International Union of Geological Sciences — the arbiter on the final status of the Anthropocene — is a member of the International Science Council which resulted from fusion in 2017 of the International Council for Science and International Social Science Council, founded in 1931 and 1952, respectively. This is a clearly helpful context for the geosciences because the Anthropocene has such wide significance. As Robin (2018b) proclaimed: "*The task of reconceptualizing planetary change for the human imagination calls for a wide range of disciplinary wisdom*". Accordingly, the geosciences need to establish a common horizon not only with other scientific disciplines but also with the social sciences which explore how people understand the world and their place in it. As an example, Semeniuk (2020) drew attention to likely shifts in humanity's comfort zone due to climate change resulting from unchecked carbon emissions. As disquieting as such projections are, shifts in climate are just one facet of the global changes that are embodied in the concept of the Anthropocene. If its 'golden spike' does turn out to be the fallout from the first atomic bomb tests, this new geological time will become a paradoxical reminder of the first resolution of the United Nations General Assembly in 1946 which called for peaceful uses of atomic energy and elimination of weapons of mass destruction.

A musing about the passage of time (Brannen 2018) provided an apt conclusion for this article:

> "*The world is old beyond comprehension, and our story on it is short. But if we are to endure as a civilization, or even as a species, for anything more than might amount to a thin layer of odd rock in some wind-swept canyon of the far future, some humility is in order about our, thus far, infinitesimal part in the history of the planet.*"

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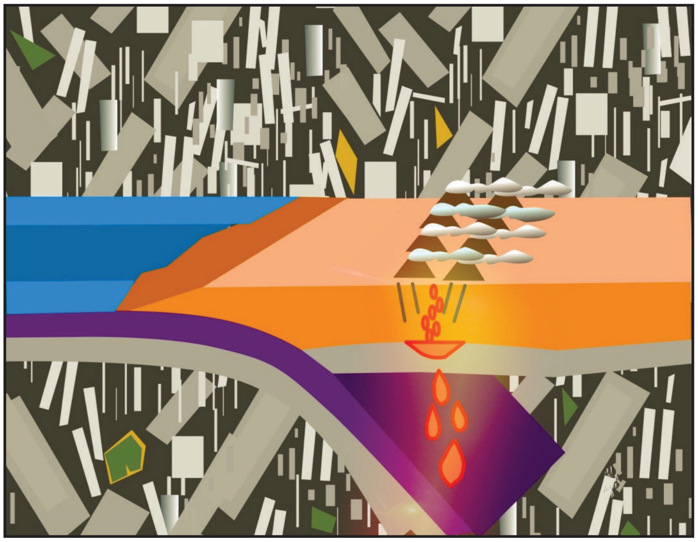

Igneous Rock Associations 25. Pre-Pliocene Andean Magmatism in Chile

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SUMMARY

Andean-type magmatism and the term 'andesite' are often used as the norm for the results of subduction of oceanic lithosphere under a continent, and the typical rock formed. Although the Andes chain occupies the whole western margin of South America, the most comprehensively studied rocks occur in the present-day Chilean territory and are the focus of this paper. Andean magmatism in this region developed from the Rhaetian-Hettangian boundary (ca. 200 Ma) to the present and represents the activity of a long-lived continental magmatic arc. This paper discusses Pre-Pleistocene volcanic, plutonic, and volcano-sedimentary rocks related to the arc that cover most of the continental mass of Chile (between the Pacific coast and the High Andes) between the latitudes of 18° and 50°S. They comprise most of the range of sub-alkaline igneous rocks, from gabbro to monzogranite and from basalt to rhyolite, but are dominated by the tonalite-granodiorite and andesite example members. Variations in the petrographic characteristics, major and trace element composition and isotopic signature of the igneous rocks can be correlated to changes in the physical parameters of the subduction zone, such as dip angle of the subducting slab, convergence rate and angle of convergence. Early Andean magmatic products (Jurassic to Early Cretaceous) are found along the Coastal Cordillera in the westernmost part of the Andes. The rock record of the subsequent stages (Late Cretaceous, Paleocene–Early Eocene, Middle Eocene–Oligocene, Miocene) is progressively shifted to the east, reflecting migration of the magmatic front towards the continent. Tectonic segmentation of the convergent margin, as attested by the magmatic record, may have occurred throughout the Andean life span but it is particularly evident from the Eocene onwards, where the evolution of the northern part of the Chilean Andes (north of 27°S latitude) is very different to that of the southern segment (south of 27°S latitude).

RÉSUMÉ

Le magmatisme de type andin et le terme « andésite » sont souvent les appellations utilisées pour décrire les résultats de la subduction de la lithosphère océanique sous un continent, et la roche typique formée. Bien que la chaîne des Andes occupe toute la marge ouest de l'Amérique du Sud, les roches les plus étudiées se trouvent dans le territoire chilien actuel et sont l'objet de cet article. Le magmatisme andin dans cette région s'est développé depuis la limite rhéto-hettangienne (environ 200 Ma) jusqu'à aujourd'hui et représente l'activité d'un arc magmatique continental persistant. Cet article a pour sujet les roches volcaniques, plutoniques et volcano-sédimentaires du pré-Pléistocène liées à l'arc qui couvrent la majeure partie de la masse continentale du Chili (entre la côte du Pacifique et les Hautes Andes) entre les latitudes de 18° et 50°S. Elles com-

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prennent la majeure partie de la gamme de roches ignées sous-alcalines, du gabbro à la monzogranite et du basalte à la rhyolite, mais sont dominées par des roches de type tonalite-granodiorite et andésite. Les variations des caractéristiques pétrographiques, de la composition des éléments majeurs et traces et de la signature isotopique des roches ignées peuvent être corrélées aux changements des paramètres physiques de la zone de subduction, tels que l'angle de pendage de la plaque plongeante, le taux de convergence et l'angle de convergence. Les premiers produits magmatiques andins (du Jurassique au Crétacé inférieur) se trouvent le long de la Cordillère de la Côte dans la partie la plus occidentale des Andes. La succession de roche des stades suivants (Crétacé supérieur, Paléocène – Éocène inférieur, Éocène moyen – Oligocène, Miocène) est progressivement déplacée vers l'est, reflétant la migration du front magmatique vers le continent. La segmentation tectonique de la marge convergente, comme l'attestent les enregistrements magmatiques, peut avoir eu lieu tout au long de la formation des Andes, mais elle est particulièrement évidente à partir de l'Éocène, où l'évolution de la partie septentrionale des Andes chiliennes (au nord de 27°S de latitude) est très différente de celle du segment méridional (sud de 27°S de latitude).

Traduit par la Traductrice

INTRODUCTION

Andean magmatism is a general term referring to the plutonic, volcanic, and volcano-sedimentary rocks cropping out in the western border of the South American plate, spanning activity from ~200 Ma to the present day. As the modern volcanism in the Andean chain, these rocks are thought to represent the products of the long-lived subduction-related magmatism that is still active. A most remarkable product of Andean magmatism is ‘andesite’ (see for example Darwin 1844), an intermediate SiO_2–alkali content volcanic and subvolcanic lithology that commonly exhibits porphyritic texture, bearing quite large phenocrysts of plagioclase or clinopyroxene or amphibole, embedded in an intersertal groundmass, with glass, plagioclase microlites and titanomagnetite. Andesite can be found in other tectonic environments in our planet but is ubiquitous in areas where subduction magmatism is developed (e.g. Gill 1981). It is formed in continental arcs by the combination of processes such as fractional crystallization and the assimilation of crustal material by ascending, depleted mantle-derived basaltic melts. Therefore, Andean magmatism is basically the result of an active subduction of oceanic lithosphere under a continental edge that has transiently recycled variable amounts of the continent itself, mixing crust with juvenile melts from the asthenosphere below the South American subcontinental lithosphere (e.g. Pichler and Zeil 1971; Dostal et al. 1977; Zentilli and Dostal 1977; Hickey et al. 1986; Hildreth and Moorbath 1988; Stern 1991; Tormey et al. 1991; Wörner et al. 1992; Kay et al. 2005).

Even though subduction has remained active during this 200 million year time span (Mpodozis and Ramos 1989), the physical parameters controlling the plate convergence, such as the dip angle of the subducted slab, or the relative velocities of the Phoenix/Farallon/Nazca and South American plates, have changed through time (Pardo-Casas and Molnar 1987; Scheuber et al. 1994; Somoza 1998; Seton et al. 2012). The geological record can be used to track those changes back in time by means of: 1) the deformation of the upper crust through brittle and ductile structures that acted as lithospheric channels of magmatic and hydrothermal flux (e.g. the Atacama and Domeyko Fault systems, Fig. 1); 2) the chemical composition of the magmatic products themselves (and any by-products, such as mineral deposits) and their emplacement (or eruptive) mechanisms; and 3) the timing, volumetric fluxes and location of the magmatism during the 200 M.y. time span.

Although the Andes extend from Venezuela to the southern tip of Chile, in this review we summarize the different stages, in time and space, of the Andean magmatism restricted to the territory of Chile (present day 18°–40°S and 69°–71°W), focusing herein on the variation of the subduction conditions that led to significant changes in magma composition, volume and foci. Other aspects such as the structural framework of the arc magmatism or the associated mineral deposits are important but beyond the scope of the present review. The starting point is the Rhaetian–Hettangian boundary, the time span for the emplacement of the oldest rocks assigned to the activity of the Andean arc in several locations along the present-day Coastal Cordillera of Chile (18°–40°S) (Dallmeyer et al. 1996; Grocott and Taylor 2002; Sepúlveda et al. 2014). The Andean igneous rocks with ages up until the Hauterivian are largely exposed in this morphotectonic unit (Fig. 1). Subsequently, the position of the magmatic front has migrated eastwards as the trench advanced over the continent (Farrar et al. 1970; Levi et al. 1973; Dostal et al. 1977; Ramos and Aleman 2000), and as parts of the latter were removed through subduction erosion (Rutland 1971; Schweller et al. 1981). Hence, Late Cretaceous igneous units are preferentially located in the Central Depression or Pre-Cordillera, whereas younger igneous rocks are principally found from the Domeyko of the Pre-Cordillera to the east (Fig. 1). Names and characteristic of units for each described period are listed in Table 1.

This paper takes advantage of accessibility to databases for Chilean rocks only but does not deal with post-Miocene volcanism. Volcanic rocks in adjacent Bolivia and Argentina and Pleistocene to Recent volcanism have been treated comprehensively in Stern (2004), Wörner et al. (2018), de Silva and Kay (2018) and the literature cited within.

REGIONAL SETTING

The Pre-Andean Basement

The southern South American Plate was built mainly during the Phanerozoic, after the break-up of Rodinia that led to the formation of the Gondwana supercontinent, with a southwestern border mainly formed by the Rio de la Plata Craton and the Brazilian Shield (Cawood 2005; Bahlburg et al. 2009). Whereas the eastern side of the proto-South American plate has been either inland or a passive margin, its western side has intermittently been a convergent margin at least since the Edi-

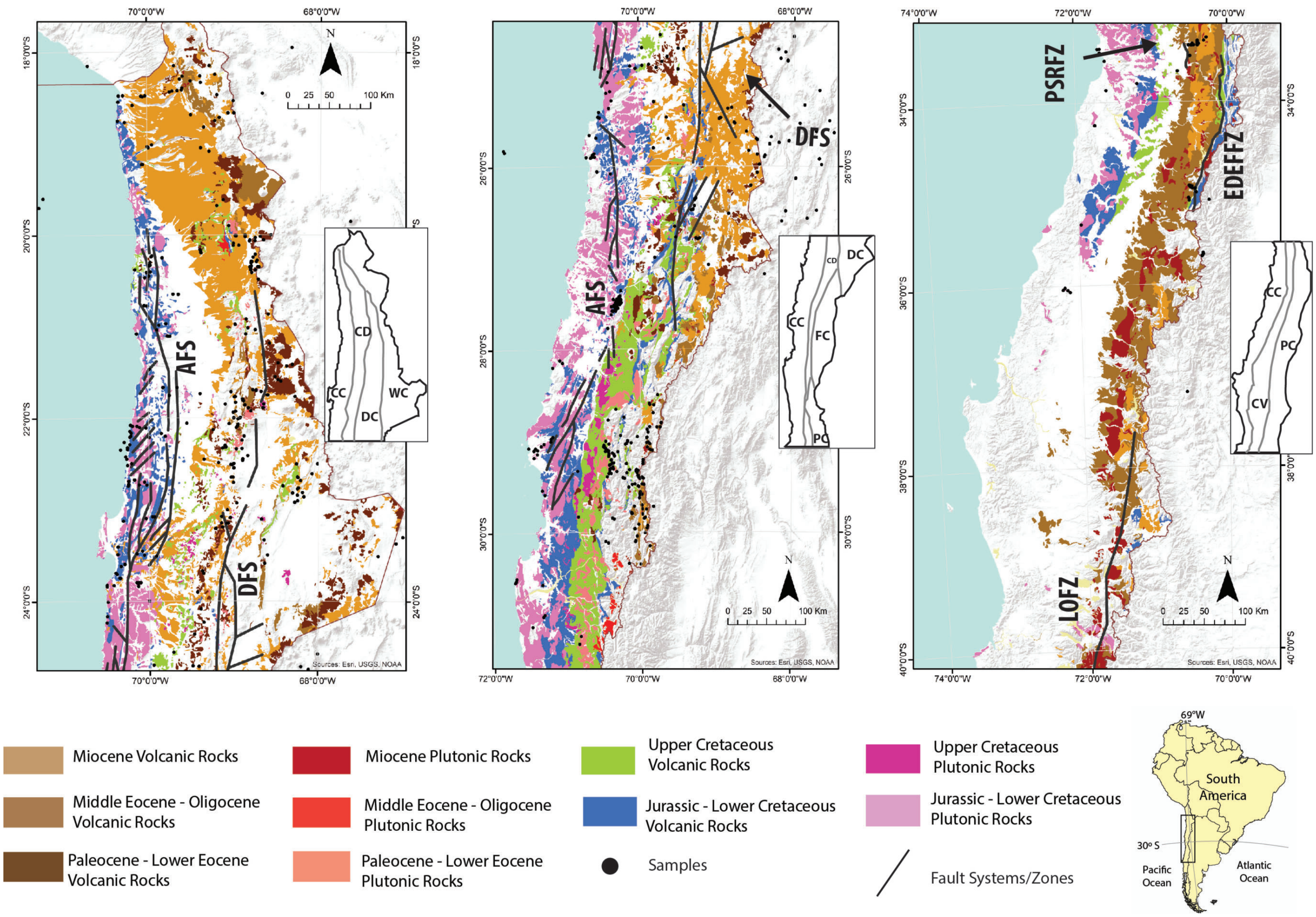

Figure 1. Simplified geological map of the Chilean territory between 18°30' and 40°S latitude, showing the distribution of Andean magmatism from the Jurassic to the Miocene (SERNAGEOMIN 2002), the main fault systems related to the Andean arc (González and Carrizo 2003; Lange et al. 2008; Niemeyer and Urrutia 2009; Armijo et al. 2010; Piquer et al. 2010). AFS: Atacama Fault System, DFS: Cordillera Domeyko Fault System, PSRFZ: Pocuro-San Ramón Fault Zone, EDEFFZ: El Diablo-El Fierro Fault Zone; LOFZ: Liquiñe-Ofqui Fault Zone Inset: main morphotectonic units in Chile, CC: Coastal Cordillera (or Coastal Range), CD: Central Depression, WC: Western Cordillera (also named "Principal Cordillera" or "High Andes", between 22° and 24°S it includes the Altiplano), DC: Domeyko Cordillera (also named "Precordillera", FC: Frontal Cordillera, PC: Principal Cordillera, CV: Central Valley.

Table 1. Names, main lithologies, ages and associated ore deposits (Maksaev 2001) for each described period of Andean magmatism.

	Units	**Main Lithologies**	**Related Ore Deposits***	**Age Range**
Early Andean Magmatism	Sierra Laguna Beds, Agua Chica Fm, La Negra Fm, Cifuncho Fm, Pichidangui Fm	Basaltic andesite, Andesite		Rhaetian-Toarcian
	Oficina Viz Fm, La Negra Fm, Camaraca Fm, Los Tarros Fm, Punta Barranco Fm, Punta del Cobre Fm, Aeropuerto Fm, Agua Salada Volcanic Complex, Arqueros Fm, Ajial Fm, Veta Negra Fm	Andesite	Stratabound Cu–Ag, IOCG, Magenite-Apatite	Aalenian-Aptian
	Morro Mejillones Tonalite, Algodones Granite, Carrizal Bajo Plutonic Complex, Talinay Plutonic Complex, Cobquecura Pluton, Hualpén Pluton	Tonalite, Granodiorite		212–200 Ma
	Coastal Batholith	Diorite, Tonalite, Granodiorite	IOCG, Magnetite-Apatite	200–145 Ma
	Coastal Batholith	Tonalite, Granodiorite	IOCG, Skarn	145–100 Ma
Late Cretaceous	Suca Fm, Pachica Fm, Cerro Empexa Fm, Cerro Cortina Fm, Quebrada Mala Fm, Paradero del Desierto/Los Trigos Fm, Cerro Azabache Fm, Llanta Fm, Cerrillos Fm, Hornitos Fm, Viñita Fm, Los Elquinos Fm, Salamanca Fm, Lo Valle Fm, Plan de los Yeuques Fm	Andesite, Dacite minor rhyolite; locally basaltic andesite	Epithermal Au–Cu, Porphyry Cu	Albian-Maastrichtian
	Sierra Buitre Batholith, Illapel Plutonic Complex, Caleu Pluton, minor plutonic bodies	Granodiorite, Granite	Porphyry Cu–Au	100–65 Ma
Paleocene–Eocene	Icanche Fm, Chincado Fm, Calama Fm, Augusta Victoria Fm, Chile-Alemania Fm, Venado Fm, Estero Cenicero Fm	Dacite, Rhyolite Andesite	Porphyry Cu–Mo Epithermal Au–Cu	Danian-Lutetian
	Columtucsa-Japu, El Bosque, Loma Colorada, Cuarto Chinchillero, Encanto, and Cuncumén granites. Minor porphyry plutonic bodies	Granite, Granodiorite	Porphyry Cu–Mo	65–42 Ma
Up Eocene–Lw Miocene	North of 28°S: subvolcanic and caldera-type deposits	Dacite, Rhyolite	Porphyry Cu–Mo	Bartonian-Aquitanian
	South of 28°S: Abanico Fm, Cura-Mallín Fm	Basaltic andesite, Basalt		
	Shallow intrusive complexes and porphyries	Granodiorite, Granite	Porphyry Cu–Mo	42–21 Ma
Miocene	North of 27°S: Ignimbrites Oxaya, Lupica, Altos de Pica (Fm), Tambillo, Río Frío, Lauca , Collacagua, La Pacana, Toconao, Atana, Tucúraro, Patao, Cajón Tuyajto, Llano Las Vicuñas, Inés Chica, Los Cristales, San Andrés, Wheelwright, Laguna Verde. San Bartolo Group	Rhyolite, Dacite	Epithermal Au–Ag Porphyry Au	Burdigalian-Messinian
	South of 28°S: Farellones Fm (and equivalents)	Andesite	Porphyry Cu–Mo	
	Shallow intrusives	Granodiorite, Granite	Porphyry Cu–Mo	21–5 Ma

*IOCG: iron oxide–copper–gold deposits, Cu: copper, Au: gold, Ag: silver, Mo: molybdenum acaran–Cambrian boundary, following the Pampean Orogeny (Rapela et al. 1998; Escayola et al. 2007; Schwartz et al. 2008). Growth of the continent, however, was not only due to crust generation at its western side, because Mesoproterozoic basement exotic terranes would have amalgamated during the Grenville-age Sunsas Orogeny (Tosdal 1996; Lowey et al. 2004), Ediacaran–Cambrian (Rapela et al. 1998; Escayola et al. 2007), Ordovician (Ramos 1988), Devonian (Ramos 1988) and Permian periods (Ramos 2008b), allowing the continental mass to expand to the west and south. The Pampean (Cambrian) and Famatinian (Ordovician) arcs would have built a western belt of South American continental crust (Rapela et al. 1998; Otamendi et al. 2012), over the Grenville-derived Mesoproterozoic Arequipa massif and at the edges of the Precambrian Sunsás Orogen and Río de la Plata Craton (see Ramos 2008a and references therein). The activity of the Famatinian arc would have ended with the collision of the Cuyania terrane (Ramos et al. 1986), adding a part of Laurentia to the South American plate (Thomas and Astini 2003). The accretion of the Chilenia terrane just to the west of Cuyania would have taken place during the Devonian (Ramos et al. 1986) and later on, during the Carboniferous, subduction resumed at the edge of the continent (Mpodozis and Ramos 1989).

The Gondwana Cycle and Pre-Andean Stage

Carboniferous subduction led to the formation of an orogenic front known as the Gondwana orogenic cycle of the proto-Andes side of South America, which was characterized by intense magmatic activity of a continental arc and the development of an accretionary prism at the western border of the forearc crust (Mpodozis and Ramos 1989; Llambías et al. 1993). The orogeny reached its maximum with the 'San Rafael phase" at the end of the Permian (Llambías and Sato 1990; Tomezzoli and Japas 2006; Kleiman and Japas 2009). Also, during the Carboniferous–Permian, at the southern end of the continent, the Patagonia terrane would have accreted to the edge of Gondwana, giving the South American plate its final configuration (Ramos 2008; Ramos and Naipauer 2014). The precise timing for this collision is still debated (Chernicoff et al 2013; Pankhurst et al. 2014; Castillo et al. 2017).

By the end of the San Rafael phase the orogen started to collapse and a period of continental extension and rifting took place for ca. 50 M.y., from the Late Permian to the Late Triassic (Kleiman and Japas 2009). This particular tectonic scenario is known as the 'Pre-Andean' cycle and has been traditionally interpreted as a period of arrested subduction and extensive crustal reworking and anatexis, due to basalt underplating at the base of the thinned lithosphere (Mpodozis and Kay 1992; Llambías and Sato 1995). More recently though, several authors have questioned this model in light of new geochemical, petrological, geochronological and geological data, arguing that subduction may have persisted throughout the Late Paleozoic and the Mesozoic, making southwestern Gondwana a long-lived convergent margin (del Rey et al. 2016; Coloma et al. 2017; González et al. 2018; Oliveros et al. 2020). Recent global reconstructions also support the idea of an active subduction zone for western Pangea and Gondwana since the Carboniferous (Matthews et al. 2016; Riel et al. 2018). Regardless of the precise tectonic setting in the continent's margin prior to the initiation of the Andean magmatism, it is widely accepted that the crust underwent significant extension and thinning at the moment when the arc started its activity (Mpodozis and Kay 1992; Kleiman and Japas 2009). In addition to that, by the Rhaetian–Hettangian times the intense latitudinal drift to which the South American continental masses were subjected to during the Late Carboniferous to Late Triassic times ended, and the Andean margin acquired its present position toward the Early Jurassic (Torsvik and Cocks 2013). New data suggest that, at least during the latest Triassic, magma generation conditions in northern Chile were indistinguishable from those in the Eocene, but very different from that of the Jurassic (Zentilli et al. 2018).

EARLY ANDEAN MAGMATISM (200–100 Ma)

All along the Coastal Cordillera of northern Chile between 18°S and 40°S latitudes, discrete outcrops of metamorphic and epimetamorphic rocks are exposed (Hervé et al. 2007). In some locations, these constitute a metamorphic paired belt of low-temperature/high-pressure metasedimentary and metaigneous rocks to the west and high-temperature/low-pressure metasedimentary rocks to the east. They have been interpreted as the remnants of a Late Paleozoic (Devonian to Permian) accretionary prism (Hervé 1988). It was over this thinned crust at the very edge of the continent that the earliest Andean arc became emplaced at ca. 200 Ma, a geological setting known as the "First Stage of the Andean Tectonic Cycle" (*sensu* Charrier et al. 2007). Rhaetian to Toarcian volcanic units such as the La Negra, Agua Chica, Cifuncho and Pichidangui formations, Sierra de Lagunas beds in Chile, and the Chocolate Formation in southern Peru, and intrusive units such as the Morro Mejillones tonalite, the Algodones Granite, Carrizal Bajo Plutonic Complex, Talinay Plutonic Complex, Cobquecura Pluton and the Hualpén Pluton (Table 1) may represent the first magmatic pulses of the arc. Most of them were emplaced nearby or directly over metasedimentary sequences (Oliveros et al. 2018). These units were followed by intense magmatic activity recorded in the Los Tarros, Camaraca, Oficina Viz, La Negra, Punta del Cobre, Bandurrias, Aeropuerto, Punta Barranco, Ajial, Horqueta, Arqueros, Quebrada Marquesa, Veta Negra and Las Chilcas formations, and in several plutonic complexes (Vergara et al. 1995; Marschik and Fontboté 2001; Morata and Aguirre 2003; Kramer et al. 2005; Lucassen et al. 2006; Oliveros et al. 2006, 2007). The outcrops of Early Andean volcanic rocks comprise thick homoclinal sequences of porphyritic lava flows bearing large plagioclase and pyroxene phenocrysts and ubiquitous titanomagnetite (they have been traditionally named 'ocoita' for the locality Ocoa in central Chile). Epiclastic or siliciclastic sandstone, siltstone, and minor conglomerate and, in some localities, shallow marine limestone and related rocks, are intercalated with the volcanic flows. The base of the sequences, or the oldest units, may have pyroclastic rocks and even caldera-like deposits, suggesting a more volatile-rich style of magmatism at the start of the arc's activity (Vásquez et al. 2018). Other than that, deposits representing explosive magmatism are not the most common type among the early phases of Andean magmatism (Oliveros et al. 2018). The outcrops of the Early Andean plutonic rocks form an 800–2000 m altitude mountain range known as the Coastal Batholith (Fig. 1). Between latitudes 16° and 33°S, the Coastal Batholith is composed almost exclusively of Mesozoic intrusions, whereas south of 33°S the Paleozoic plutons of the Gondwana cycle become the largest exposed units (Fig. 1). The Mesozoic (200–100 Ma) intrusions are medium-grained and have ubiquitous plagioclase, biotite, amphibole, quartz and titanomagnetite; less common are pyroxene, alkali feldspar, apatite and titanite. The largest plutonic bodies have tabular shapes (resembling large sills), with the traditionally depicted vertical dyke-like bodies, showing evidence of incremental growth through extensional stress in the crust controlled by major faults (Grocott et al. 2009). Fine grained stocks also crop out and intrude both the volcanic and plutonic rocks, whereas epizonal porphyritic stocks are very rare; less differentiated microphaneritic to porphyritic dykes crosscut the volcanic sequences and, along with the aforementioned stocks, have been interpreted as feeders to the volcanism (Oliveros et al. 2006). Typical ore deposits of this Andean stage are the stratabound ‘Manto’ type copper, silver deposits and iron oxide–copper–gold (IOCG) types deposits, hosted mainly in the homoclinal volcano-sedimentary sequences and associated stocks and small intrusive units, with a distinct low-S/Fe type of mineralization (e.g. Boric et al. 2002; Sillitoe 2003).

According to regional and global plate reconstructions, the Phoenix Plate had a strongly oblique convergence against the South American plate from the Triassic–Jurassic boundary until at least its break-up into the Chasca and Cataquil plates, and later evolution to the Farallon/Aluk plates (Zonenshayn et al. 1984; Matthews et al. 2016). This resulted in a partition of the stresses, with arc-normal extension and arc-parallel sinistral transtension (Grocott and Taylor 2002) that dominated upper crustal deformation along the precursors of the Atacama Fault System (AFS), a paleo-trench parallel structure now exposed along 1000 km, in northern Chile (Fig. 1). Magmatic activity was then concentrated in intra-arc basins, located at sea level or slightly above, bounded to the east by marine back-arc or marginal basins with little volcanic activity (now exposed in the Central Depression and Domeyko and Frontal Cordilleras) (Rossel et al. 2013; Espinoza et al. 2019). The emplacement of the Jurassic to Early Cretaceous plutonic complexes is tightly related to the present-day traits of the AFS (Scheuber and González 1999; Cembrano et al. 2005); several mylonitic zones are developed along the interface of plutonic bodies and specific branches of the AFS, which acted as the footwalls or channels of magmatic flux (Cembrano et al. 2005). On the other hand, the intra-arc basins in which the volcanic flows and sediment were deposited, do not seem to have been controlled by the AFS as no spatial or temporal link has yet been observed, except for some Early Cretaceous depocentres in northernmost Chile (~21°S latitude, Vásquez et al. 2018).

The fact that the arc’s foundation was upon a rather young crystalline basement at this time and that extensional tectonics prevailed, may have strongly influenced the composition of Early Andean magmatism, since the melts derived from the flux-induced melting of the asthenospheric wedge under the thin lithosphere did not stall at the base of the crust nor exchange material with it (Lucassen et al. 2006). Thus, the geochemical signature of the first pulses of Andean magmatism reflect primarily a mantle source and only limited crustal assimilation (Kramer et al. 2005; Lucassen et al. 2006; Rossel et al. 2013). This can be inferred from the low–intermediate SiO_2 content of both volcanic and plutonic rocks spanning 200 to 140 Ma (Fig. 2a), along with low Sr/Y and La/Yb and relatively high Eu/Eu* (Oliveros et al. 2018) (Fig. 2g, h) retained in these units.

Jurassic volcanic rocks are mainly basaltic andesite to andesite, with less significant amounts of basalt, and scarce rhyolite and dacite; younger volcanic rocks (140–100 Ma) are more differentiated, with andesite as the dominant lithology followed by dacite and rhyolite (Marschik and Fontboté 2001; Oliveros et al. 2006). By contrast the 200–100 Ma intrusive bodies have more varied compositions, but with a strong predominance of amphibole and biotite diorite and tonalite (Oliveros et al. 2018). In contrast with their Permian and Triassic counterparts, granite is rare amongst the Early Andean Plutonic complexes, and syenogranite completely absent (Oliveros et al. 2018). Some Norian–Rhaetian intrusive units, however, are monzogranite (e.g. the Algodones, La Estrella and Pichilemu plutons; Vásquez et al. 2011; Coloma et al. 2017). Bimodal plutonic complexes such as the Limarí Complex (Parada et al. 1999) have mafic and intermediate lithologies but also lack granite intrusive compositions. Thermobarometic conditions calculated from minerals in Jurassic and Early Cretaceous plutons suggest middle to upper crust emplacement for the magmas, with ranges of 150 to 400 MPa (González 1999).

Magmatic affinities for Jurassic volcanic and plutonic rocks are dominantly tholeiitic to low-K calc-alkaline (Fig. 2b), and intrusive rocks are mostly metaluminous having affinities to volcanic arc granite (VAG). Lower Cretaceous volcanic rocks may have tholeiitic affinities (particularly the units cropping out in central Chile at ca. 31°–33°S latitude) but the most common trend is that of a medium- to high-K calc-alkaline series. Systematic enrichment in large ion lithophile elements (LILE) relative to high field strength elements (HFSE) is a typical feature of Jurassic to Lower Cretaceous magmatism (Fig. 2c, d), suggesting a rather depleted mantle source that has been preferentially enriched in fluid-mobile elements, such as Rb, Sr and Ba, likely derived from a subducted (and altered) slab or from subducted sedimentary material (Vergara et al. 1995; Marschik and Fonboté 2001; Lucassen et al. 2006). It is widely accepted that by the Jurassic Andean magmatism was chiefly subduction related (Lucassen et al. 2006; Oliveros et al. 2007). Furthermore, the Sr–Nd–Pb isotopic compositions of igneous rocks spanning 200 to 100 Ma, require the combination of two sources, a depleted mantle and a Paleozoic crust, to be explained, which is also a characteristic of continental arc magmatism (Lucassen et al. 2006; Rossel et al. 2013). Even though the Early Andean magmatism is very homogeneous in its petrological and chemical composition, an evolution through time in key chemical parameters has been observed and can be

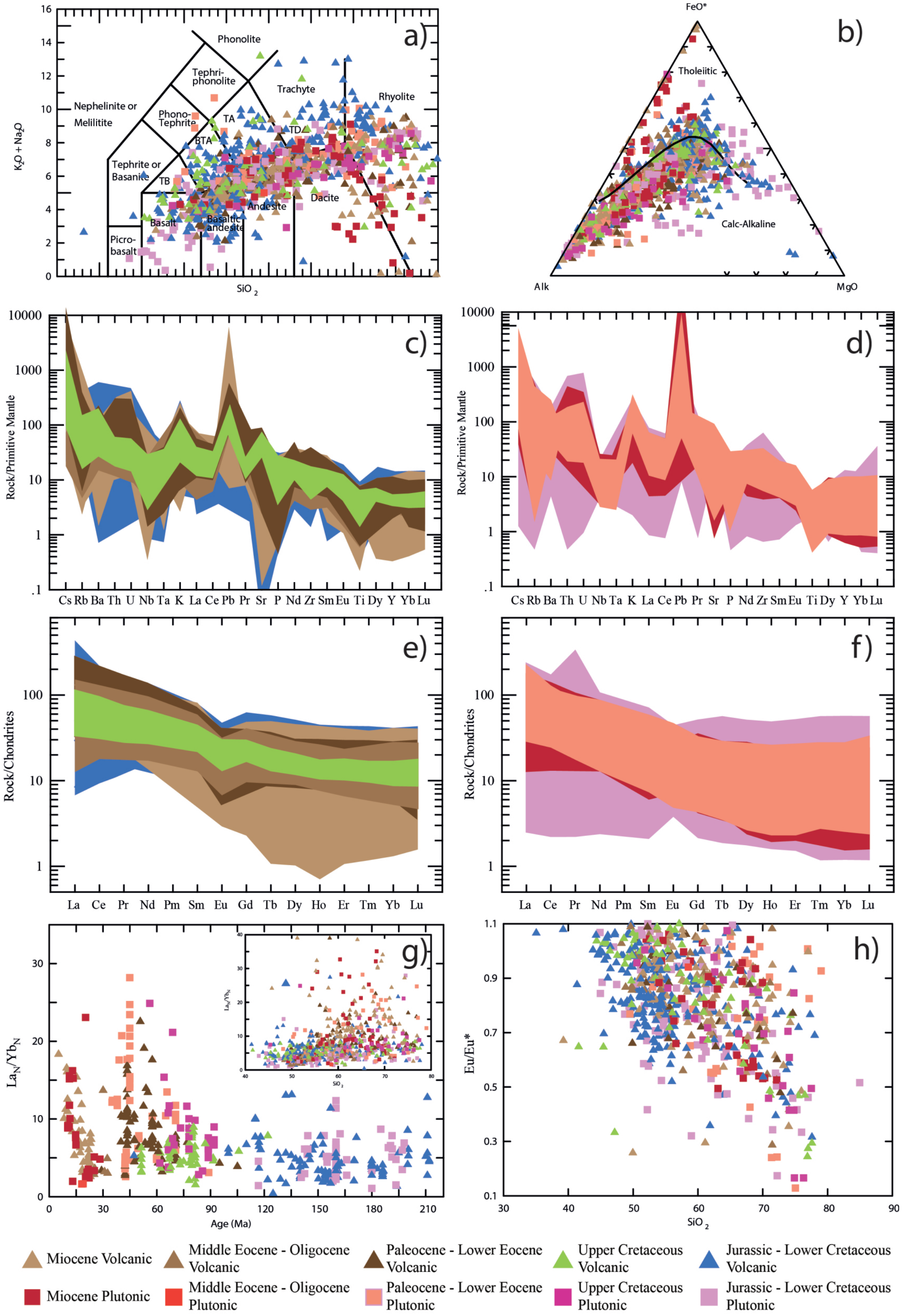

Figure 2. After Irvine and Baragar (1971): a) Total Alkali versus Silica (TAS) diagram, and b) Alkali-FeO*–MgO (AFM) diagram for Andean rocks; Primitive mantle-normalized trace elements composition for Andean: c) volcanic and d) plutonic rocks; Chondrite-normalized REE compositions for Andean rocks: e) volcanic and f) plutonic rocks; g) Chondrite-normalized La/Yb versus age (inset: chondrite-normalized La/Yb versus SiO_2); h) Eu/Eu* (Eu*=Eu/(Sm*Gd)^{½}) versus age plots. Chondrite and primitive mantle compositions are from Sun and McDonough (1989). Data and references are provided in the supplementary material SMT-1. BTA: basaltic trachyandesite, TA: trachyandesite, TB: trachybasalt, TD: trachydacite.

related to tectonic phases of crustal thickening or compressive deformation. For example, La/Yb and Sr/Y increase with time, suggesting that the depth of magma generation (and hence the thickness of the crust) may have increased from 200 to 100 Ma (Hascke et al. 2006; Mamani et al. 2010). Sr, Nd, Pb isotopic ratios for all plutonic and volcanic rocks between 18° and 31°S latitude exhibit a similar pattern (Fig. 3a, b), increasing ^{87}Sr/^{86}Sri and decreasing ^{143}Nd/^{144}Ndi (εNd$_i$) with time, suggesting more involvement of crustal material as the arc evolved towards the present day (Mamani et al. 2010) (Fig. 3c, d). Nonetheless, a reverse pattern is observed for volcanic and plutonic rocks of central Chile, where isotopic ratios for Early Cretaceous units suggest a more depleted mantle source than for the Jurassic igneous rocks. This particular pattern would represent the formation of an ensialic or aborted marginal basin right behind the arc, with extensive crustal thinning during the Barremian to Albian (Vergara et al. 1995) (Fig. 4).

Another prominent characteristic of the Early Andean igneous rocks is the lack of unaltered samples or outcrops. The vast majority of the volcanic or plutonic units studied and described so far exhibit features of either very low to low grade metamorphism (Levi 1969; Losert 1974; Aguirre et al. 1999; Robinson et al. 2004), hydrothermal alteration or metasomatic/deuteric alteration, such as selective replacement of phenocrysts, devitrification, infilled veins and amygdules, or groundmass alteration. Typical secondary mineral assemblages include albite (or more precisely albitized plagioclase, in relation to Ca–Na exchange), quartz, calcite, chlorite–smectite and titanite. Less common secondary minerals are zeolites, celadonite, sericite, clays, adularia and actinolite. Deuteric alter-

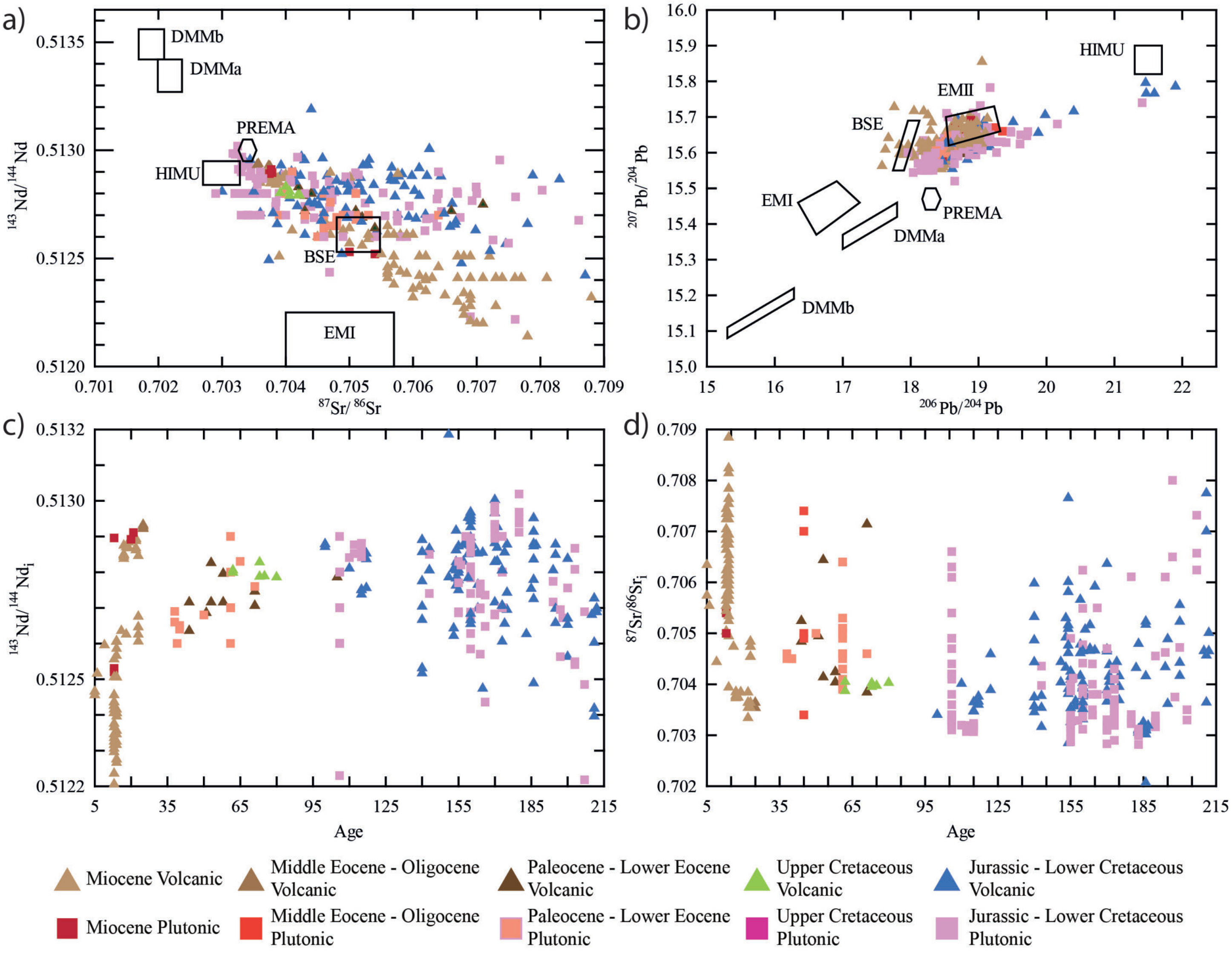

Figure 3. a) ^{87}Sr/^{86}Sr versus ^{143}Nd/^{144}Nd and b) ^{206}Pb/^{204}Pb versus ^{207}Pb/^{204}Pb diagrams for Andean rocks; c) initial ^{143}Nd/^{144}Nd and d) initial ^{87}Sr/^{86}Sr versus age for Andean rocks. Mantle fields are from Zindler and Hart (1984). DMM: depleted mantle MORB; BSE: bulk silicate Earth; HIMU: high U/Pb mantle; PREMA: prevalent mantle; EM: enriched mantle.

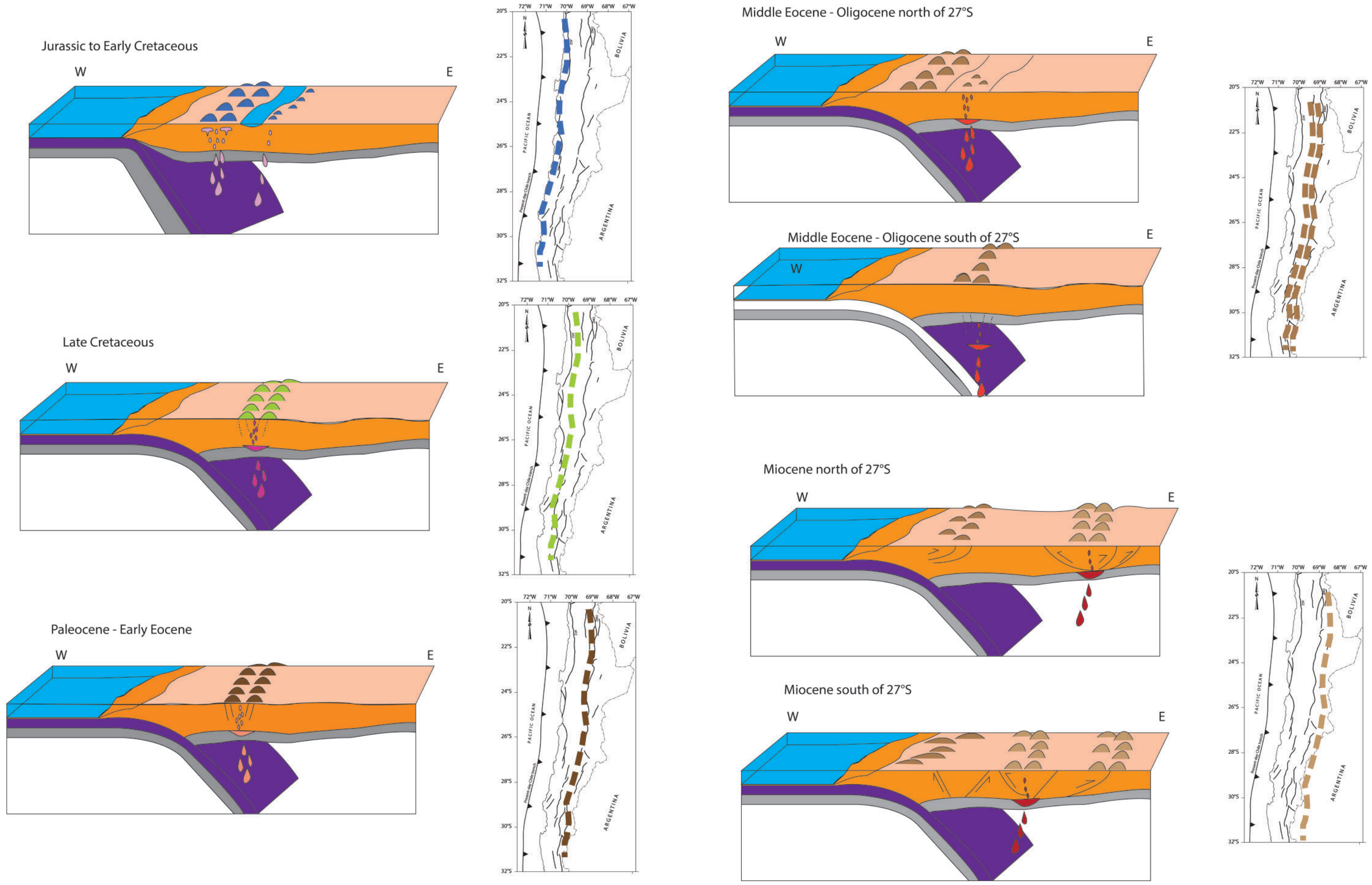

Figure 4. Schematic tectonic setting for Andean magmatism and arc position during the Jurassic–Early Cretaceous, Late Cretaceous, Paleocene–Early Eocene, Middle Eocene–Oligocene north of 27°S latitude, Middle Eocene–Oligocene south of 27°S latitude, Miocene north of 27°S latitude, Miocene south of 27°S latitude.

ation is commonly represented by replacement of either pyroxene or hornblende by pargasite. Independent of the origin of the secondary or late magmatic mineralogy, its ubiquitous occurrence is representative of high fluid flux through the upper crust and elevated thermal gradients (Losert 1974; Aguirre et al. 1999; Robinson et al. 2004), likely due to the magmatic activity of the arc (Fuentes et al. 2004; Robinson et al. 2004; Oliveros et al. 2006, 2007; Rossel et al. 2013).

LATE CRETACEOUS ANDEAN MAGMATISM (100–65 Ma)

The Peruvian Orogeny (ca. 90 Ma) separates the periods of magmatism and tectonic evolution into which the Andean orogenic cycle is subdivided (Coira et al. 1982; Charrier et al. 2007, 2015). The younger period is marked by the construction of a Cordilleran arc orogenic system and a rear arc domain that passed from a back-arc to a foreland basin stage at ~100 Ma (Fig. 4) (Charrier et al. 1996, 2007, 2015; Tunik et al. 2010; Aguirre-Urreta et al. 2011; Fennell et al. 2017). The changes induced by this compressive event can be correlated to the contrasting characteristic of the Late Cretaceous magmatism in comparison to the older arc products. First, igneous rocks younger than 100 Ma are located either in the eastern flank of the Coastal Cordillera or farther east, in the Central Depression or Pre-Cordillera. They represent a voluminous phase of Andean magmatism, although less voluminous than the previous stage (Fig. 1), and their composition, textures and structures are also different from the older rocks. Representative volcanic units of this period are the Suca, Pachica, Cerro Empexa, Cerro Cortina, Quebrada Mala, Paradero del Desierto/Los Trigos, Cerro Azabache, Llanta, Cerrillos, Hornitos, Viñita, Los Elquinos, Salamanca, Lo Valle and Plan de los Yeuques formations (Rivano and Sepúlveda 1991; Iriarte et al. 1996, 1999; Gana and Wall 1997; Emparán and Pineda 1999; Marinovic and García 1999; Tomlinson et al. 1999, 2010; Wall et al. 1999; Cortés 2000; Fuentes et al. 2002; García et al. 2004; Arévalo 2005; Matthews et al. 2006, 2010; Marinovic 2007; Espinoza et al. 2011, 2012; Blanco et al. 2012; Medina et al. 2012; Blanco and Tomlinson 2013; Gardeweg and Sellés 2013; Jara and Charrier 2014; Mosolf et al. 2019; Muñoz et al. 2018). Numerous plutonic bodies are also products of this magmatism, although in general their volume is much smaller than for the Jurassic to Lower Cretaceous intrusions (Fig. 1). Only between 28° and 31°S latitude do large plutonic complexes crop out, such as the Sierra Buitre Batholith or the Illapel Plutonic Complex (Rivano and Sepúlveda 1991; Morata et al. 2010). The dominant petrographic type among the Late Cretaceous plutonic rocks is by far the hypabyssal stocks and porphyries. Chemically, these younger arc products are also distinctive, showing evidence of incipient arc maturation and crustal thickening (Haschke et al. 2002, 2006; Mamani et al. 2010).

Volcanic rocks spanning 100 to 65 Ma in age are mainly porphyritic andesite, including the very large plagioclase phenocryst-bearing lavas known as 'ocoites' (Vergara et al. 1995), to dacite, with minor trachyte, trachyandesite, basaltic andesite, and scarce basalt. Only south of 33°S latitude, do basaltic andesite and basaltic lavas flows and tuff dominate Late Cretaceous volcanic deposits. Primary mineralogy consists of plagioclase, hornblende, pyroxene, titanomagnetite and minor quartz phenocrysts in an intersertal to trachytic groundmass. Pyroclastic rocks are also very common, and include dacitic to rhyolitic, vitric and crystalline tuff, commonly welded and forming ignimbrite deposits, in some cases with fluidal textures, as well as volcanic and epiclastic breccia and minor ashfall deposits. In spite of the more explosive volcanism that took place at this time, the units mostly crop out as homoclinal sequences with intercalations of lava flows and clastic beds. A few caldera-type deposits are known from the Late Cretaceous, such as the Condoriaco or Cerro el Indio dacitic dome and tuff deposits (Emparán and Pineda 1999). All these volcanic units are generally overlying or interbedded with red clastic continental sedimentary rocks of Lower to Upper Cretaceous age that would represent the first stages of foreland sediment accumulation in the Andean range (Charrier et al. 1996, 2007, 2015; Tunik et al. 2010; Aguirre-Urreta et al. 2011; Martínez et al. 2016; Fennell et al. 2017).

The plutonic activity of the Late Cretaceous is represented by numerous fine-grained to porphyritic stocks that range in composition from andesitic or microdioritic to rhyolitic, with a predominance of the more intermediate compositions that bear amphibole, biotite, pyroxene, plagioclase, quartz and titanomagnetite. Larger intrusions are usually medium- to fine-grained ranging from gabbro to syenogranite, with a predominance of monzodiorite to monzogranite. Mafic assemblages are hornblende–biotite, two pyroxenes or biotite; hornblende–pyroxene assemblages are also found but are less common. The Illapel Plutonic Complex is one of the largest units of this period; it is composed of four sub-units: mafic, trondhjemite, tonalite and granodiorite, reflecting a progressive differentiation of the magmatism (Morata et al. 2010; Ferrando et al. 2014). Along with the ca. 95 Ma Caleu pluton in central Chile, the Illapel Plutonic Complex records the transition from an extensional to a compressional tectonic regime and rapid cooling after emplacement (Parada et al. 2005; Ferrando et al. 2014).

Geochemically, the Late Cretaceous igneous rocks have intermediate to high SiO_2 contents of 53–70% (Fig. 2a), and major elements trends that reflect plagioclase, pyroxene, and amphibole fractionation during magma evolution. In terms of trace elements, there is a systematic enrichment of LILE over HFSE (Fig. 2c, d), indicative of slab-derived fluid-induced melting on the sub-arc mantle, whereas specific elements, such as La, Ba, Cs, Rb, Dy, Yb suggest a more significant contribution of crustal material to the magmatism, and amphibole control in the magma source, suggesting an incipient thicker crust above the arc (Haschke et al. 2006; Mamani et al. 2010) (Fig. 2e, f). This is also supported by the isotopic composition of the igneous rocks, which is more radiogenic in terms of initial $^{87}Sr/^{86}Sr$ and $^{208,207,206}Pb/^{204}Pb$ and less radiogenic for initial $^{143}Nd/^{144}Nd$ (εNd_i) (Fig. 3a, b). Thus, the original depleted mantle basaltic melts would have assimilated part of the continental crust. Magmatic affinities are largely medium- to high-K calc-alkaline, with minor low-K or tholeiitic trends (Fig. 2b).

North of 33°S the chemistry of plutonic and volcanic rocks ranging in age from ca. 100 to 65 Ma is interpreted to record products of continental arc-type magmatism under compression (see Parada et al. 2007 and references therein). Recently, Late Cretaceous volcanic units have been identified in the main Cordillera south of 33°S (at these latitudes, only plutonic rocks were recognized in the Chilean side of the Andes, in the Coastal Batholith) (Iannelli et al. 2017; Muñoz et al. 2018). These sequences are mainly composed of basalt and basaltic andesite with tholeiitic to transitional-OIB affinities. They have been interpreted as having been emplaced into an intra-arc basin, related to a sub-arc slab-window, with a dominant extensional tectonic regime at the time (Muñoz et al. 2018), suggesting that not only compressive stresses prevailed during the construction of the Late Cretaceous Andean arc.

PALEOCENE–EARLY/MIDDLE EOCENE ANDEAN MAGMATISM (65–45/40 Ma)

The evolution of the arc in this time frame is characterized by an extensional and transtensional tectonic setting, partly inherited from the previous Mesozoic stage, that ended with the 'Incaic Orogeny' (Charrier et al. 2007). Most of the volcanic and volcanoclastic units of this period unconformably cover the Lower Cretaceous sequences, suggesting that a likely compressive deformation event would have taken place during the Cretaceous to Paleogene transition. Such an event is called the 'K–T' or 'Incaic I' tectonic phase (Charrier et al. 2007). Between 21° and 27°S latitude, the Domeyko fault system (Fig. 1) is tightly related to the emplacement of the magmatic products of the Paleocene to Eocene arc (Fig. 4). South of 27°, the DFS and its relation to the magmatic units is not observed, likely due to the Miocene cover (Charrier et al. 2009).

The magmatic units of this stage are widely distributed from northern Chile (~18°S) to 35°S latitude, where outcrops are lost, and between 37° and 39°S latitude (Charrier et al. 2009). The volcanic products of this period are subalkaline basalt to rhyolite (Fig. 2a); these are mostly related to caldera-type deposits and pervasive hydrothermal alteration. Representative units cropping out at 18–30°S latitude are the Icanche, Chincado, Calama (lower member), Augusta Victoria, Chile-Alemania and Venado formations (García 1967; Chong 1973; Montaño 1976; Maksaev 1978; Sepúlveda and Naranjo 1982; Naranjo and Paskoff 1985). They are composed of andesitic lava flows and proximal pyroclastic deposits, bimodal sequences, high-K calc-alkaline rocks (Fig. 2b), and thick sequences of trachyandesitic to dacitic lava flows, that range in age from ca. 60 to 46 Ma (Marinovic et al. 1995; Blanco et al. 2003; Espinoza et al. 2012; Gardeweg and Sellés 2013). The sedimentary upper member of the Calama Formation hosts imbricated clasts that are interpreted as sediment accumulation due to tectonic reactivation of a meso-scale fault, such as the West Fault in the Chuquicamata mining district (Charrier et al. 2007). Consequently, these units are the precursors of the Eocene–Oligocene arc (Charrier et al. 2007). South of this latitude, the outcrops of Paleocene volcanic units decrease significantly, with the 63 Ma Estero Cenicero Formation the main volcanic sequence (Bergoeing 2016) (Fig. 1). Between 18° and 30°S latitude, the eruptive units are intruded by small stocks and sills of mainly felsic composition, such as the Columtucsa-Japu granitoid units (Gardeweg and Sellés 2013), the El Bosque and Loma Colorada monzogranite plutons (Emparán and Pineda 1999), the Cuarto Chinchillero diorite (Pineda and Emparán 2006) or the Encanto and Cuncumén plutons (Bergoeing 2016), with their ages ranging between 60 and 43 Ma. North of 26°S latitude, the small intrusive bodies of Paleocene and Eocene age are structurally controlled (Charrier et al. 2007, 2009 and references therein). Even though the outcrops of Paleocene–Eocene volcanic rocks decrease significantly south of 30°S, the plutonism was widespread and volumetrically important at these latitudes; the Cogoti Superunit of ca. 67–38 Ma is a good example of this (Parada et al. 1999) (Fig. 1).

Paleocene–Eocene magmatic units are distinctly medium- to high-K calc-alkaline, intermediate to felsic in composition (Fig. 2a, b) and characterized by low Sr/Y and La/Yb (Fig. 2g) that increase for younger sequences, suggesting a progressive deepening of the magmatic sources and consequently crustal thickening towards the Late Eocene (Charrier et al. 2007).

During the Early to Middle Eocene, the Incaic Orogeny (or 'Incaic II' tectonic phase) took place, likely inducing the formation of an 'Incaic Cordillera' (Charrier et al. 2009) some time between 50 and 30 Ma, as suggested by radiometric dating (ca. 38.5–44 Ma, Hammerschmidt et al. 1992; Tomlinson and Blanco 1997). Inversion of Cretaceous to Paleocene structures that controlled the emplacement of the previous arc led to significant crustal thickening (Charrier et al. 2007 and references therein). The uplift of the mountain chain implied high erosion rates and resulted in the accumulation of thick sedimentary sequences (Charrier et al. 2009). The conspicuous decrease of Paleocene–Eocene arc-related outcrops south of 30°S latitude may be due to higher exhumation and uplift during the Incaic Orogeny at these latitudes and increased erosion of the arc rocks. During this orogeny and related to the intrusion of small stocks and porphyries, important metallic ore mineralization developed, generating Cu–Mo porphyry deposits, such as Cerro Colorado, Spence and Lomas Bayas (Sillitoe and Perelló 2005; Mpodozis and Cornejo 2012 and references therein). This metallogenic belt is economically very significant in Peru (39 Mt Cu) but less so in Chile (12.7 Mt Cu) (Camus 2003).

MID EOCENE–EARLY MIOCENE ANDEAN MAGMATISM (45–22 Ma)

The tectonic, and consequently magmatic, evolution of the Andean arc after the Incaic Orogeny is significantly segmented along the Chilean margin. North of 27°S latitude the arc remained in the position of the former stage and a retro arc basin developed to the East (Charrier et al. 2007). Magmatic activity was channeled through trans-lithospheric discontinuities represented by the Domeyko Fault system (Charrier et al. 2009 and references therein) (Figs. 1 and 4). Large epizonal batholiths of granodioritic to granitic composition and shallower porphyry systems were the feeders of a magmatic hydrothermal flux that contributed to the accumulation of huge volumes of S and chalcophile base metals in the upper crust, generating some of the largest Cu–Mo porphyry-type deposits on Earth identified so far (Camus 2003), such as Chuquicamata (35–31 Ma, Charrier et al. 2009), Ministro Hales (35 Ma, Zentilli et al. 2018), El Abra (40 Ma, Ballard et al. 2001). A common feature of these magmatic units is their high Sr/Y (> 40) and La_N/Yb_N (> 40) which is known as the 'adakitic' signature and is thought to be related to either: a) melting of young and hot slabs during subduction (Defant and Drummond 1990); b) melting of newly underplated basaltic crust under a thick crust (Petford and Atherton 1996); c) eclogitization of a thickened lower crust (Kay and Mpodozis 2002); d) melting of the mafic crust tectonically eroded from the continental margin (Goss et al. 2013); e) fractionation from hydrous mafic magmas (garnet residue) at deep crustal levels and high-pressure melting of lower crust (Chiaradia et al. 2012; Rabbia et al. 2017); or f) hydrating of the oceanic slab in fracture zones (Reich et al. 2003), among other factors. These adakitic magmas are commonly associated with large porphyry copper and epithermal gold–copper deposits (Chiaradia et al. 2012), and if linked to garnet residues or eclogitization in the lower crust, they should be a direct result of the Incaic Orogeny.

These shallow intrusive complexes correspond to granodiorite and granite (and subvolcanic equivalents, dacite to rhyolite), with SiO_2 of 65–79 wt.%, and high alkali content. The alkaline affinities, however, may be the result of the intense hydrothermal alteration recorded in the plutonic and subvolcanic rocks (LOI > wt.%). The whole rock REE patterns indicate the absence of an Eu anomaly, suggesting hornblende fractionation in highly oxidized magmas and likely garnet was present during melting of the source (Zentilli et al. 2018) (Fig. 2e, f).

On the other hand, south of 28°S latitude a wide intra-arc extensional basin located east of the Incaic Cordillera, the Abanico basin, was developed (Fig. 4). The estimated dimensions of this basin are at least 1000 km, between present-day 28 and 39°S latitude (Charrier et al. 2005, 2007, 2009; Flynn et al. 2008), 70 km wide and 3 km in thickness, and with representative units the Abanico (Aguire 1960) and Cura Mallín formations (Niemeyer and Muñoz 1983).

The Abanico Formation is a 3100-m-thick sequence of mafic volcanic rocks and felsic pyroclastic and epiclastic deposits, interbedded with lacustrine sediments, and an upper section made of basaltic lava flows (Nyström et al. 2003). The geochemical signature of this unit is characterized by calc-alkaline to tholeiitic affinities (Fig. 2b), significant enrichment of LILE over HFSE, with distinct Nb–Ta depletions relative to primordial mantle, and light rare earth elements (LREE) enrichment with concave patterns for MREE and HREE (medium and heavy rare earth elements, respectively) (Nyström et al. 2003) (Fig. 2c–f). The isotopic composition of the volcanic units is rather uniform, with low (< 0.706) $^{87}Sr/^{86}Sri$ and εNd_i of between +5.6 and +5.8, suggesting a depleted mantle source for the magmas, with little contribution of continental crust (Nyström et al. 2003) (Fig. 3a, c). This agrees with the prevailing extensional tectonic conditions for the arc at these latitudes and time span (Nyström et al. 2003). Radiometric dating of volcanic rocks belonging to the Abanico Formation constrain an age for the magmatism between 31 (Vergara et al. 1999) and 25 Ma (Nyström et al. 2003), although younger episodes of volcanism have been reported (23 Ma, Muñoz et al. 2006). The Cura Mallín Formation is composed of andesitic, dacitic and rhyolitic volcanic rocks (Guapitrio member) and lacustrine and fluvial deposits (Río Pedregoso member) (Suárez and Emparán 1997). The geochronological (26.3–22.8 Ma) and stratigraphic relationship between the Abanico and Cura-Mallín formations suggests that both units represent a common tectonomagmatic setting (Jordan et al. 2001; Radic et al. 2002; Kay et al. 2006; Iannelli et al. 2017) of crustal extension and high heat flux that generated tholeiitic magmatism (Nystrom et al. 1993; Kay and Kurtz 1995; Charrier et al. 2002). Fuentes et al. (2004) and Muñoz et al. (2006) proposed a decline in the subduction component and an increase in the crustal contamination of the magmas to the east.

Even though the most representative sequences of the intra-arc basin are restricted to the Oligocene–Early Miocene period, the existence of older units in central Chile, located to the west of the Abanico Formation, with igneous rocks that can be related to magmatism in an extensional setting (e.g. the Cordón Los Ratones Beds, 33°S, Sellés and Gana 2001; Muñoz-Gómez et al. 2020) suggests that the initial stages of the basin may have started as early as 43 Ma, during the Mid Eocene.

MIOCENE ANDEAN MAGMATISM (22–5 Ma)

After the period of extension during the Oligocene and Early Miocene, an important regional tectonic event took place at ca. 22.7 Ma induced by the fragmentation of the Farallon Plate into the Nazca and Cocos plates (Barckhausen et al. 2001; Bello-González et al. 2018). The fragmentation resulted in a net increase of the plate convergence (Pardo-Casas and Molnar 1987; Somoza 1998; Bello-González et al. 2018) that triggered compression and the inversion of the crustal structures that previously accommodated the Abanico basin depocenters, as well as older Paleozoic discontinuities (Charrier et al. 2009) (Fig. 4). This period of increased plate convergence coincides with the Pehuenche Orogeny (Charrier et al. 2009), which took place between the end of the Oligocene and the beginning of the Miocene (Yrigoyen 1993) and represents the tectonic inversion in response to the change in convergence parameters (Ramos and Nullo 1993). The magmatic, tectonic and geomorphologic segmentation that characterized the development of the Andean margin north and south of 27°S latitude prior to the Late Miocene, persisted after 15 Ma and until the generation of the present-day flat slab segment at ca. 12–5 Ma (see below).

North of 27°S explosive felsic volcanism dominated the magmatic activity in the Western Cordillera, but the volcanic deposits covered the Pre-Cordillera and Altiplano domains into Bolivia and Argentina as well (Charrier et al. 2009). The enormous volume of silicic magmatism represented by ignimbrite deposits now exposed in these areas has been interpreted as a magmatic flare-up, probably linked to slab shallowing (de Silva 1989; Kay and Coira 2009). Representative units of this volcanism are the ignimbrites Oxaya, Lupica, Altos de Pica (Formation), Tambillo, Río Frío, Lauca , Collacagua, La Pacana, Toconao, Atana, Tucúraro, Patao, Cajón Tuyajto, Llano Las Vicuñas, Inés Chica, Los Cristales, San Andrés, Wheelwright, Laguna Verde, the San Bartolo Group (including ignimbrites Artola, Sifón, Yerba Buena, Pelón, Puripicar and Chaxas), and related shallow intrusive and subvolcanic units, whose ages range between the Early Miocene and Late Pliocene (Galli 1957; Galli and Dingman 1962; Montecinos 1963; García et al. 2004; Matthews et al. 2006; Matthews et al. 2010; Blanco et al. 2012; Clavero et al. 2012; Cornejo et al. 2013; García et al. 2013; Gardeweg and Sellés 2013; Henríquez et al. 2014). In general, these deposits are the result of pyroclastic flow or ash fall of dacitic to rhyolitic composition, generated in volcanic eruptions of Plinian type (Ramírez and Gardeweg 1982). Petrographically, the rocks correspond to vitric and crystalline ash tuff with high lithic content. Typical phenocrysts are plagioclase, quartz, biotite, and amphibole. They are geochemically rather uniform in composition, with SiO_2 content of 65–79% and calc-alkaline affinities (Kay and Coira 2009; Mamani et al. 2010) (Fig. 2a, b). Their Sr/Y, Sm/Yb and Dy/Yb ratios suggest that they derive from magmas generated and stored under a very thick crust with garnet in the source (Wörner et al. 2018) (Fig. 2e–g).

South of 27°S latitude, following the Pehuenche Orogeny, Andean magmatism developed above and slightly east of the inverted basin, and was characterized in the volcano-sedimentary sequences of the Farellones Formation (Klohn 1960) and related small and shallow intrusive bodies (Kurtz et al. 1997). Several isolated hills in the modern central depression basins (Santiago basin) are the remnant outcrops of these intrusions and volcanic rocks (Vergara et al. 2004). The age of the Farellones Formation is bracketed at between 22 and 17 Ma according to radiometric dating of plagioclase by the K/Ar and $^{40}Ar/^{39}Ar$ methods (Beccar et al. 1986; Aguirre et al. 2000). The formation is further subdivided into three members: the lower member comprises pyroclastic rocks and lacustrine deposits, the middle member is composed of basaltic-andesitic lava flows, and the upper member is composed of intermediate to felsic lava flows and domes (Nyström et al. 2003). The lower part of this unit is either concordant or slightly discordant to the Abanico Formation, suggesting only limited deformation exerted by the Pehuenche Orogeny at these latitudes (Nyström et al. 2003). The K_2O and Na_2O content of the volcanic rocks of the Farellones Formation are high enough to classify them as calc-alkaline in affinity and typically subduction-related (Nyström et al. 2003 and references therein) (Fig. 2a, b). The

La/Yb ratios are higher than those of the Abanico Formation, suggesting a deeper partial melting of the mantle source (Fig. 2e, f). REE patterns of the intermediate to acid rocks are subparallel, indicating that magmatic evolution likely occurred through fractional crystallization from primitive, or slightly hybridized, magmas (Nyström et al. 2003). In contrast, rhyolite units have distinct negative Eu anomalies and strongly concave-up REE patterns (Fig. 2f). This reflects the transitional geochemical and tectonic position of lower and middle members in contrast to the compressional regime for the upper member of the Farellones Formation. The isotopic composition of the Miocene igneous rocks is more variable than the Abanico magmas: εNd_i varies between +4.4 and +5.1 and Pb ratios are as follows: $^{206}Pb/^{204}Pb$ = 18.453–18.570, $^{207}Pb/^{204}Pb$ = 15.548–15.610 and $^{208}Pb/^{204}Pb_i$ = 38.262–38.478 (Fig. 3).

This period of the Andean magmatism terminated with the subduction of the Juan Fernández ridge, a process that started at ca. 12 Ma but was fully developed by the end of the Miocene, and which generated a tectonic segmentation that prevails until today, dividing the Chilean Andes into roughly three segments: 18°30’ to 27°S, 27°–33°S and 33°–55°S latitudes (Barazangi and Isacks 1976; Jordan et al. 1983; Isacks 1988; Gutscher 2002; Yáñez et al. 2002; Ramos et al. 2002). The ridge subduction would have induced the flattening of the subducting plate between 27° and 33°S (Yáñez et al. 2001; Kay and Mpodozis 2002), eastward migration of the magmatism and, later, its ultimate shut-off in this segment, and thick-skinned deformation in the Frontal Cordillera. The resulting deformation and uplift were contemporaneous to the formation of Cu–Mo porphyry deposits.

For comprehensive reviews on the modern (Pleistocene to Recent) Andean volcanism, the reader is referred to the works of Stern (2004), Wörner et al. (2018), de Silva and Kay (2018) and the literature cited within.

CONCLUDING REMARKS

The rock record for Andean magmatism since the Rhaetian–Hettangian until the end of the Miocene, is geographically widespread, comprising most of the Chilean territory between 18°30’ and 40°S latitudes (Fig. 1) and even down to 55°S. From the petrographic, stratigraphic, and geochemical characteristics of the igneous rocks that represent the evolving Andean arc it is possible to infer the following:

- Andean magmatism is of dominantly calc-alkaline affinity and includes sub-alkaline series where tonalite–granodiorite and andesite are the dominant lithologies. Exceptions are the Early Andean magmatism which is dominated by diorite/tonalite and basaltic-andesite lithologies, and the Miocene magmatism north of 27°S latitude, where the most abundant products are dacite/rhyolite and granite.
- Variations in the trace element and isotopic compositions of Andean igneous rocks through time and space mostly reflect distinct tectonic conditions for the magmatism, these being the main parameters controlling such variations as the angle of the subducting slab, the convergence rate and obliquity, and crustal thickness.
- The main magmatic source would have been the depleted sub-arc mantle, which assimilated variable amounts of Paleozoic crust through time.
- Tectonic segmentation of the arc may have occurred since the Cretaceous, but it is most evident from the Eocene onwards, where the magmatism north of 27°S latitude is significantly more silicic and evolved (related to increased contributions from Paleozoic crust and/or the lithosphere) than that emplaced south of 27°S latitude, which is dominated by more mafic lithologies and reflects a dominant depleted mantle source.

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For access to the Oliveros et al. (2020) Supplementary Material Table 1, Geochemical data for Andean rocks of Chile and adjacent territories, (SMT-1), please visit the GAC's open source GC Data Repository for the Igneous Rock Associations Series at: https://gac.ca/gc-data-repository/

SERIES

Classic Rock Tours 4.
Long Walks, Lost Documents and the Birthplace of Igneous Petrology: Exploring Glen Tilt, Perthshire, Scotland

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SUMMARY

The spectacular angular unconformity at Siccar Point is the most famous site associated with James Hutton (1726–1797), but it was not his only place of insight. In 1785, three years before he discovered Siccar Point, Hutton examined outcrops in the still-remote valley of Glen Tilt, in the Scottish Highlands. He documented contact relationships between Precambrian metasedimentary rocks and Paleozoic granite bodies, although he had no knowledge of their true ages. Near to the hunting lodge where he and his colleague John Clerk of Eldin stayed, veins of granite clearly cut through relict bedding in the stratified rocks and disrupt their layering, breaking apart individual strata and leaving fragments (xenoliths) surrounded by granite. Hutton correctly deduced that the granite must originally have been in a *'state of fusion'* and was forcefully injected into much older *'schistus'*. Such conclusions contravened prevailing ideas that granite bodies formed from aqueous solutions, and also refuted a wider philosophical view that granite and other crystalline rocks were the oldest and first-created parts of the Earth. Hutton's key outcrops in Glen Tilt are easy to visit, although they do require a long (but easy) roundtrip hike of some 25 km. These are certainly not the most spectacular intrusion breccias that I have ever seen, but they are very instructive, and were very influential, because they sparked a long, and at times acrimonious, debate about the origins of igneous rocks and especially granite. This controversy had many strange twists and turns. These include the disappearance of Hutton's original manuscript after his death, and its serendipitous rediscovery a century later, and the similar loss and rediscovery of exquisite drawings by John Clerk, almost two centuries after they were first penned. Among the lost drawings is an early example of detailed outcrop-scale mapping, which would become a key field-work technique.

Hutton's vision of granite as the product of hot, liquid material that moved upward in the Earth's crust (plutonism) eventually prevailed over the idea that crystalline rocks formed from a primordial ocean that once enveloped the Earth (neptunism), but this victory did not come easily or quickly. In another strange twist of history, new evidence from the Cape of Good Hope in South Africa eventually acted to further the plutonist cause. Glen Tilt has changed very little since the time of Hutton, but the observations that were made here, and the long debate that followed, brought fundamental changes in our understanding of the Earth. Although Siccar Point should remain the first entry on the bucket list of any prospective geopilgrim to Scotland, the long and beautiful valley of the River Tilt should also be a priority.

RÉSUMÉ

La spectaculaire discordance angulaire de Siccar Point est le site le plus célèbre associé à James Hutton (1726–1797), mais ce n'était pas le seul lieu qui l'ait inspiré. En 1785, trois ans avant de découvrir Siccar Point, Hutton a examiné des affleurements dans la vallée encore enclavée de Glen Tilt, dans les Highlands écossais. Il a documenté les contacts entre les roches métasédimentaires précambriennes et les corps granitiques du Paléozoïque, bien qu'il ne connût pas leur véritable âge. Près du pavillon de chasse où lui et son collègue John

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Clerk of Eldin ont séjourné, des veines de granit ont clairement percé le litage relique dans les roches stratifiées et perturbé leur superposition, brisant les strates individuelles et laissant des fragments (xénolithes) entourés de granit. Hutton a correctement déduit que le granit devait à l'origine être dans un « état de fusion » et qu'il avait été injecté de force dans des « schistes » beaucoup plus anciens. De telles conclusions contrevenaient aux idées dominantes selon lesquelles des corps granitiques se formaient à partir de solutions aqueuses et réfutaient également une vision philosophique plus large selon laquelle le granit et d'autres roches cristallines étaient les parties de la Terre les plus anciennes et les premières créées. Les principaux affleurements de Hutton à Glen Tilt sont faciles à visiter, bien qu'ils nécessitent une longue randonnée (mais facile) d'environ 25 km aller et retour. Ce ne sont certainement pas les brèches d'intrusion les plus spectaculaires que je n'ai jamais vues, mais elles sont très instructives et ont eu un rôle très influent, car elles ont déclenché un long débat, parfois acrimonieux, sur les origines des roches ignées et en particulier du granit. Cette controverse a eu de nombreux rebondissements étranges. Ceux-ci incluent la disparition du manuscrit original de Hutton après sa mort, et sa redécouverte fortuite un siècle plus tard, et la perte et la redécouverte similaires de dessins remarquables de John Clerk, près de deux siècles après qu'ils aient été esquissés. Parmi les dessins perdus, se trouve un premier exemple de cartographie détaillée à l'échelle des affleurements, qui deviendra une technique clé de travail sur le terrain.

La vision de Hutton du granit en tant que produit d'un matériau chaud et liquide qui s'est déplacé vers le haut dans la croûte terrestre (plutonisme) a finalement prévalu sur l'idée que des roches cristallines se sont formées à partir d'un océan primordial qui enveloppait autrefois la Terre (neptunisme), mais cette victoire n'est pas venue facilement ou rapidement. Dans une autre tournure étrange de l'histoire, de nouvelles preuves provenant du Cap de Bonne-Espérance en Afrique du Sud ont fini par faire avancer la cause plutoniste. Glen Tilt a très peu changé depuis l'époque de Hutton, mais les observations qui ont été faites ici, et le long débat qui a suivi, ont apporté des changements fondamentaux dans notre compréhension de la Terre. Bien que Siccar Point devrait rester en haut de la liste des lieux à visiter de tout visiteur potentiel lors d'un pèlerinage géologique en Écosse, la longue et belle vallée de la rivière Tilt devrait également être une priorité.

PROLOGUE

Scotland has no shortage of sites to interest geologically minded visitors, and Edinburgh is where modern geology was born through the work of James Hutton (1726–1797). The most famous Hutton locality is the unconformity at Siccar Point, described in many comprehensive accounts, and summarized in an earlier article from this series (Kerr 2018). Hutton also established some key principles in igneous petrology, which are equally relevant to our modern view of the dynamic Earth. In 1785, he examined river exposures in Glen Tilt, in the Perthshire Highlands, and proposed that granite formed in a "fused condition" and had forced its way through other (older) rock types. These linked concepts of intrusion and cross-cutting relationships are now central to field geology and petrology but contradicted the dogma of those times. Hutton's detailed descriptions of these key exposures did not appear in full until long after his death, but his initial suggestions sparked a long and at times acrimonious debate that endured for more than 50 years. Hutton was accompanied in the field by the famous artist John Clerk of Eldin, who captured Glen Tilt in drawings, watercolours and engravings, which include one of the earliest detailed geological maps. Hutton's text and Clerk's exquisite artwork were likely intended for the never-to-be completed third volume of Theory of the Earth, but both were lost for centuries. These lost documents form interesting stories in their own right, more fully recounted by Adams (1938), Bailey (1967) and Craig et al. (1978).

Glen Tilt may lack the fame of Siccar Point, and Hutton's key outcrops today bear not even a simple historical marker, but it is a place of insight, and is well worth visiting. It is easy to find, although you cannot drive there, and it requires a roundtrip hike of about 25 km. However, the hike is easy, and also leads into the Cairngorms National Park, so there is much to enjoy beyond local geology. The fastest mode of transport is with a mountain bike (these are allowed on the trail) and when I return, it will definitely be on two wheels rather than two legs. I have no doubt that the long downhill return run will be more fun than trudging back with sore feet.

This article was conceived following my own visit in 2019, but the bulk of the information comes from other sources (notably Craig et al. 1978; Stephenson 1999; Smith et al. 2011; Barron et al. 2011; Stephenson et al. 2013a, b), historical and biographical accounts (Geikie 1897; Bailey 1967; Dott 1967; Faul and Faul 1983; Pitcher 1993; Young 2003; Master 2009) and the words of Hutton and other early geologists (e.g. Hutton 1788, 1794; Playfair 1802; Seymour 1815; MacCulloch 1816). The article first summarizes key aspects of local geology and gives practical information to assist visitors, and then discusses Hutton's work and the ensuing debate in the wider context of 18th and 19th century natural science. Such knowledge is certainly not essential to hike in this lovely Highland glen, but I firmly believe that it can enrich such an experience.

GEOLOGICAL AND HISTORICAL BACKGROUND

Regional and Local Geology

Scotland is largely underlain by late Precambrian to Paleozoic rocks of the Caledonian Orogenic Belt (Fig. 1), and it was originally contiguous with parts of the Appalachian Orogenic Belt of eastern Canada. Central Scotland is dominated by the Midland Valley, underlain by Devonian and Carboniferous rocks, including coal measures. The northern boundary of the Midland Valley is the Highland Boundary Fault, north of which Precambrian to Paleozoic metamorphic and igneous rocks dominate the rugged landscape (Fig. 1). Large igneous intrusions are mostly of Silurian to Devonian age and are collectively termed 'Caledonian Granites'. These igneous massifs occupy most of the high country in the Cairngorms National Park, including Ben Macdui (1309 m), which is the second

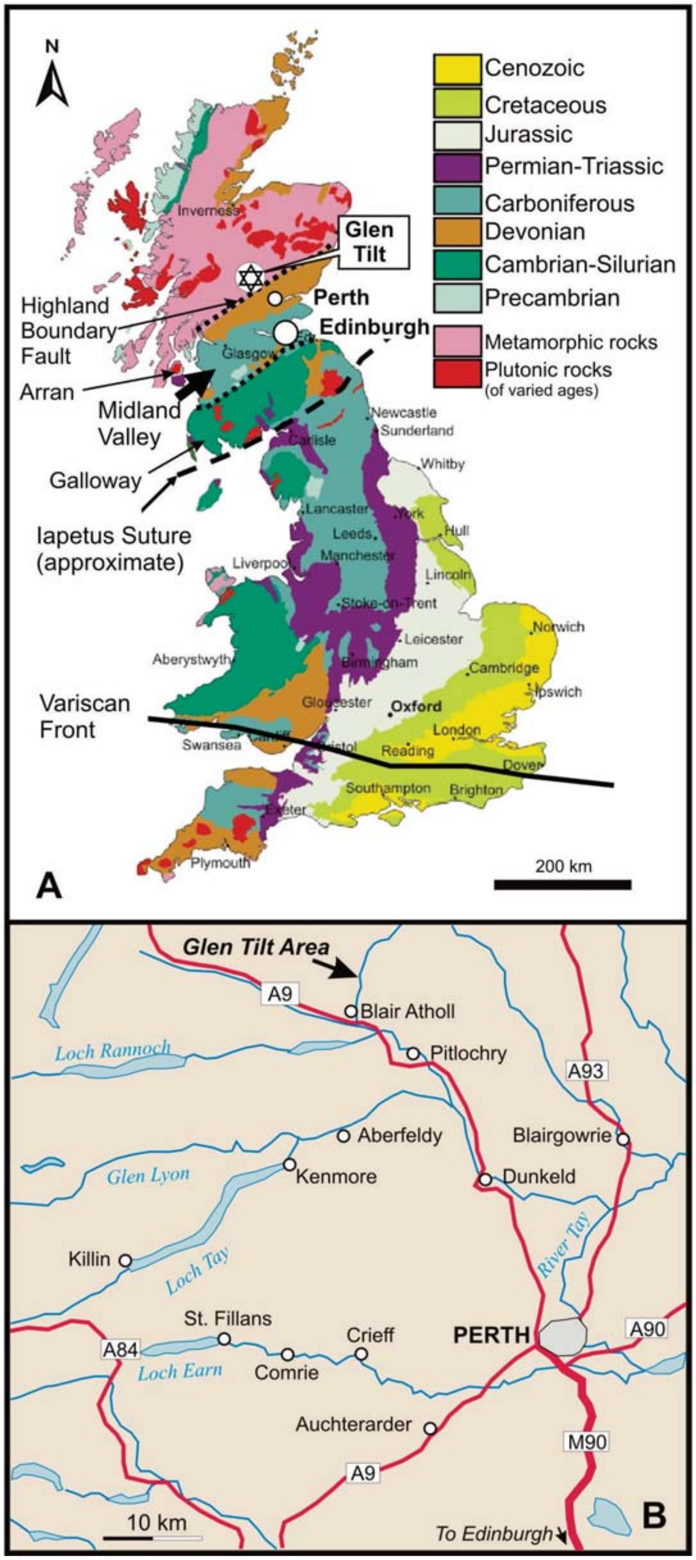


Figure 1. (A) Simplified bedrock geology of Great Britain as published online by the British Geological Survey, showing the locations of Edinburgh, Perth and Glen Tilt. (B). Locations and major roads in the area around Perth, Pitlochry, and Glen Tilt, showing the route to the area of interest.

highest peak in Scotland. The Glen Tilt area lies along the southern edge of the Glen Tilt Pluton (or 'complex'), which is mostly granite, with lesser diorite (Smith et al. 2011; Fig. 2). This igneous complex includes some of the youngest Paleozoic granitic rocks in the Scottish Highlands, dated at 390 ± 5 Ma (Oliver et al. 2008). The adjacent older country rocks mostly form part of the Dalradian Supergroup, comprising metasedimentary rocks that were deposited between late Precambrian and earliest Paleozoic times, and then deformed and metamorphosed during the Grampian Event of the Caledonian Orogeny, ~ 470 Ma ago (see review by Stephenson et al. 2013a). This event correlates broadly with the Taconic Orogeny as defined in the Appalachians, and metasedimentary rocks that likely correlate with the Dalradian occur in Newfoundland, Canada (van Staal et al. 2014). Studies of the Scottish Dalradian were influential in geology, defining mineralogical changes associated with regional metamorphism (Barrow 1893) and later ideas about thrust faults ('slides') and fold interference patterns (e.g. Ramsay 1967). In Glen Tilt, the contact between Paleozoic igneous rocks and the Dalradian Supergroup is in part defined by the Loch Tay Fault, which also controls the course of the upper river valley (Fig. 2). The fault displaced the area to its southeast downward relative to its northwest side, and also caused a sinistral displacement of several kilometres. Most, but not all, of the Paleozoic plutonic rocks lie on the northwestern (upthrown) side of the Loch Tay Fault (Smith et al. 2011; Fig. 2).

The complex stratigraphy of the Dalradian Supergroup records sedimentation from late Proterozoic to earliest Paleozoic times (Harris et al. 1994; Soper et al. 1999; Tanner and Sutherland 2007; Stephenson et al. 2013a, b). The rocks around Glen Tilt are the lower part of the sequence, including parts of the Grampian, Appin and Argyll groups (Smith et al. 2011; Fig. 2). These are mostly quartz-rich metasedimentary rocks (termed 'psammite'), accompanied by aluminous units (termed 'pelite') representing original impure sandstone and mudstone, respectively. Terms such as psammite or pelite were used widely over the years and are retained here for consistency, even though usage is less common today. Discontinuous units of marble and amphibolite represent original limestone and mafic flows or dykes, respectively. There have been many debates about details and changes to the stratigraphic nomenclature of the Dalradian over time; in the absence of fossil control, differences of opinion about the exact assignment of lithologically similar units are unavoidable. The regional map shown in Figure 2 is therefore not completely consistent with more detailed interpretations of areas within it, as illustrated by Smith et al. (2011). The Dalradian experienced several episodes of ductile deformation, during which early recumbent folds ('nappes') were refolded repeatedly. For those with a taste for more detail, and insight into long-lasting debates, the review papers of Stephenson et al. (2013a, b) are highly recommended.

The post-Ordovician history of the region was largely one of uplift and erosion, with detritus from the crystalline rocks transported and deposited within the adjacent Midland Valley. Brittle deformation along the trace of the Loch Tay Fault like-

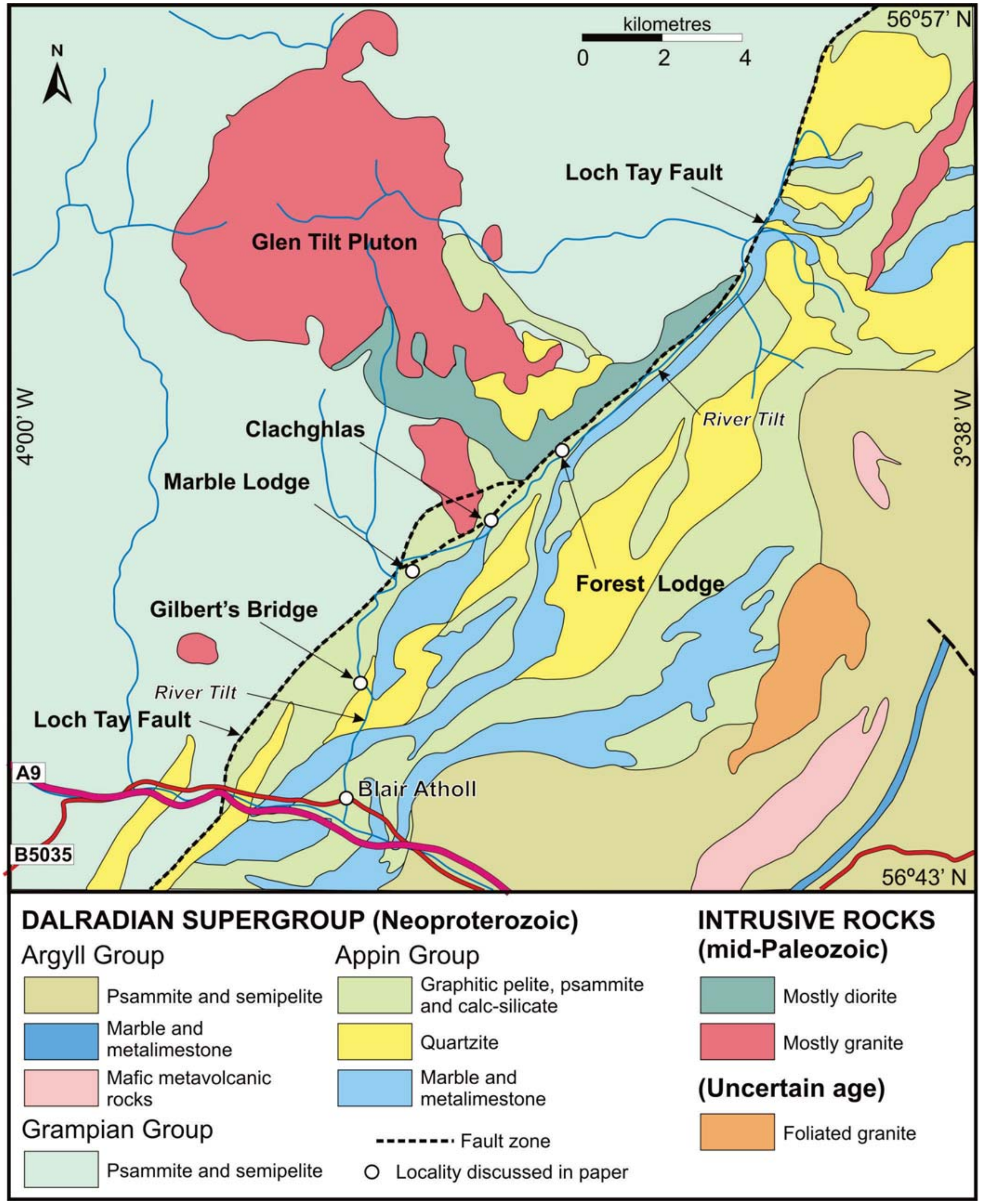


Figure 2. Simplified regional geology of the area around Blair Atholl and Glen Tilt, southern Scottish Highlands. Information compiled from the "Geology of Britain" website application provided by the British Geological Survey, and earlier published maps at 1:250,000 and 1:50,000 scales (British Geological Survey 1986, 2008). Note that due to scale differences, this map does not show detailed unit distributions discussed in the text. The site locations are approximate.

ly records this time period, although the structure may have an earlier history that partly overlaps the emplacement of Devonian igneous rocks (Smith et al. 2011). The Cairngorm Mountains are also well known for their glacial geomorphology and stratigraphy, discussed in detail by Smith et al. (2011) and Barron et al. (2011).

Neptunists and Plutonists: A Primer

In the 18th century, none of the above was known or even suspected, and the history of the Earth was viewed by most through the lens of the Bible, but early natural scientists speculated on the origins of various rock types and what they might tell us about Earthly processes. Modern analogues of sedimentary rocks could be seen in rivers and lakes or along seashores, so many thought that *all rock types* formed from some 'primeval ocean'. Abraham Werner (1749–1817), a mineralogist from Saxony (Germany) was the most famous of these *neptunists*, whose views prevailed for decades. Neptunists suggested that crystalline rocks were the very first to form from God's primeval ocean, much like salts precipitate from modern seawater. The stratified sedimentary rocks were then suggested to have formed by erosion and/or redissolution of such 'primitive' crystalline rocks, followed by redeposition. Such processes were generally assumed to have been catastrophic and were attributed to Noah's great flood. Thus, the neptunist view demanded that crystalline rocks be *older* than sedimentary rocks, even if the age difference between them was held to be thousands of years at most. After all, biblical scholars then decreed that the Earth itself had only existed for around six thousand years. Recent and modern volcanism presented problems for the neptunists, but these were seen as local phenomena, and volcanic heat was attributed to the local burning of underground coal seams (if it lacked a divine origin). Geologists had yet to make a connection between typically glassy modern lavas and ancient basalt or rhyolite units, which were considered to have 'aqueous' origins, because they commonly appeared to be stratified.

In 1785, James Hutton first proposed that geological processes were driven by heat from deep within the Earth, and he later pointed to the insolubility of quartz and feldspar, and their common intergrowth in granite, as evidence that granite had *"risen in a fused condition from subterranean regions"* (Hutton 1788, 1794). This idea carried no requirement that granite should always be *older* than sedimentary rocks, and he reasoned that it could be tested by observation. The initial expedition to Glen Tilt in 1785 was based on this premise, and Hutton became the first of the *plutonists*, who argued instead that igneous rocks formed directly from hot, molten liquids akin to modern lavas, rather than settling out of some mysterious primordial ocean. Such views were controversial, and provoked strong responses from the 18th century scientific establishment, which was heavily influenced by Werner and his fellow neptunists. For a wider discussion of the neptunist–plutonist controversy, which of course involved many more people than Werner and Hutton, readers are referred to the excellent book by Hallam (1983).

Geological Relationships near Forest Lodge, Glen Tilt

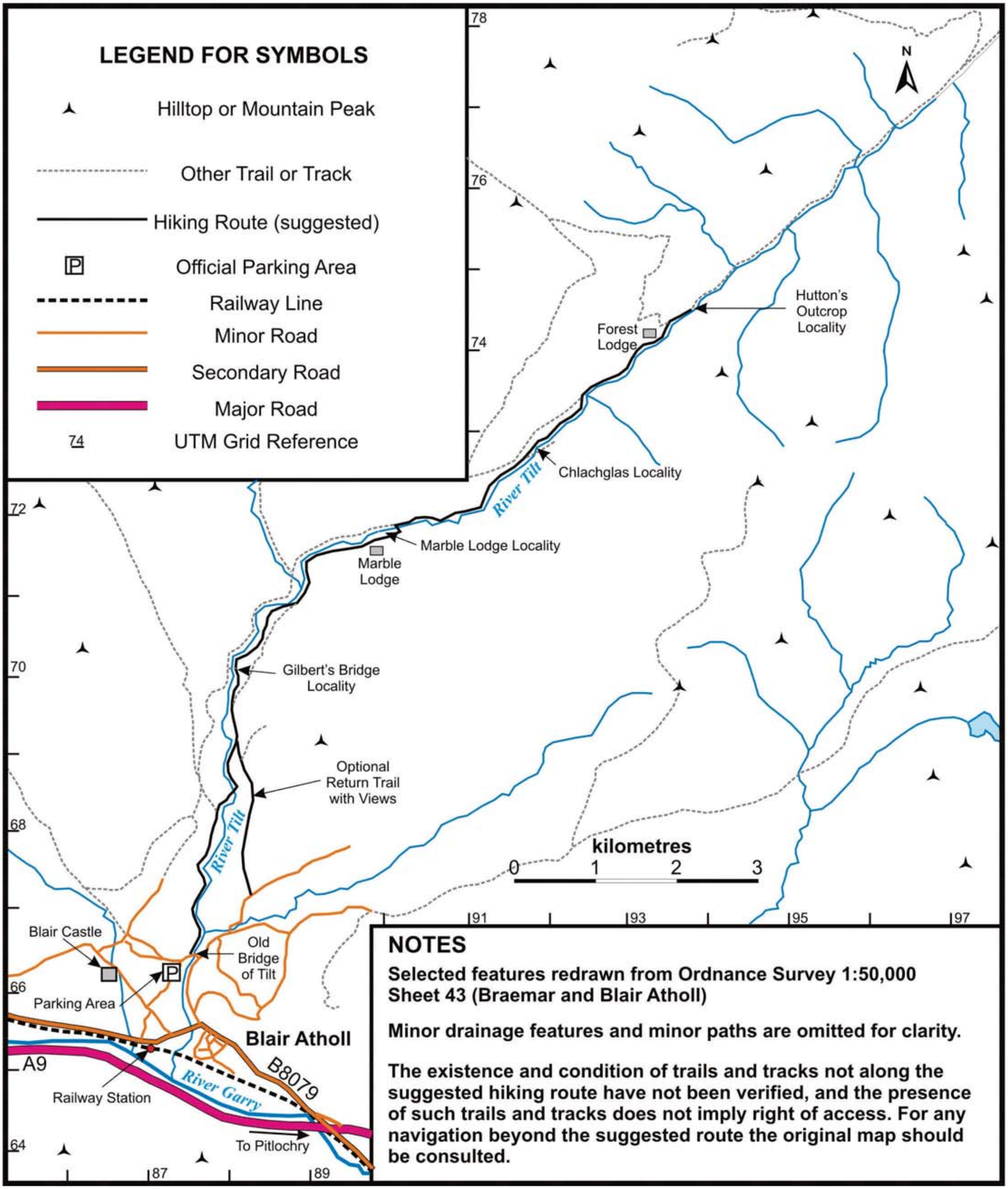
The exposures that Hutton first examined in 1785 from Glen Tilt would be familiar to most undergraduate students and many have probably visited similar sites. They are examples of 'intrusion breccia', in which older solid rock types (in this case, those of the Dalradian Supergroup) were broken apart and disrupted by liquid magmas of variable composition and state, probably in several discrete episodes. These exposures are chaotic and composite, dominated by metasedimentary rocks, but including many areas of granite, most commonly forming veins, sheets and diffuse irregular pods. Contacts between igneous and metasedimentary rocks demonstrate cross-cutting relationships, where primary layering (bedding) is truncated and disrupted by granite, proving that deposition and lithification of the original sediments long predated the arrival of the granite, which was emplaced as a viscous liquid. Recrystallization and new mineral growth in the older metasedimentary rocks demonstrates contact metamorphism, indicating that magmas were emplaced at high temperatures, and affected the older rocks in various ways. The actual concept of metamorphism did not exist in 1785, but Hutton recognized these physical changes, which he attributed to heating and 'softening'. This was another important insight from this locality.

Intrusion breccia outcrops are unusual but not exactly uncommon, and inferences about relative age based on such cross-cutting relationships would not generate any discussion today. I have seen plenty of exposures like these in my career, and many are more spectacular than those in Glen Tilt. But my comparison is irrelevant, as this idyllic spot on a Scottish river is where our *understanding and interpretation of such relationships first came*, and where the long conflict between plutonism and neptunism first began. In many respects, this is the birthplace of modern igneous petrology, so it has clear importance in the history of science and is rightly designated as a heritage site (e.g. Stephenson 1999). Although Siccar Point is rightly associated with our understanding of geological time, the intrusive relationships in Glen Tilt are an equally striking demonstration of its immensity.

EXPLORING THE GEOLOGY OF GLEN TILT

Directions, Local Geography and Local Access

Glen Tilt is a long, deeply incised valley in the southern Cairngorm Mountains (Figs. 2, 3) that is partly controlled by the trace of the Loch Tay Fault. The entrance to the glen is at Blair Atholl, located about 50 km from the city of Perth, northwest of Edinburgh (Fig. 1). The nearby town of Pitlochry, known as the "Gateway to the Highlands" contains abundant services for visitors. Blair Atholl is adjacent to the main trunk road between Perth and Inverness (A9), but along a parallel secondary road (B8079). There is a small railway station on the main line from Perth to Inverness, and the village is also served by long-distance buses, but such services are not frequent. The easiest way to visit the area is through use of a private vehicle. Coming from the southeast from Pitlochry into Blair Atholl on the B8079, turn right at the signpost for "The Old Bridge of



NOTES

Selected features redrawn from Ordnance Survey 1:50,000 Sheet 43 (Braemar and Blair Atholl)

Minor drainage features and minor paths are omitted for clarity.

The existence and condition of trails and tracks not along the suggested hiking route have not been verified, and the presence of such trails and tracks does not imply right of access. For any navigation beyond the suggested route the original map should be consulted.

Figure 3. Location map for the lower section of Glen Tilt, from Blair Atholl to Forest Lodge and beyond. Information compiled and simplified from Ordnance Survey 1:50,000 map sheet 43 (Braemar and Blair Atholl).

Tilt" and carefully negotiate the narrow single-track road, which crosses the river on an even narrower bridge, and leads to a parking area on the left. From the railway station, turn right (east) on the road through the village to find this side road. Parking was free in 2019, but space is limited, and it may be busy in the summer months.

From the parking area, walk back towards the old bridge, and pass through a gated entrance on the left labelled "Atholl Estates". This unsurfaced road on the west side of the river leads to the important exposures and all branch hiking routes (Fig. 3). Like many parts of the southern Highlands, this is part of a private estate, but the road and trails are open for public use, although not by motorized vehicles. At times, access is restricted due to deer-stalking activities and shooting; information on activities and access is available from *atholl-estates.co.uk*. In the summer months, a small information centre operates in conjunction with the Cairngorms National Park in Blair Atholl. The route described here follows the narrow gravel road to the Forest Lodge area, but uses a secondary hiking trail for part of the return to avoid repetition and facilitate some scenic views (Fig. 3); however, the road can be used for a slightly quicker return. Approximate distances are provided in the following descriptions, and the sites are located using latitude and longitude values from GPS. The Glen Tilt area lies entirely within Ordnance Survey Landranger sheet 43 (Braemar and Blair Atholl; 1:50,000 scale). A copy of this map is strongly recommended for hiking beyond the route described below.

Although the lands around Glen Tilt are largely privately owned, the area is subject to restrictions intended to protect the natural environment of the region (Cairngorms National Park Authority 2007). Visitors are required to respect these at all times, and the estate suggests consulting the Scottish Outdoor Access Code for guidance. The exposures are all located in or adjacent to the River Tilt, and ease of safe examination depends on the water levels. In times of high water levels it may be impossible to examine some or all exposures safely. In all conditions, you should avoid wet surfaces and the danger of falling into the river. The location at Forest Lodge, where Hutton made many of his observations, includes two waterfalls separated by deep cliff-bounded pools with strong currents, and a mistake here could be deadly even for strong swimmers. Locations at Gilbert's Bridge and Forest Lodge are designated as Sites of Special Scientific Interest (SSSI) and hammering exposures or collecting samples are prohibited. Take great care at all times!

Blair Atholl to Gilbert's Bridge

It is about 4 km from the trailhead to Gilbert's Bridge, and this walk will take close to one hour. There is little to see as the trail is mostly high above the river valley on a steep wooded hillside. After about 3 km, the trail descends to cross the River Tilt on a stone bridge and continues northeastward closer to the river. A small and nondescript exposure of folded metasedimentary rocks (location: 56.7947 N; 3.8330 W) is the only site of geological interest on this section.

Gilbert's Bridge

This is another graceful old stone bridge (location: 56.8004 N; 3.8340 W) but the main route up the glen remains on the southeast bank of the river beyond it. Gilbert's Bridge is designated as a Site of Special Scientific Importance (SSSI), because exposures in the river downstream from the bridge form part of a zone of strong deformation known as the *Boundary Slide*, long considered to be an important tectonic boundary in the eastern Highlands (see Fig. 2). The site was summarized by Barron et al. (2011) and was described in more detail by R.A. Smith in Stephenson et al. (2013b). The area downstream of the bridge is not easy to access safely if water levels are high (as they were in 2019), but flaggy, highly strained metasedimentary rocks (pelite), showing spectacular muscovite on many foliation surfaces, can readily be seen under the bridge and upstream, where they dip steeply to the east (Fig. 4).

For many years, the Boundary Slide was considered to be the boundary between the Dalradian Supergroup and an older, more enigmatic, package of Precambrian rocks termed the "Moine Series" or simply *"the Moine"*. However, all of the metasedimentary rocks in Glen Tilt are now placed in the Dalradian (Stephenson et al. 2013b), so the structure has lost some of its former prestige, but is still traceable over long distances. It is now considered to be a tectonic boundary between rocks of the Appin Group and the older Grampian Group (lowermost division of the Dalradian), which occurs mostly to the northwest of the Loch Tay Fault (Fig. 2). The boundary is defined by an increase in the intensity of penetrative deformation rather than by lithological contrasts, although the rocks exposed upstream from the bridge are generally more diverse in character than those below. For a more complete discussion of the Gilbert's Bridge locality, and the long and convoluted debate about the details of Dalradian stratigraphy and structure and the significance of the Boundary Slide, readers are referred to Stephenson et al. (2013b).

Marble Lodge and Vicinity

From Gilbert's Bridge the access road continues northeast for about 2.5 km, along the southeast bank of the River Tilt, leading to the cottages at Marble Lodge, in more open country with fine views of the Cairngorm Mountains (Fig. 5). Upstream of Marble Lodge is the site of a small quarry or quarries that once exploited marble and calc-silicate units within the Dalradian Supergroup. The rocks exposed between Gilbert's Bridge and this locality are now defined as a discrete stratigraphic unit within the Appin Group, termed the Glen Banvie Formation (formerly 'series'), and are more varied in character than those seen downstream from Gilbert's Bridge. Notably, they include marble, calcsilicate units and amphibolite, in addition to the metasedimentary rocks (psammite and pelite) that typify much of the sequence.

The marble units are best exposed in the southeast bank of the river, downstream and upstream of the bridge just beyond the lodge buildings (example location: 56.8246 N; 3.8040 W). Here, they are interlayered with strongly deformed dark grey-green amphibolite, which may represent metamorphosed and

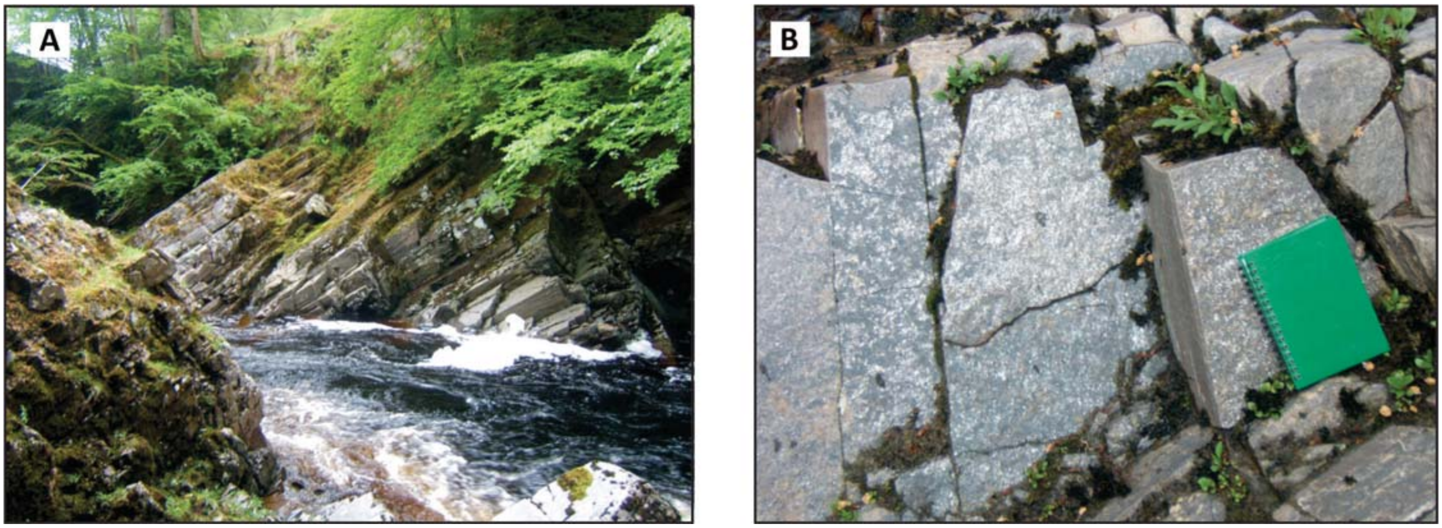


Figure 4. Outcrops at Gilbert's Bridge, en route to Forest Lodge. (A) gently dipping, flaggy quartz-rich metasedimentary rocks now assigned to the Dalradian Supergroup, although originally considered to be part of an older package of Precambrian metasedimentary rocks known as "the Moine". (B) Mica-rich foliation surfaces in metasedimentary rocks upstream from the bridge. Gilbert's Bridge is considered to be an important locality, but the key section downstream from the bridge is difficult to examine safely in times of high water levels.

transposed dykes (Fig. 5). Some amphibolite–marble contacts here appear to me to retain some local discordance, although this would likely be debated by any group of visiting geologists. The marble units contain distinctive dark green patches, elongated within the foliation (Fig. 5), that consist largely of antigorite (a serpentine mineral). The antigorite is believed to be a retrograde metamorphic mineral formed from higher grade diopside or forsterite in the marble (Stephenson et al. 2013b). Isoclinal folds are also visible in many parts of the marble outcrop (Fig. 5). The Glen Banvie Formation has a complex structural history and, due to its relative compositional diversity, the pelitic rocks provide important information about metamorphic conditions, notably through the local presence of kyanite (Stephenson et al. 2013b).

Clachghlas and Vicinity

Just beyond Marble Lodge, the road crosses another bridge to the northwest side of the River Tilt, and then continues for about 2 km to Clachghlas (location: 56.8335 N; 3.7550 W). This upper section of Glen Tilt is strikingly linear and is oriented almost exactly northeast–southwest, as it is controlled by the Loch Tay Fault, which is exposed here in the river. A wooden bridge with a gate provides access to the opposite (southeast) side of the river. The exposures in the river upstream from the bridge consist largely of fractured and brecciated pink to brick-red granite (Fig. 6), with screens of silicified metalimestone and massive quartzite of the Dalradian Supergroup. The fault plane is marked by a waterfall directly underneath the bridge and downstream in the southeast bank are intermittent exposures of metasedimentary rocks (pelite) and metalimestone. The term 'metalimestone' is used for carbonate-rich units in this area because most lack the coherency and texture of true marble (D. Stephenson, pers. comm. 2020). From Clachghlas to the exposures described by Hutton around Forest Lodge, the local geology is dominated by granite and diorite, rather than by metasedimentary rocks, at least on the northwest side of the river.

Forest Lodge and Vicinity

From Clachghlas, it is about 3 km to Forest Lodge, where James Hutton stayed during his field work. The lodge is a large building that enjoys a spectacular setting in this narrow section of Glen Tilt, and it looks very much the same today as in a drawing completed by John Clerk in 1785 (included in Craig et al. 1978). Beyond the lodge, the gravel road becomes a narrower track, passing through a gate. There is then another gate after several hundred metres, beyond which the upper waterfalls and river exposures are easily visible. The location for the main site (designated as a site or special scientific interest or SSSI) is 56.8512 N; 3.7422 W. There are smaller river exposures visible all along the route from Clachghlas Bridge; those on the northwest side of the river are mostly granitic, but strongly affected by proximity to the Loch Tay Fault; folded metasedimentary rocks of the Dalradian Supergroup can be seen locally on the opposite bank. The key area for examination at Forest Lodge lies between the upper waterfalls, which include a prominent rocky island in the middle of the river, and the ruins of a bridge. Interesting exposures also occur downstream from the bridge ruins but are harder to access if water levels are high. The most detailed description is by Stephenson (1999) who also provided a detailed map of the contact region (simplified as Figure 7). The key exposures are part of the contact zone between the Glen Tilt Pluton, which forms the mountains to the northwest, and the quartzite, psammite and metalimestone of the Dalradian Supergroup. In most locations, this regional contact is marked by the Loch Tay Fault Zone, and the River Tilt lies almost exactly along the line of the fault, but this small area lies northwest of the brecciated fault zone, so the original relationships are better preserved. Important features of these exposures are highlighted in Figure 8.

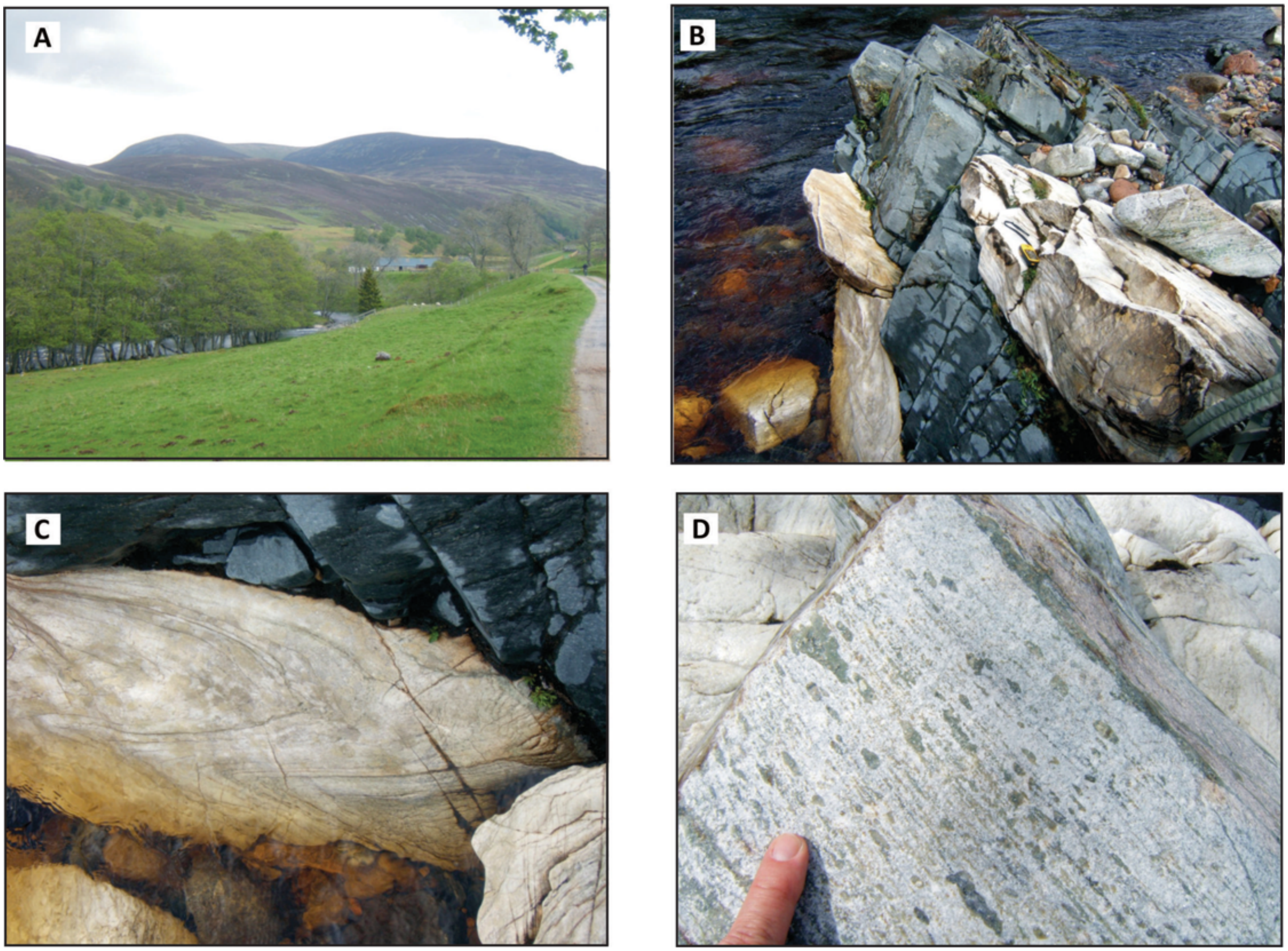


Figure 5. The Marble Lodge area, about halfway to Forest Lodge. (A) View upstream of the river valley, south of Marble Lodge, with the Cairngorm Mountains in the background. (B). White to pale beige marble exposed in the riverbank, in contact with dark grey massive amphibolite, possibly representing originally intrusive mafic dykes. (C) Tight folds defined by relict lamination (?) in the white marble. (D) Detail of marble containing dark green patches of serpentine minerals (antigorite) interpreted to have been derived by retrogression of metamorphic forsterite and/or diopside (R.A. Smith in Stephenson et al. 2013b).

The upper waterfall and its prominent rocky island consist largely of metasedimentary rocks, which strike across the river and dip steeply to the southwest. These include a grey metalimestone unit, and an overlying unit of more pelitic composition. The carbonate-rich units show distinctive recessive weathering and locally preserve tight to isoclinal folds, like those seen at Marble Lodge. Brown garnet is locally prominent, notably at the contacts between carbonate-rich and quartz-rich metasedimentary rocks, and probably indicates contact metamorphism and metasomatism (Stephenson 1999). This part of the outcrop also contains numerous thin granite veins, but many are subparallel to the strong fabric in the metasedimentary rocks, so they are not obvious at first sight. However, closer examination reveals that granite veins cut across the compositional layering (relict bedding) of the country rocks. In the area of the ruined bridge, and further downstream near the lower waterfall, granitic material forms many more extensive pod-like zones, separated by grey metasedimentary rocks that are pervasively dissected by thinner veins. These relatively homogeneous zones of pink granite also contain numerous inclusions and xenoliths of metasedimentary rocks (pelite and psammite, and also of marble). In some areas later thin granitic veins cut through xenoliths or earlier granite veins, attesting to the multistage nature of intrusive brecciation. More detailed descriptions (Stephenson 1999) also referred to dioritic rocks that are locally in contact with metasedimentary rocks, but these are not as obvious as pink granite, and the diorite–granite contact relationships were reported as equivocal in terms of age relationships (Beddoe-Stephens 1999; Smith et al. 2011). Dioritic rocks were reported to not contain the diverse xenolith populations typical of the granitic hosts, suggesting that they might be younger, and perhaps postdate initial brecciation caused by granite intrusion (Stephenson 1999). In summary, these exposures contain

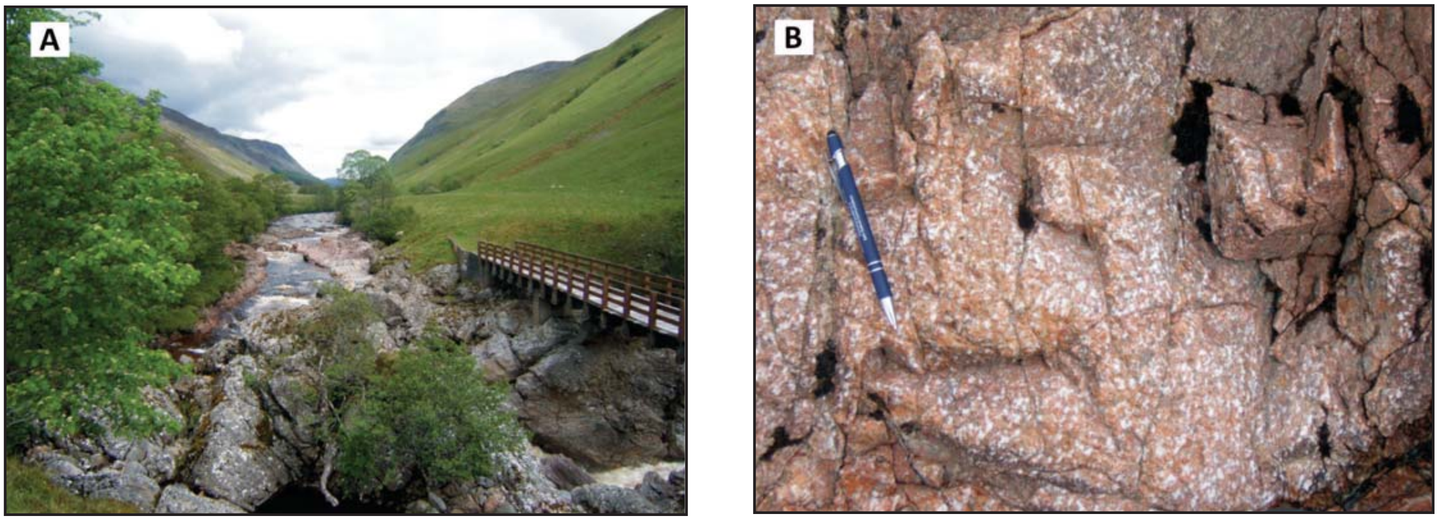


Figure 6. The Clachghlas area, en route to Forest Lodge area. (A) View northeastwards along Glen Tilt, which is here defined by the trace of the Loch Tay Fault; the area to the left is dominated by intrusive rocks, and the area to the right is mostly Dalradian Supergroup. (B) Relatively well-preserved granite exposed in the riverbed, containing prominent white quartz crystals; most of these exposures exhibit tectonic brecciation due to late fault movements.

many excellent examples of intrusive relationships, at a wide variety of scales from centimetres to tens of metres (Fig. 8).

The northwest bank of the river is easy to access as it is adjacent to the trail. It may not be possible to safely cross the river in any location here if water levels are high, as they were in 2019. However, features similar to those noted above can be readily seen on the opposite bank, looking across the water, and several larger zones of pink granite are evident. Descriptions by Stephenson (1999) and Smith et al. (2011) indicate that deformational effects related to the Loch Tay Fault are displayed well on the southeast side of the river. The granite is affected by fault-related deformation and brecciation, but earlier movements on the fault were likely synchronous with the emplacement of some granite (Oliver et al. 2008; Smith et al. 2011). To examine these areas directly might require returning to Clachghlas and then walking back upstream on the southeast bank, which adds significantly to an already long hike. The Dail-an-Eas bridge (meaning "Field of the Waterfall"), located below the falls, unfortunately collapsed in the 1970s. Its presence undoubtedly made field work far more convenient for Hutton and his colleagues, as did the comforts of nearby Forest Lodge!

Return Hiking Options and Other Diversions

To return from Forest Lodge, hikers must unavoidably retrace much of the hike described above, as the valley is narrow and steep-sided. About 1 km southwest from Marble Lodge, a side hiking trail leads up the hillside and continues southward at higher elevations for around 4 km to eventually join a road that leads back downhill to the Old Bridge of Tilt and the parking area. This diversion provides some superb views towards the Cairngorm mountains in the northwest and is a welcome break from the gravelled surface of the access route. In the village of Blair Atholl, the Atholl Arms Hotel is the most obvious choice for the refreshment that such a long walk clearly demands. The entire hike requires at least 9 hours, allowing time for examining the exposures and a suitably timed lunch break. The best-known visitor attraction at Blair Atholl is the magnificent Blair Castle (Fig. 3), the seat of the Duke of Atholl, which is open to visitors for much of the year. It may seem familiar, perhaps because it has been used as a location for many historical dramas and films. The castle and grounds can easily occupy much of a day, so a visit cannot easily be combined with a hike into the glen. It might better be reserved for a second more leisurely day, following good food and an overnight stay.

GLEN TILT, GENESIS AND GRANITE: THE LONG DISCOURSE

The peaceful nature of Glen Tilt, little changed since the time of Hutton, belies the long and fierce debate that his observations here initiated. The exposures in the river allowed him but one interpretation, i.e. granite is *younger* than the adjoining rocks and had forcefully invaded them in a liquid state. At least here, granite could not represent the 'primitive' material of the Earth. Hutton's view opposed prevailing scientific dogma, and indirectly opposed theology, so such implications were strongly resisted. It would take another half century and two more generations of geologists to make plutonism a core principle of geology, but at least in part this may have been Hutton's responsibility. A few scraps of supporting evidence were published in his lifetime, but the complete account only appeared after the serendipitous rediscovery of the lost manuscript for the third volume of *Theory of the Earth* at the end of the 19th century. In the early 1800s, adherents of the neptunist doctrine mounted strong defences against this plutonist heresy. To make things worse, the centre for the neptunist world view had by then shifted from Werner's Germany to Scotland, and some of its most vociferous advocates were influential Edinburgh intellectuals, such as John Walker and Robert Jameson (see below).

Most field geologists place more faith in observation than on theory, and the largely philosophical neptunist concept

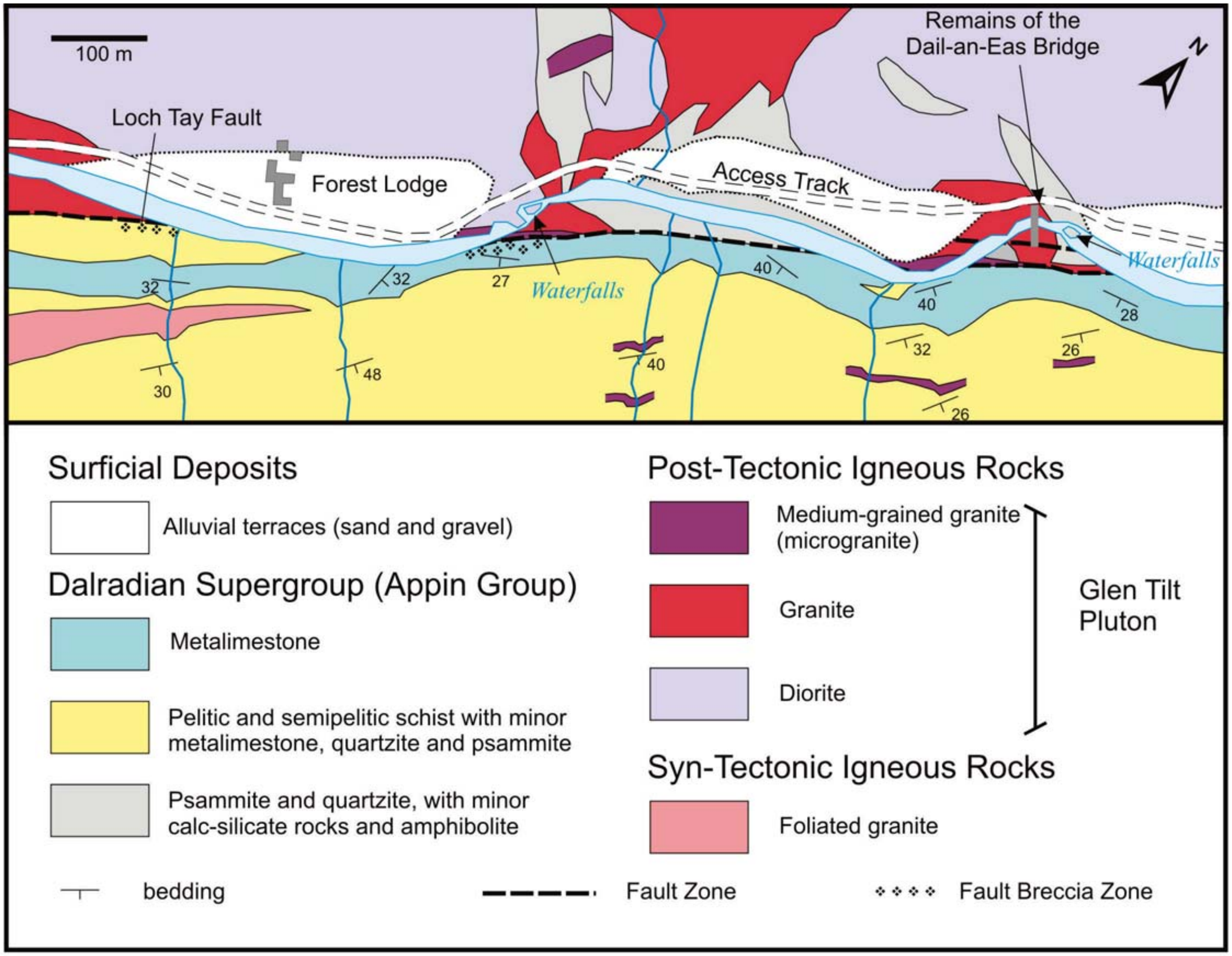


Figure 7. Local geology in the valley of the River Tilt around Forest Lodge, where Hutton completed his early work. This map is simplified from Stephenson (1999), who described the relationships and rock types in this area as part of the Geological Conservation Review. Aspects of site geology were also discussed by Smith et al. (2011).

slowly lost many of its champions. By the middle of the 19th century the concept of hot liquid magmas ('subterranean lavas', as they were initially called) that penetrate upward through the Earth's crust had largely prevailed. A wider debate about how magmas formed, and indeed whether *all* granite had such origins, would later begin, but another full century would pass before global plate tectonics provided our modern context for magmatic processes. This is another long story, told well by Davis Young's excellent book *Mind over Magma* (Young 2003). In this article, I summarize only some of the earliest steps on the long road that began in Glen Tilt and eventually led us to more-or-less unified theories of magmatism.

The Glen Tilt Expedition of 1785 and Other Early Investigations of Granite

The *Theory of the Earth* is renowned for many things, but not for its clarity of writing. Hutton's good friend and first biographer, John Playfair (1748–1819) is rightly credited with bringing his ideas to others, through his *Illustrations of the Huttonian Theory of the Earth* (Playfair 1802; hereafter, simply *The Illustrations*). Hutton first went to Glen Tilt in 1785, the same year that his ideas were first presented to the Royal Society of Edinburgh in abbreviated form (Hutton 1785), but there is little mention of granite in the earliest writings. Nevertheless, his references to internal heat driving a dynamic Earth, and the implication that some rocks might originate in a 'fused' condition did not escape the notice of his nemesis, the Irish scientist Richard Kirwan (1733–1812), who attacked him on several points (see Kirwan 1793). In response, Hutton read a short paper on granite to the Society in 1790, but four years elapsed before its publication (Hutton 1794). By the standards of Huttonian prose, it is unusually lucid, and it illustrates his evolving thoughts, albeit with scanty observational details.

Hutton (1794) initially confessed that

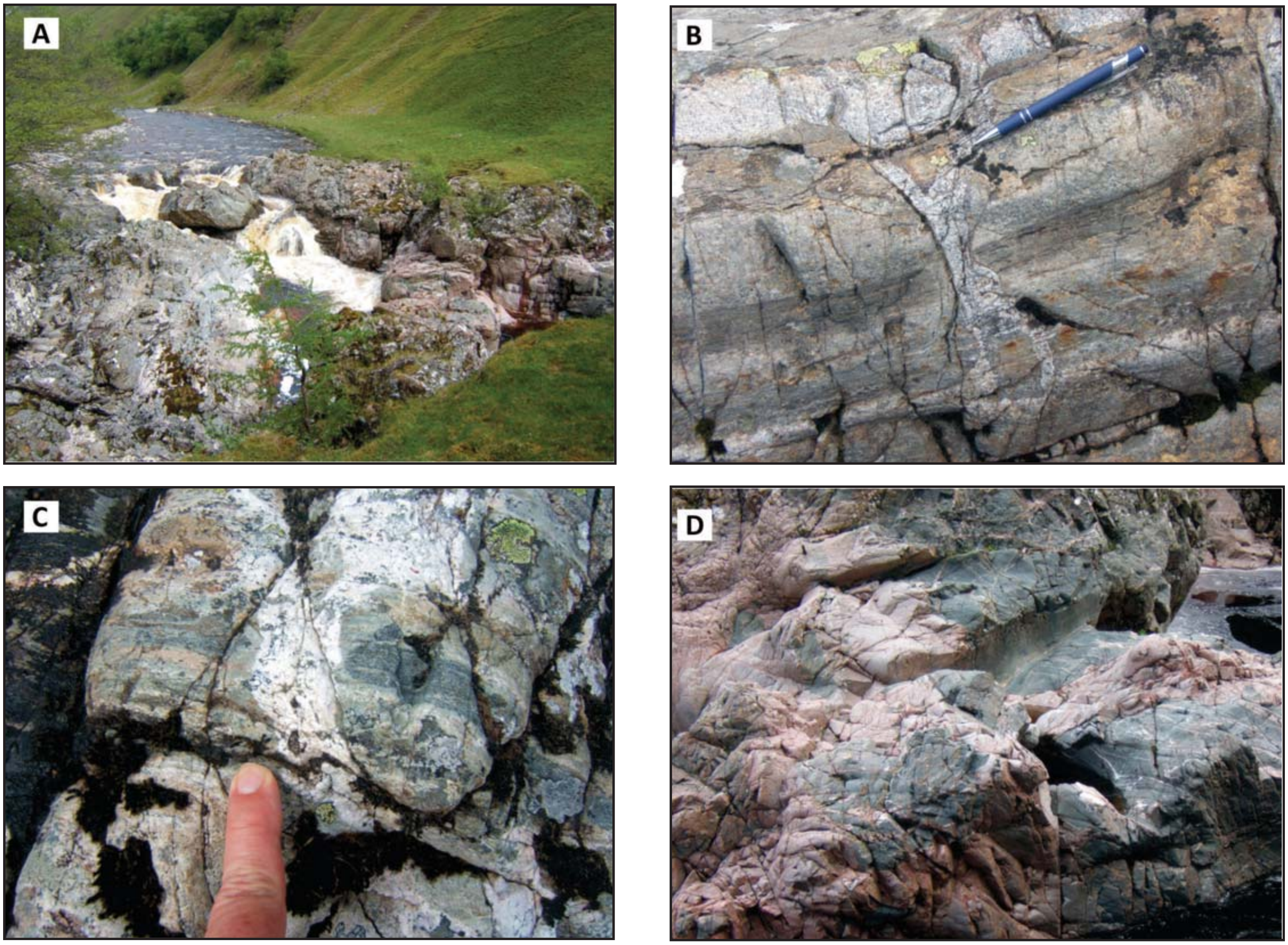


Figure 8. (Panel 1). Exposures in the area near Forest Lodge, where James Hutton made his key observations about the nature and origin of granite. (A) A general view of the key exposure at the upper waterfall, just above the ruins of the Dail-an-Eas bridge. The grey rocks at left and on the prominent rocky island are metasedimentary rocks of the Dalradian Supergroup, intersected by veins of white and pink granite; the area to the right is a chaotic mixture of pink granite and older country rocks (grey) forming an intrusion breccia. (B) Detailed view of bedded quartz-rich (psammitic) metasedimentary rocks with both concordant and discordant white granite veins. (C) Detailed view of granite vein cutting compositional layering (relict bedding) in the metasedimentary rocks. (D) Intrusion breccia near the ruined bridge, consisting of older country rocks (grey) and younger granite (pink) forming veins and irregular masses.

> *"...at that time, however, I was not perfectly decided in my opinion concerning granite; whether it was to be considered as a body which had been originally stratified by the collection of its different materials, and afterwards consolidated by the fusion of those materials, or whether it were not rather a body transfused from the subterraneous regions, and made to break and invade the strata, in the manner of our whinstone or trapp, and of the porphyries, into which the whinstone often graduates."*

Hutton then described his visit to Glen Tilt in 1785, and later visits to Galloway in southwestern Scotland in 1786, and to the island of Arran in 1787, where he observed several other contacts between granite plutons and adjacent rocks. His interest was in examining contacts to determine if *"...the granite that is found in masses has been made to flow in the bowels of the Earth."*, and he stated that this question could only be resolved by *"...the examination of that species of granite upon the spot, or where it is to be found in immediate connection with those bodies that are evidently stratified; bodies, consequently, whose natural history we have some means of tracing."*

He was seeking key contact relationships, as do all makers of geological maps, in order to clarify age relationships between stratified rocks and granite units. This use of cross-cutting relationships in determining the timing of events was a very important deductive step, every bit as fundamental as Nicolas Steno's principle of superposition. Hutton already knew that granite was abundant north of Blair Castle (the seat of the Duke of Atholl, who owned the hunting lodges in Glen Tilt) but that *schistus* (a general term then in use for low- to medium-grade metamorphic rocks) dominated most areas to the south. He concluded that by ascending the River Tilt or some of its branches he must meet eventually encounter the

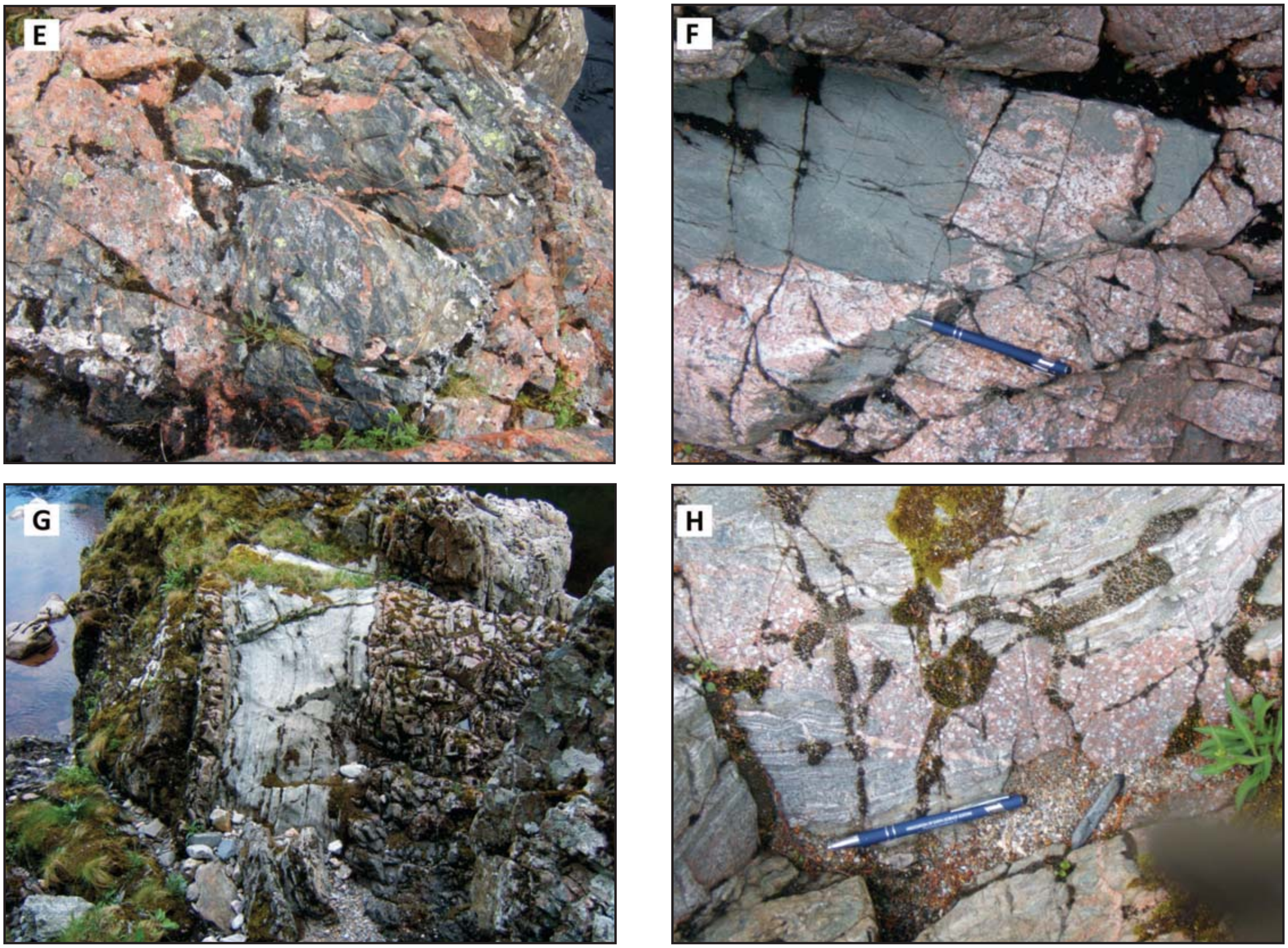


Figure 8. (Panel 2). Exposures in the area near Forest Lodge, where James Hutton made his key observations about the nature and origin of granite. (E) complex intrusion breccia showing numerous thin veins of pink granite cutting metasedimentary rocks and numerous xenoliths within more continuous areas of granite. (F) Detailed view of granite veins and xenoliths in a clean section of this exposure. (G) Pink granite veins emplaced within white calc-silicate unit in a broadly concordant fashion, although discordant in detail. (H) Discordant pink granite vein cutting through banded metasedimentary rock and bedding-parallel quartz segregations, but itself cut by a later fine-grained aplite vein just above the pen.

junction between schistus and granite. So, Hutton and his artist colleague John Clerk of Eldin arranged to visit the Duke of Atholl (who was well known to Clerk), and they stayed at Forest Lodge as his guests. This proved to be fortuitous, as the key location was only ten minutes on foot from residential comfort, and a very convenient bridge allowed them to explore both sides of the river without even getting their feet wet. Reportedly, it was from this bridge that Hutton first noticed the distinctive exposures of intrusion breccia, and its viewpoint must have aided Clerk greatly in his depiction of their features. In Hutton's own words:

> *"Little did we imagine that we should be so fortunate as to meet with the object of our search almost upon the very spot where the Duke's hunting-seat is situate, and where we were entertained with the utmost hospitality and elegance.........I had here every satisfaction that it was possible to define, having found the most perfect evidence, that the granite had been made to break the alpine strata, and invade that country in a fluid state."*

Hutton (1794) continued with some descriptions of similar relationships observed in coastal outcrops in Galloway, and then alluded to his field observations on the island of Arran, although he provided no actual details of the latter. The conclusion of the paper included a clear summary statement:

> *"GRANITE, which has been hitherto considered by naturalists as being the original or primitive part of the Earth, is now found to be posterior [i.e. later] to the Alpine schistus; which schistus, being stratified, is not itself original; though it may be considered, perhaps, as primary, in relation to other strata, which are evidently of a later date."*

In addition to its statement on the origins of granite, this sentence also encapsulates Hutton's thinking on the repeated cyclic nature of geological processes, and the implications for the vast age of the Earth. The final sentence of the short 1794 paper asks that his contribution be *"....considered merely as a notice given of certain new facts and observations, which I mean fully to describe and explain hereafter"*. Unfortunately, this did not happen, as he died in Edinburgh just three years later.

At the time of his death, the full account of Hutton's work at Glen Tilt, Galloway, and Arran existed only in a manuscript for the planned third volume of *Theory of the Earth*. It would not actually appear in print until 1899, largely through the efforts of Sir Archibald Geikie (1835–1924), director general of the Geological Survey of Great Britain. Hutton's lost manuscript apparently first passed into the hands of John Playfair, who for some reason did not push it through to publication, and it eventually came to rest in a cupboard at the Geological Society premises in London, where it was accidentally discovered by the Canadian geologist Frank D. Adams (1859–1942). Adams brought it to the attention of Geikie, who had been looking for it in other locations for many years. Amazingly, Hutton's lost manuscript was sitting next to the Society's treasured original copies of Volumes 1 and 2 of *Theory of the Earth*. Bailey (1967) provides an interesting account of the manuscript's long odyssey and its eventual publication at the end of the 19th century (as Hutton 1899) and tellingly comments that *"It is a great pity that Chapters IV, V and IX, dealing with Glen Tilt, Galloway and Arran, were not published in Hutton's lifetime, or as soon as possible after his death. They show Hutton at his best, and could scarcely have failed to accelerate the advance of geology."*

Bailey (1967) also provides a good summary of the main observations and points that Hutton made through his work in these areas, and he provides some memorable quotes. One phrase in particular has been quoted in many other accounts (e.g. Stephenson 1999) but it still bears repetition:

> *"...the granite is now found breaking and displacing the strata in every conceivable manner, including the fragments of the broken strata, and interjected in every possible direction among the strata which appear. This is to be seen, not in one place only of the valley, but in many places, where the rocks appear, or where the river has laid bare the strata."*

It appears that Hutton also travelled widely, and with some effort, into the rugged and remote hill country around Glen Tilt, trying to understand the wider relationship between the massive granite and the *schistus*:

> *"Having, therefore, with some difficulty, mounted the precipitous bed of a rivulet that comes from this long ridge of mountain, and which is fit for no other than the footsteps of a goat, we were rewarded with a view of the strata of the hill, being a perpendicular section across this ridge of mountain, the nucleous (sic) of which, or the internal strata, were the object of our search.....Immediately after which we found the granite under the alpine schistus"*

It is difficult to establish the exact location of this panorama, but I would very much like to find it on some subsequent visit.

John Playfair did not participate in the 1785 expedition, but he would later visit the area with Sir James Hall (1761–1832), the founder of experimental petrology, who would also play a key role in later debates (see below). Nevertheless, Playfair (1802) provided an account of Hutton's Glen Tilt antics in *The Illustrations*, based apparently on information from John Clerk of Eldin, which showcases both Playfair's skilful and amusing writing, and aspects of Hutton's character that many modern geologists can probably identify with:

> *"....when they reached Forest Lodge, about seven miles up the valley, Dr. Hutton already found himself in the midst of the objects which he wished to examine. In the bed of the river many veins of red granite (no less, indeed than six large veins in the course of a mile) were seen traversing the black micaceous schists, and producing by the contrast of colour, an effect that might be striking even to an unskilful observer. The sight of objects which verified at once many important conclusions in his system, filled him with delight; and as his feelings, on such occasions, were always strongly expressed, the guides who accompanied him, were convinced that it must be nothing less than the discovery of a vein of silver or gold, that would call forth such strong marks of joy and exultation."*

Not surprisingly, this snippet of text has also found its way into other accounts of Hutton's contributions. Although there was apparently no testimony from Clerk on such matters, I think it very likely that there was a lively celebration in the warm and presumably well-fed comfort of Forest Lodge following that particular day of field work.

Lost Drawings, Lost Maps and Lost Samples

Hutton's manuscript was not the only item that vanished for centuries after his death. A folio of drawings, paintings and engravings by John Clerk of Eldin languished for years in the family archives, only coming to light in 1968 after the death of one of his distant descendants. These were later published with notes about the field expeditions and those involved in them (Craig et al. 1978). Many of these beautiful illustrations are related to Glen Tilt. Craig et al. (1978) is not easy to locate but some of these images can be viewed at *www.clerkofeldin.com*, where high-resolution colour reproductions can be purchased; notes from a lecture about Clerk's wider work and its significance (Bertram 2012) are also available there.

The most striking image appears to be a geological map of part of the key river exposure, painted as if Clerk was floating tens of metres above the water (Fig. 9). This image can also be found in the USGS online archives, although the artist is there misidentified as Hutton. Significantly, it is described as a map, and this is what it is. There is undoubtedly artistic license (as in any geological map) but the depiction of geological relationships is remarkably accurate, even down to individual granite veins (Craig et al. 1978). Beyond its great intrinsic beauty, this is an historically important document, as it represents one of

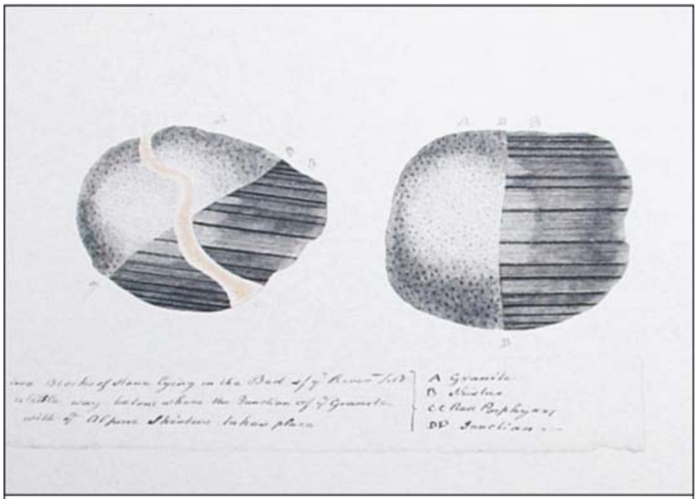
Figure 9. Watercolour image by John Clerk of Eldin, completed in 1785 or shortly thereafter, and rediscovered as one of the "lost drawings" intended for inclusion in the never-completed third volume of James Hutton's Theory of the Earth. The image is a stylized but accurate geological map of the key exposures in the River Tilt that influenced Hutton's thinking on the origins of granite. The flow direction of the river is towards the top of the image, in a southwesterly direction. The rectangular areas at the top of the image are the foundations of the bridge that used to exist here. Image recovered from the United States Geological Survey (USGS) online archives, also available at www.clerkofeldin.com. The original image measured 48 cm by 27 cm.

the earliest known geological maps, and perhaps records the first use of detailed mapping as a method of understanding three-dimensional problems.

Other striking images from Glen Tilt feature boulders that contain intrusive contacts between granite veins and metasedimentary rocks (Fig. 10). Several accounts suggest that Hutton was partial to collecting very large samples that demonstrated important relationships, and some were transported to Edinburgh, despite weighing hundreds of kilograms. It seems that the father of modern geology was like some present-day colleagues of mine who, given time, will easily fill all available storage space with their expedition trophies. The removal of such massive specimens from a remote Scottish glen long before proper roads or motorized vehicles is an interesting accomplishment in itself. James Hutton's rock collection is long lost, although it might lurk here and there in the foundations of modern Edinburgh. He died intestate, and his rock collection was acquired by the University of Edinburgh, but it was apparently never seen again; this might perhaps have some connection to individuals who were then directing the Department of Natural Sciences at that institution. Two similarly large boulders were removed more recently from Glen Tilt, to have prominent places in the *James Hutton Memorial Garden*, situated on the exact site of his house in Edinburgh. Some other boulders in the garden are of conglomerate, intended to illustrate his concept of cyclicity in geological processes (Butcher 2002; Fig. 11). An encounter with the Memorial Garden on a walk in Edinburgh led journalist Ben Dolphin to write a short article about Glen Tilt that provides an excellent summary for non-geologists (Dolphin 2015). As Hutton's actual burial site is unknown, this is now the only place in Edinburgh for geological pilgrims to pay their respects, but Siccar Point or Glen Tilt are probably more inspiring choices.

Neptune's Response: Why and How Field Evidence was Questioned

Hutton's initial writings contained enough inferences to provoke prominent scientists of the day. His nemesis Richard Kirwan (1733–1812) was opposed to the idea that rocks could form from a liquid state, but was equally disturbed by Hutton's heretical concept of an unimaginably old Earth. There was then little knowledge of internal heat in the planet, so the lack of a mechanism to liquefy rocks was a key objection. He asked *"...where then will he find those enormous masses of sulphur, coal or bitumen necessary to produce that immense heat necessary for the fusion of those vast mountains of stone now existing?"* In responses to Hutton's ideas on granite, Kirwan (1793, 1794) did not address the field evidence, but focused instead on how crystallization from aqueous solutions better explained the textures of granite. Of course, nothing was then known about the complexity of crystallization in silicate magma. Ironically, the familiar term plutonic was actually coined by Kirwan in his critiques to express his derision for a theory that, in his mind, was *"fanciful and groundless"*.



Transcription of hand-written caption:

“Two blocks of stone lying in the bed of the River Tilt a little way below where the junction of granite with the Alpine schistus takes place”

A	Granite	CC	Red porphyry
B	Schistus	DD	Junction

Figure 10. An engraving of two large granite boulders collected by James Hutton from the riverbed at the Forest Lodge locality, completed by John Clerk of Eldin in the late 18th century, and including a hand-written caption. There is no scale included, but samples collected by Hutton were reputedly very large, weighing hundreds of kilograms. The boulder at left demonstrates the multi-cyclic nature of intrusive processes, as the ‘red porphyry’ (CC) cuts both metasedimentary layering and the discordant contact of a wider granite vein (DD). The boulder at right shows the perpendicular discordant contact between a granite vein and the layering in the older ‘schistus’. The faint hand-written caption (transcribed below the image) may be the writing of Clerk, or perhaps even that of Hutton himself. The original artwork measured 30 cm by 24 cm, and remains in the collections at Blair Castle, in Blair Atholl. Image from Craig et al. (1978), also available at *www.clerkofeldin.com*.

Both Pitcher (1993) and Young (2003) suggested that Kirwan’s initial attacks on Hutton might have prompted him to express ideas about ‘plutonic granite’ more clearly in 1794, and then to respond to Kirwan’s objections with a full chapter in the 1795 edition of *Theory of the Earth*. Kirwan’s arguments were in truth driven as much by his religious convictions than by any scientific observations. Hutton (1795) offered this summary statement:

> *“I had given, as I thought, a kind of demonstration, from the internal evidence of the stone, that granite had been in the fluid state of fusion, and had concreted by crystallization and congelation from the melted state. This no doubt must be a stumbling block to those who maintain that granite mountains are the primitive parts of our Earth. It must also be a great, if not invincible obstacle in the way of the aqueous theory, which thus endeavours to explain those granite veins that are found traversing strata; and therefore necessarily of a posterior formation.”*

As noted by Bailey (1967) the progress of igneous petrology might have been more rapid if the information from Glen Tilt, Galloway and Arran had actually appeared in the 1795 version of *The Theory*. It is believed that these descriptive accounts were written prior to 1788, but by 1797 Hutton was dead and buried, and his pivotal work would remain buried for another full century. In the early 1800s a new generation of plutonists, including both contemporaries and younger disciples of Hutton, then had to mount a progressive assault on the defences of the neptunists. The torch first passed to Hutton’s friend and advocate John Playfair, and then to other early geologists, many of whom (like Playfair) had originally studied under prominent neptunists such as John Walker (1731–1803) and Robert Jameson (1774–1854) at the University of Edinburgh. Scotland was very much at the centre of this debate, and until the 1820s, it was actually the only place where ‘plu-

Figure 11. Photos from the Hutton Memorial Garden in the City of Edinburgh. (A) A boulder retrieved from Glen Tilt that contains granite veins cutting metasedimentary rocks, sitting alongside a boulder of conglomerate. They respectively are intended to illustrate the principle of intrusive granite and the cyclicity of geological processes, both key elements of Hutton’s thinking. (B) The plaque at the Memorial Garden, including the most famous quote from Hutton’s work, “we find no vestige of a beginning, no prospect of an end”. The photos were taken by journalist Ben Dolphin, and are used with his permission. For more information about the Hutton Memorial Garden, including its location, see Butcher (2002) and Dolphin (2015).

tonic granites' were claimed to exist. But reinforcement would eventually come from a faraway location that would ultimately prove influential in concluding at least this part of the granite debate.

John Playfair worked quickly by the standards of the time to complete his landmark *Illustrations of the Huttonian Theory of the Earth* (Playfair 1802), but the evidence from Glen Tilt and other areas remained obscure, because Playfair had not then visited these localities. Playfair argued on textural and chemical grounds that granite simply could not form from aqueous solutions. Some neptunists then suggested that granite 'veins' were not equivalent to more important 'massive granites' and formed from aqueous solutions that percolated downward from the surface, dissolving and redepositing the 'primitive' granite elsewhere. In modern parlance, this corresponds to 'remobilization', which is sometimes still invoked to dispose of inconvenient field relationships. Playfair (1802) also contended that xenoliths provided clear evidence of both age relationships and the forceful injection of granite, stating that *"it is impossible to deny that the containing stone is more modern than the contained"*. In response, neptunists claimed that these relationships were simply illusions produced where three-dimensional geometry intersected a planar surface, and that xenoliths did not really exist. These were all attempts to cast doubts on the reliability of field evidence.

The most prominent later neptunist critic was Robert Jameson (1774–1854) who presided in Natural Sciences at the University of Edinburgh for many decades, and was a former student of John Walker (1731–1803), who had held that same post during the period when Hutton's rock collection vanished. Walker was a contemporary of Hutton but also one of his fiercest early critics, and both Walker and Jameson were also ministers in the Church of Scotland. John Playfair was another former Church minister, and also another former student of Walker, so it is perhaps not surprising that Jameson took direct aim at his plutonist ideas in an essay shortly after *The Illustrations* appeared (Jameson 1802). In it, he contended that many granite bodies were clearly stratified, but that the degree of stratification was perhaps least evident in the oldest, most primitive, examples. He also concluded that granite veins were nothing more than 'strata of granite', and that there was no evidence to connect such features to larger masses of more homogeneous granite. Metamorphic rocks as we define them were not yet recognized, and many rocks that we now call gneiss were then termed 'stratified granite', which Jameson argued to have sedimentary origins. Strangely, he argued that the *absence* of granite veins from most outcrops of sedimentary rocks argued against such veins being products of liquid injection wherever they were actually observed. Another prominent critic was the Scottish geologist John Murray (1786–1851), best remembered as a *scriptural geologist* determined to explain the geological record as consistent with Genesis. On these grounds alone, Hutton's theories were unlikely to impress Murray. He argued that the presence of feldspar crystals within quartz crystals was inconsistent with crystallization of both from a liquid because feldspar was *'a substance of easy fusibility'* compared to quartz (Murray 1802). At the time, of course, there was no knowledge of binary or ternary eutectic systems.

During this debate, it seems that the key outcrops in Glen Tilt received few visitors, and even John Playfair had yet to see this key evidence. In 1807, he arrived with another prominent amateur natural scientist of the era, Lord Webb Seymour (1777–1819), but the actual presentation of their opinions was delayed for several years (Seymour 1815). Another Scottish geologist, John MacCulloch (1773–1835) had presented a very lengthy and rambling discourse about Glen Tilt in 1813, and this possibly roused Seymour and Playfair to the task. In the end, MacCulloch's written effort actually appeared *after* Seymour and Playfair's paper (MacCulloch 1816). MacCulloch somehow managed to avoid expressing any clear opinions on the origin of granite, and he rivals Hutton himself for length of presentation and opacity of meaning, but he did include a cross-section depicting relationships that is completely consistent with the views of Hutton and Playfair (Fig. 12). It is very hard to trace and attribute the observations in these articles to the actual individuals involved, and MacCulloch himself published a later discussion that more explicitly supported the plutonist views (MacCulloch 1822). Seymour (1815) provided better descriptions of relationships, and he and Playfair also made a key observation. They suggested that igneous rock (described this time as a 'sienite') was:

> *"....in a state of igneous fusion, was impelled from below, by a violent force, against the strata; that it bent them, dispersed them, and filled up the intervals, which it now occupies; that the fragments of the strata were in some degree softened by the heated sienite, so as to admit of a mutual action; that, while the whole intermixed mass was still soft, some further dislocation took place in it, and that all this occurred under a great confining pressure of incumbent matter."*

This is both a clear statement of the forceful nature of magmatic injection and also one of the first descriptions of what we would now call contact metamorphism, although the term itself had yet to be coined.

From Caledonia to the Cape: The Weight of Evidence Finally Prevails

Although debate over the origins of granite in the early 1800s remained focused on Scotland, granite itself is widely distributed, and must surely have been observed by many other early geologists. I find it rather strange that so many years passed before someone actually argued for the plutonic origins of granite from another location. The discourse also remained focused on observational data or philosophical principles, rather than experimentation. The founder of experimental petrology was Sir James Hall (1761–1832) who had discovered the Siccar Point unconformity with Hutton and Playfair in 1788, and then went on to re-examine outcrops in Galloway that Hutton had also briefly described, fully supporting his views (Hall 1794). Before Hutton's death, Hall began experimenting with natural rocks at high temperatures, by placing modified gun barrels in early blast furnaces, and he eventually

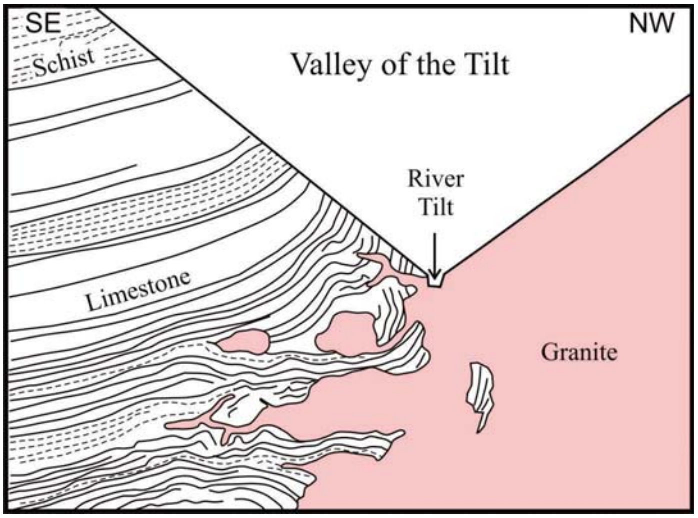


Figure 12. A schematic cross-section of the valley of the River Tilt near Forest Lodge (looking southwest), included by MacCulloch (1816) in his very lengthy description of Glen Tilt and the surrounding area. Although he did not seemingly express any clear opinion on the origins of the granite and its relationship to the metasedimentary rocks, this representation clearly accords with the views of Hutton and John Playfair. It does not show the Loch Tay Fault, which commonly forms the boundary of granite and metasedimentary rocks, as this structure was not then recognized. This line drawing was redrafted from a representation given by Pitcher (1993) rather than the original.

published a landmark study outlining his results (Hall 1800). He was the first to suggest that mixtures of minerals might have substantially lower melting temperatures than the individual minerals, and he also observed that rates of cooling determined grain size and crystal development in both commercial glasses and natural systems. This provided a mechanism by which the coarse-grained crystalline textures of granite and other igneous rocks could develop. Over the years, James Hall would make many other important and influential contributions to experimental petrology, as reviewed by Wyllie (1999). Note that Hall's name should not be linked with that of the prominent American paleontologist James Hall Jr. (1811–1898), who was unrelated. Sir James Hall the Scottish aristocrat did indeed have a son, but he was named Basil. Basil Hall (1788–1844) eventually pursued a naval career but he maintained a strong interest in geology and natural sciences from times spent with his father and John Playfair.

Basil Hall travelled the world with the navy, and one of his ports of call was the Cape of Good Hope, at the southern tip of Africa, where he climbed Table Mountain and made observations of the geology. He wrote to his father and John Playfair about his findings, and in 1812 he became the first person to advocate an igneous, plutonic origin for granitic rocks beyond Scotland. The story of early work on the "Cape Granites" is told in an excellent article by Master (2009), drawn from Basil Hall's autobiography and many other diverse sources, and my account is drawn from this paper. The oldest rocks in this region are deformed and folded clastic metasedimentary rocks of Neoproterozoic age that are intruded by Neoproterozoic to Cambrian (550 to 510 Ma) granite plutons. Both the Neoproterozoic metasedimentary rocks and the granite bodies are then unconformably overlain by early Paleozoic quartzite, sandstone and conglomerate (Master 2009, and references therein). Thus, the Cape of Good Hope contains two classic elements of Hutton's thinking – intrusive granite and unconformities – and reveals them in three dimensions. Basil Hall described how veins of granite transected older inclined and folded sedimentary rocks, but never penetrated above the unconformable base of the younger sedimentary sequence. He compared relationships to those described from the Scottish Highlands by Hutton, Playfair and his own father, and the results were presented to the Royal Society of Edinburgh (Playfair and Hall 1815). Unfortunately, these new contributions from far away did not convince the formidable and still-fulminating Robert Jameson, who in his response (Jameson 1819) was nothing short of dismissive:

> *"The junctions of the granite and gneiss, and of the sandstone and slate, do not present any species of veins, or varieties of intermixtures, or of imbedded portions (fragments of the Huttonians), or convolutions, that do not occur at the junctions of universally admitted Neptunian rocks, such as limestone, claystone, gypsum and sandstone."*

Others who visited the Cape of Good Hope also concurred with the idea that granite must have been emplaced forcefully in a liquid state. These included naturalist Clarke Abel (1780–1826) and the botanist and geologist Dugald Carmichael (1772–1827). Interestingly, both Abel and Carmichael were former students of Robert Jameson at the University in Edinburgh, but had obviously abandoned the neptunist doctrine. Master (2009) also described several other early studies related to the geology of the Cape of Good Hope, from both plutonist and neptunist perspectives, completed during the 1820s and 1830s. Finally, in 1837, the Cape was visited by Robert Jameson's most famous student, who was then on the last leg of a voyage on an equally famous schooner named the *Beagle*. Charles Darwin (1802–1882) needs no introduction as the joint originator of the then theory of evolution, but he had originally studied geology, and actually blamed his early disenchantment with it on Jameson's teaching. Luckily, Darwin would later be strongly influenced by Charles Lyell (1797–1875), the famous author of *Principles of Geology* and originator of the principle of uniformitarianism. Darwin eventually described his own observations from the Cape long before writing the *On the Origin of Species*. Master (2009) provided a quote from Darwin's descriptions (published in 1844), in which he made the key observation that granite seemed to have preferentially intruded along the 'cleavage planes' of the 'clay-slate' as it disrupted these strata, thus accounting for the consistent orientations of cleavage and bedding among remnants of the older rocks. The Glen Tilt exposures, along with many other examples of intrusion breccia, also illustrate this important process. The study of the Cape granite played an important role in finally dispelling the remaining neptunist resistance, and by the mid-19th century the idea of granite as the product of liquid magma was widely accepted by geologists, as was the igneous origin of rocks such as basalt and rhyolite. Robert Jameson never publicly accepted the victory of plutonism over neptunism at the hands of his former students, but anecdotal accounts (e.g. Adams 1938) claim that he eventually verbally acknowledged the intrusive and igneous origin of granite at a meeting of the Geological Society of Edinburgh. Just prior to finalization of this article, Stone (2020) published an interesting analysis of Jameson's reluctant conversion based on some archived lecture notes compiled by former students. These suggest that he did eventually concede some ground to plutonism in the 1830s.

EPILOGUE

Glen Tilt is not as famous or as spectacular as Siccar Point, and I have seen more explicit and extensive examples of intrusion breccia elsewhere. Nevertheless, the site clearly shows that liquid granitic magma invaded, disrupted and altered pre-existing stratified rocks of sedimentary origin. Just as Siccar Point demonstrated cyclicity and unimaginable periods of time, Glen Tilt refuted an accepted chronology that linked Earth History to the Bible. Glen Tilt is thus an important place for geologists because it caused a fundamental change in thinking, which established key principles that endure, but not without lengthy argument. Glen Tilt was the starting point for the long and arduous debate that proved the intrusive igneous origins of granite, and replaced the misguided philosophy of neptunism by deductions based upon logical reasoning that could be confirmed by further observation and (or) experiments. It is the birthplace of modern igneous petrology. I believe that the long walk up the valley to Forest Lodge is well worth the effort, and I hope that those who complete it will agree.

Geologists relish a good controversy, so it is no surprise that discussions about the *exact origins* of granite continued long after the mid-19th century, and some contend that questions remain. There were long exchanges on the relationships between the parental magmas to mafic and felsic rocks, and then more sophisticated experimental studies, culminating in the landmark research of Tuttle and Bowen (1958). The books by Pitcher (1993) and Young (2003) provide a full account of this long story. There was also an interesting 20th century division between those who adhered to Hutton's original concept of liquid magma, and those who believed that granite was actually produced by solid-state metasomatic transformation of other rock types. This great debate was most famously framed by H. H. Read (1889–1970) in his book entitled *The Granite Controversy* (Read 1957). In the introduction to his book, Read uses a quote from *Theory of the Earth* that I have not seen elsewhere, but which seems very appropriate to close this article, because it applies to science in general, as well as to granite.

> *"While man has to learn, mankind must have different opinions. It is the prerogative of man to form opinions; these are often, commonly I may say, erroneous; but they are commonly corrected and it is thus that truth in general is made to appear."*

Read (1957) probably liked this quote because he considered his theory of metasomatic 'granitization' to be the final scientific truth, although the work of Tuttle and Bowen (1958) would soon prove otherwise. But this detail is unimportant. Advances are made by forming ideas but then accepting that others should try to demolish them, even if they are not invited to do so. Hutton's ideas survived many such efforts and it is appropriate that the global conference on the geology and petrology of granite, held every four years, is known as the *Hutton Symposium*.

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