EARTH SCIENCE ABSTRACTS

Vol.41, No.2 (April – June, 2018)

A Quarterly Document

Selective Abstracts on Recent Geological Articles (other than on Indian Geology) published in different periodicals received by Central Library

Geological Survey of India

2018

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ARTICLES COLLECTED FROM THE FOLLOWING PERIODICALS

Sl. No.	***Title of Periodicals***	***Volume, Issue & Year***	***Abbreviation used***
1.	**Acta Geologica Sinica**	***91(4), 2017*** ***91(5), 2017***	***Acta Geol. Sinica***
2.	**American Mineralogist**	***102(7), 2017*** ***102(8), 2017*** ***102(9), 2017*** ***102(10), 2017***	***American Mineral.***
3.	**Atomic Spectroscopy**	***38(6), 2017***	***At. Spectr.***
4.	**Canadian Mineralogist**	***55(5), 2017*** ***55(6), 2017***	***Canadian Mineral.***
5.	**Current Science**	***114(8), 2018*** ***114(9), 2018***	
6.	**Economic Geology**	***112(8), 2017***	***Econ. Geol.***
7.	**Elements**	***13(5), 2017*** ***13(6), 2017***	***Elements***
8.	**Journal of Geological Society**	***175(1), 2018*** ***175(2), 2018***	***J. Geol. Soc.***

9.	**Journal of Petrology**	***58(8), 2017*** ***58(10), 2017***	***J. Petrol.***
10.	**Science**	***357(6357), 2017*** ***358(6367), 2017*** ***359(6379), 2018*** ***359(6380), 2018*** ***359(6381), 2018*** ***360(6386), 2018***	***Science***
11.	**South African Journal of Geology**	***119(4), 2016***	***South African J. Geol.***

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SUBJECT INDEX

ECONOMIC GEOLOGY

1. **ASSIS Rafael Rodrigues de, XAVIER Roberto Perez and CREASER Robert A.:** Linking the timing of disseminated granite-hosted gold-rich deposits to Paleoproterozoic felsic magmatism at Alta Floresta Gold Province, Amazon Craton, Brazil: insights from pyrite and molybdenite Re-Os geochronology. *Econ. Geol.* 112(8), 2017, 1937-1957. [rafael.assiss@gmail.com]

The Alta Floresta gold province consists of Paleoproterozoic (2.0–1.75 Ga) plutonic-volcanic sequences that originated from successive magmatic arcs accreted to the central Amazon tectonic province in the southwestern portion of the Amazon craton. A significant number of high-grade, low-tonnage (<5 t) gold systems occur in this province along a NW-SE-striking belt, particularly in its eastern segment, close to the limits between Ventuari-Tapajós (1.95–1.80 Ga) and Rio Negro-Juruena (1.80–1.55 Ga) geochronological provinces or Tapajós-Parima (2.1–1.87 Ga) and Rondônia-Juruena (1.82–1.54 Ga) tectonic provinces. Most of these gold systems are hosted by oxidized, I-type, calc-alkaline to subalkaline, medium- to high-K, metaluminous to weakly peraluminous granitic intrusions. Among these, Pé Quente, Luizão, and X1 are the major representative deposits in the eastern segment of the Alta Floresta gold province in which gold mineralization occurs, mainly disseminated, in the host intrusions. These include biotite tonalite (1901 ± 6.8 Ma) and monzonite (1979 ± 31 Ma) for the Pé Quente, syenogranite-monzogranite (1970 ± 3 and 1964 ± 1 Ma) for the Luizão, and biotite granodiorite (1904 ± 4.6 Ma) and quartz-feldspar porphyry (1784 ± 10 Ma) for the X1 gold deposits. Within the gold-rich zones, the host granites are strongly altered to sericite-muscovite + chlorite + quartz (phyllic-like alteration) and contain abundant pyrite with variable amounts of chalcopyrite ± molybdenite ± hematite together with subordinate barite, sphalerite, galena, and Bi-Te-Ag-bearing phases. These zones are enveloped by widespread and pervasive potassic alteration with orthoclase + microcline ± hematite, which is preceded by more localized sodic alteration with albite ± quartz. The gold commonly occurs as inclusions (<180 μm) in pyrite, although pyrite-molybdenite appears in frequent association with gold at the X1 deposit. These petrographic relationships suggest that precipitation of gold and sulfides was coeval. Gold-related pyrite from the Luizão and Pé Quente and molybdenite from the X1 intrusion-hosted deposits were dated by the Re-Os method to constrain the timing of the gold metallogeny and its potential genetic link with specific felsic intrusion events in the province. The Re-Os pyrite ages for the Pé Quente deposit vary from 1792 ± 9 to 1784 ± 11 Ma, whereas those for the Luizão deposit are between 1805 ± 21.5 and 1782 ± 8.9 Ma. The X1 molybdenite yields ages of 1787 ± 7 and 1785 ± 7 Ma. These ages are markedly distinct from those of their host granites but display a close temporal association with the quartz-feldspar porphyry intrusion at the X1 deposit. Porphyries have been recognized in other gold

deposits of the eastern sector of the province, but only a few have been dated and returned ages of ca. 1.80 to 1.78 Ga. These ages mark an important gold metallogenetic event in the Statherian in which the ore-forming processes are temporally connected with the felsic magmatism developed during the last stages of evolution of the Juruena magmatic arc (ca. 1.81–1.75 Ga). This felsic magmatism is represented by volcanic rocks and intrusions of the Colíder Group and epizonal granitic rocks of the Paranaíta Intrusive Suite. Despite the dominance of 1.97 and 1.87 Ga granitic intrusions as hosts to gold mineralization in the eastern sector of the Alta Floresta gold province, our Re-Os ages suggest that intrusions temporally equivalent to the Juruena felsic magmatism, particularly porphyries, may have been potential sources for fluids and metals. Thus, the Re-Os data have constrained the timing of the gold metallogeny in the Paleoproterozoic Alta Floresta gold province and have opened new perspectives for gold exploration in the province.

2. **BROWN Gordon E., HOCHELLA Michael F. and CALAS Georges:** Improving mitigation of the long term legacy of mining activities: nano and molecular level concepts and methods. *Elements* 13(5), 2017, 325-330. [gebjr@stanford.edu]

Mining activities over several millennia have resulted in a legacy of environmental contamination that must be mitigated to minimize ecosystem damage and human health impacts. Designing effective remediation strategies for mining and processing wastes requires knowledge of nano- and molecular-scale speciation of contaminants. Here, we discuss how modern nano- and molecular-level concepts and methods can be used to improve risk assessment and future management of contaminants that result from mining activities, and we illustrate this approach using relevant case studies.

3. **CALAS Georges:** Mineral resources and sustainable development. *Elements* 13(5), 2017, 301-306. [georges.calas@upmc.fr]

Mineral resources have been used for millennia and are a key to society's development. With the growing importance of new technologies and the energy revolution, questions have arisen regarding the future availability of resources of metals and industrial minerals. As discovering large high-grade deposits has become increasingly rare, the concept of "sustainable development" will become viewed as essential to extract metals/minerals from new low-grade deposits. In addition to economic considerations, it is essential to reconcile mining activity with environmental protection and to allay the concerns of local populations. This issue of Elements highlights the progressive movement towards an active environmental and societal strategy for sustainably harnessing mineral resources.

4. **FAYOL Noemie and JEBRAK Michel :** Archean Sanukitoid gold porphyry deposits : a new understanding and genetic model from the Bachelor Gold deposit, Abitibi, Canada. *Econ. Geol.* 112(8), 1913-1936. [noemiefayol@gmail.com]

In the Abitibi subprovince of the Superior craton, Canada, recognition of intrusion-related gold deposits is improving, but their formation remains poorly understood. The recently reopened Lac Bachelor deposit in the northeastern part of the Abitibi subprovince is located on the edges of a syenitic complex, and this deposit is an example of a highly fractionated, Fe-Mg-poor, quartz-syenite to alkali-granite centered deposit. Gold is associated with pyrite in localized alkaline, fluorine, and hematite-rich metasomatized zones in magnetite-rich host rock. Minor mineralization is present in a quartz vein stockwork on the edges of the syenitic complex. A genetic model is proposed, wherein alkaline-oxidized magma, which favors sulfur and gold solubility and transport, migrates through the crust via major and subsidiary faults. The presence of miaroles, transolvus, and low-temperature crystallization conditions confirms the shallow emplacement of the magma. The high fluorine content of the magma, which lowers both viscosity and solidus temperature, favored the shallow emplacement of the magma and permitted the development of a long-lived magmatic-hydrothermal system. Oxygen and hydrogen isotopes, miaroles filling, and mineralized zone paragenesis confirm that oxidized hydrothermal fluids were exsolved from the magma. The planar geometry of the metasomatized ore zones indicates that hydrothermal fluid circulation and metasomatism reactions occurred preferentially in high permeability pathways, such as preexisting faults in the host rock. The redox contrast between the oxidized magmatic-hydrothermal fluid and the intermediate volcanic host rock caused sulfide precipitation and gold deposition. This genetic model is applied to the Abitibi subprovince and other Archean cratons.

5. **LAMPINEN Heta M., LAUKAMP Carsten, OCCHIPINTI Sandra A. et al. :** Delineating alteration footprints from field and ASTER SWIR spectra, geochemistry and gamma-ray spectrometry above Regolith-covered base metal deposits – an example from Abra, Western Australia. *Econ. Geol.* 112(8), 2017, 1977-2003. [heta.lampinen@research.uwa.edu.au]

Shortwave infrared (SWIR) field and laboratory reflectance spectra were used to identify and characterize mineral assemblages in regolith within a study area around the Abra base metal deposit. The Abra deposit is situated at 300-m depth from surface and hosted by weathered sedimentary rocks of the Mesoproterozoic Edmund Group of the Capricorn Orogen of Western Australia. The deposit contains a chlorite-siderite (±white mica) alteration halo delineated from drill core, surrounded with host rocks that are

modally poor in detrital and metamorphic chlorite and white mica. Mineral assemblages identified from the regolith SWIR data, which were verified through XRD analysis and preexisting geochemistry data, were used to identify three schematic SWIR mineral domains in the regolith. These domains are (1) poorly crystalline kaolinite in an extremely weathered transported regolith, (2) well-crystalline kaolinite and muscovite in regolith overlying unaltered bedrock, and (3) phengite ± chlorite ± well-crystalline kaolinite mineral footprint in regolith overlying the Abra deposit and nearby base metal prospects. Furthermore, we identified that the mineral footprint detected from regolith samples can be traced in a combined potassium gamma-ray spectrometry and ASTER AlOH group composition map. The combined use of mineralogical and geophysical remote sensing data, and the strategically planned ground validation through mineralogical and geochemical sampling, proved to be a powerful and cost-effective exploration method for regional mapping of mineral footprints potentially related to sedimentary rock-hosted base metal.

6. **SCHINDLER Michael, LUSSIER Aaron J., BELLROSE Jacob et al.:** Mobilization and agglomeration of uraninite nanoparticles: a nano-mineralogical study of samples from the Matoush uranium ore deposit. *American Mineral.* 102(9), 2017, 1776-1787. [mschindler@laurentian.ca]

The occurrence of uraninite nanoparticles in the alteration zones of uranium ore deposits suggests potential mobilization of U(IV) under reducing conditions, which is important for understanding the mobility of uranium in contaminated sites and potential repositories for nuclear waste. This study investigates the occurrence of uraninite nanoparticles in the outer alteration zone of the Matoush uranium ore deposit, Quebec, Canada. Selected samples with finely disseminated uraninite from the outer alteration zone of the deposit are examined by X-ray fluorescence spectroscopy, scanning electron microscopy, and high-resolution transmission electron microscopy on specimens prepared using the focused ion beam milling technique. Uraninite nanoparticles occur as single particles, in clusters, and in larger aggregates in close association with the Cr-rich phases chromceladonite (Cr-rich mica), ideally KMgCr3+(Si4O10)(OH)2, eskolaite, ideally Cr2 3+O3, bracewellite, Cr3+OOH, and an amorphous Cr-rich oxide matrix as well as with fluorapatite and galena. Nanoparticles on the surface and in the outer rim of single uraninite crystals indicate the growth of larger uraninite crystals via crystallization through particle attachment and Oswald ripening. The flow texture of the uraninite nanoparticles in the amorphous Cr-rich oxide matrix, their aggregation on the surface of nanocrystals of bracewellite, the absence of products of a redox reaction involving U(VI) and Fe(II), and the occurrence of amorphous Fe-depleted alteration layers between uraninite and eskolaite, and uraninite and Cr-rich mica indicate that the uraninite nanoparticles have been mobilized under reducing conditions (leaching of Fe2+ from the

alteration layer) at low T (amorphous character of the alteration layer) after the main mineralization event from the center of the mineralization to the outer parts of the Matoush dike complex. These results indicate that fluids can mobilize U(IV) under reducing conditions in the form of uraninite nanoparticles albeit over limited distances. The potential mobilization of these nanoparticles may also explain the occurrence of proximal mineralized zones in U-ore deposits that lack common products resulting from the reduction of U(VI) by Fe2+ (e.g., hematite and other Fe3+-phases).

7. **SUTHERLAND F. Lin:** Sapphire, a not so simple gemstone. *American Mineral.* 102(7), 2017, 1373-1374. [linsutherland1@gmail.com]

Sapphire is a gemstone of considerable reach and much studied, and yet still delivering scientific surprises. This is most recently exemplified by a new paper in this issue of *American Mineralogist* by Palke and Breeding (2017) that re-interprets the origin of needle-like rutile inclusions that form "silk" in sapphires. Sapphire as a gem variety of corundum with wide use in the gem trade as one of the more historically valuable colored gem stones (CGS). It is mined from a great variety of continental gem deposits across the world. A masterly compendium on this gemstone and its ramifications is available.

8. **VIDAL Olivier, ROSTOM Fatma, FRANCOIS Cyril et al. :** Global trends in metal consumption and supply : the raw material-energy Nexus. *Elements* 13(5), 2017, 319-324. [olivier.vidal@univ-grenoble-alpes,fr]

The consumption of mineral resources and energy has increased exponentially over the last 100 years. Further growth is expected until at least the middle of the 21st century as the demand for minerals is stimulated by the industrialization of poor countries, increasing urbanization, penetration of rapidly evolving high technologies, and the transition to low-carbon energies. In order to meet this demand, more metals will have to be produced by 2050 than over the last 100 years, which raises questions about the sustainability and conditions of supply. The answers to these questions are not only a matter of available reserves. Major effort will be required to develop new approaches and dynamic models to address social, economic, environmental, geological, technological, legal and geopolitical impacts of the need for resources.

9. **WALL Frances, ROLLAT Alain and PELL Robert S. :** Responsible sourcing of critical metals. *Elements* 13(5), 2017, 313-318. [f.wall@exeter.ac.uk]

Most critical raw materials, such as the rare-earth elements (REEs), are starting products in long manufacturing supply chains. Unlike most consumers, geoscientists can become involved in responsible sourcing, including best environmental and social practices, because geology is related to environmental impact factors such as energy requirements, resource efficiency, radioactivity and the amount of rock mined. The energy and material inputs and the emissions and waste from mining and processing can be quantified, and studies for REEs show little difference between 'hard rocks', such as carbonatites, and easily leachable ion-adsorption clays. The reason is the similarity in the embodied energy in the chemicals used for leaching, dissolution and separation.

10. **WIT Mike C. J. de:** Early Permian diamond-bearing proximal eskers in the Lichtenburg/Ventersdorp area of the north west province, South Africa. *South African J. Geol.* 119(4), 2016, 585-606. [dewit@icon.co.za]

Diamond-bearing gravels of the Lichtenburg-Ventersdorp area of the North West Province are associated with north-south orientated sinuous 'runs' that occur almost entirely on a flat erosional surface of the Malmani dolomites (Transvaal Supergroup) at some 1,500 m elevation. East to west, this dolomite plain measures 150 km, and northsouth it is on average 40 km wide. This unconformity, which first developed before the Pretoria Group sedimentation over a period of at least 80 Myr, is marked by siliceous breccias (palaeo-karst infill) and conglomerates (reworked breccias). It was exhumed in pre-Karoo and post-Gondwana times. Glacial pavements and remnants of thin Lower Karoo sediments are also found on this polyphase surface. The gravels that make up these 'runs' and sinkholes directly or indirectly linked to these runs, are coarse-grained, very poorly-sorted, and are best described as diamictites. The 'runs' are narrow, elongated, generally positive ridges that meander across the dolomite surface and are up to 30 km long and between 80 to 300 m wide. They have always been regarded as post-Cretaceous drainage features linked to southward-flowing river systems. Diamonds were discovered in these 'runs' and they have produced some 12 million carats. However, no Cainozoic fossils or artefacts have ever been found in almost 90 years of mining. From new field evidence, geomorphological studies, age dating from inclusions in diamond and zircon and clay analyses, it is proposed that these coarse-grained runs represent proximal palaeoeskers of the last deglaciation of the Dwyka continental ice sheet, that are preserved on this ancient 'palimpsest' surface. The age of the deposit is constrained by two populations of agate within the diamictites that are linked to two separate volcanic units of the Pretoria Group. In addition, the youngest crustal zircon ages from the gravels are 1 Ba, but mantle zircons from Lichtenburg suggest that these have been derived from

Cambrian age kimberlites. Analysis of inclusions in diamond support a Neoproterozoic to Cambrian source for the diamonds, so the absence of diamonds from Mesozoic kimberlites and Cainozoic fossils within the gravels support the conclusion that the runs are of Karoo age.

GENERAL GEOLOGY

11. **BLATTLER C. L., CLAIRE M. W., PRAVE A. R. et al. :** Two billion year old evaporates capture earth's great oxidation. *Science* 360(6386), 2018, 320-323. [blatter@princeton.edu]

Major changes in atmospheric and ocean chemistry occurred in the Paleoproterozoic era (2.5 to 1.6 billion years ago). Increasing oxidation dramatically changed Earth's surface, but few quantitative constraints exist on this important transition. This study describes the sedimentology, mineralogy, and geochemistry of a 2-billion-year-old, ~800-meter-thick evaporite succession from the Onega Basin in Russian Karelia. The deposit consists of a basal unit dominated by halite (~100 meters) followed by units dominated by anhydrite-magnesite (~500 meters) and dolomite-magnesite (~200 meters). The evaporite minerals robustly constrain marine sulfate concentrations to at least 10 millimoles per kilogram of water, representing an oxidant reservoir equivalent to more than 20% of the modern ocean-atmosphere oxidizing capacity. These results show that substantial amounts of surface oxidant accumulated during this critical transition in Earth's oxygenation.

12. **JEBRAK Michel and MONTEL Jean-Marc:** Educating the resource geologist of the future : between observation and imagination. *Elements* 13(5), 2017, 331-336. [jebrak.michel@uqam.ca]

Training geologists for a career in the mining industry has changed over the years. It has become at the same time more specialized and with a broader approach. The modern resource geologist needs to understand new styles of ore deposits, the impact of energy transition on the types of deposits and to implement mining processes, the increasing number of mining regulations, and the shift toward educating populations in countries that are new to mining. Based on observation and imagination, rooted in fundamental science, the education of a resource geologist has been transformed by the digital revolution and the integration of the principles of sustainable development. Training future resource geologists means changing the role of teachers to better develop

the imaginations of their students and to increasing what students know about the social impact of mining.

13. KILLICK A. M. : The Geological structure of the Muizenberg Block, Cape Peninsula, South Africa. *South African J. Geol.* 119(4), 2016, 677-690. [akillick@iafrica.com]

The Muizenberg Block, is an outlier of the Table Mountain Group (Cape Supergroup) and lies to the west of the main occurrence of the Cape Fold Belt. Structural mapping of this outlier has identified a spaced cleavage in Peninsula Formation quartz arenites, and an exposure of dolerite that have not been previously documented. Monoclinal folding, an unrelated spaced cleavage, low-angle faults, and steeply dipping faults, that strike east-northeast – west-southwest, are similar to structures found in the syntaxis domain of the Cape Fold Belt and are therefore thought to have formed during the Late Permian – Early Triassic Cape Orogeny. However, as the Muizenberg Block lies outside the presently accepted boundaries of the syntaxis domain, those boundaries may deserve re-examination. Sub-vertical dilational quartz veining, jointing, cataclastic faulting and the intrusion of a sub-parallel dolerite dyke, that all strike northwest – southeast, are thought to represent a younger tectonic event. They are provisionally attributed to the Upper Jurassic to Cretaceous taphrogenesis that preceded the drifting apart of South America and Africa.

GEOCHEMISTRY

14. GUAN Yao, SUN Xiaoming, SHI Guiyong et al. : Rare earth elements composition and constraint on the genesis of the polymetallic crusts and nodules in the South China Sea. *Acta Geol. Sinica* 91(5), 2017, 1751-1766. [eesxm@mail.sysu.edu.cn]

The rare earth elements (REE) composition of the polymetallic crusts and nodules obtained from the South China Sea (SCS) were analyzed through inductively coupled plasma mass spectrometry. Results revealed great differences in the REE abundances (ΣREE) of the SCS polymetallic crusts and nodules; the crusts show the highest ΣREE, whereas the nodules exhibit the lowest ΣREE. The similarity in their NASC–normalized patterns, the enriched light REE (LREE), the markedly positive Ce anomaly (δCe), and the non– or weakly positive Eu anomaly (δEu), suggest that the polymetallic crusts and nodules are of hydrogenetic origin. Moreover, the REE contents and their relevant parameters are quite different among the various layers of the crusts and nodules, which

probably results from the different marginal sea environments and mineral assemblages of the samples. The growth profiles of the SCS polymetallic crusts and nodules reveal the tendency ΣREE and δCe to slightly increase from the outer to the inner layers, suggesting that the growth environments of these samples changed smoothly from an oxidizing to a relatively reducing environment; in addition, the crust ST1 may have experienced a regressive event (sea–level change) during its growth, although the REE composition of the seawater remained relatively stable. On the basis of the regional ΣREE distribution in the SCS crusts and nodules, the samples collected near the northern margin were influenced by terrigenous material more strongly compared with the other samples, and the REE contents are relatively low. Therefore, the special geotectonic environment is a significant factor influencing the abundance of elements, including REE and other trace elements. Compared with the oceanic seamount crusts and deep–sea nodules from other oceans, the SCS polymetallic crusts and nodules exhibit special REE compositions and shale–normalized patterns, implying that the samples are of marginal sea–type Fe–Mn sedimentary deposits, which are strongly affected by the epicontinental environment, and that they grew in a more oxidative seawater environment. This analysis indicates that the oxidized seawater environment and the special nano property of their Fe–Mn minerals enrich the REE adsorption.

15. O'CALLAGHAN Jonathan W., LINNEN Robert L., LIGHTFOOT Peter C. : Mineralogical and geochemical characteristics of Sudbury breccia adjacent to footwall Cu-Ni-Pge sulfide veins and structures in the Creighton and Coleman deposits. *Canadian Mineral.* 55(5), 2017, 909-943. [jonwocallaghan@gmail.com]

The Sudbury Breccia is an impactite that formed in the target rocks of the 1850 +1.3/–2.4 Ma Sudbury impact structure in Ontario, Canada. The breccia is interpreted to have formed during crater excavation or modification at the time of the impact event. Copper-Nickel-Platinum Group Elements sulfide melts moved away from contact mineralization at the base of the melt sheet to form veins and stockworks in the footwall. The distribution of both Sudbury Breccia and the later sulfide melts is partially controlled by pre-existing weaknesses in the footwall, such as lithological contacts; as a result, the two are often spatially associated. A combination of early magmatic-hydrothermal and late metamorphic fluids modified the sulfide mineralization to create broad haloes of metalliferous hydrous silicate minerals proximal to the Sudbury Breccia and in the footwall rocks. This study examines variations in the trace-element geochemistry of the breccia-matrix mineral assemblage developed adjacent to footwall mineralization in the North Range (Coleman Mine) and the South Range (Creighton Mine). The Sudbury Breccia is widely considered to have formed in a single event, contemporaneous with the meteorite impact, therefore it provides a relatively consistent baseline for studying subsequent metamorphic and hydrothermal processes, unlike the Archean Superior

Province and Paleoproterozoic Southern Province, which experienced pre-impact alteration associated with tectonic and igneous activity.

16. **PATHAK Sunita and SENGUPTA Arijit:** Development of ICP-AES- based methodology for the determination of trace metallic constituents in Zr-Nb alloy. *At. Spectr.* 38(6), 2017, 174-185. [arijita@barc.gov.in]

A simple methodology was developed for the determination of trace metallic constituents (Ag, B, Ba, Bi, Ca, Cd, Ce, Ga, Gd, In, K, La, Li, Lu. Mg, Mn, Na, Co, Cr, Cu, Dy, Eu, Fe, Nd, Ni, Pb, Pr, Sm, Sr, Ti and Zn) in Zr-Nb alloy. The systematic study of the spectral interference of Zr as well as Nb was carried out on these analytes. This includes identification of interference-free lines, tolerance level, and correction factors associated with each line. The analytical performance of these lines including detection limit, sensitivity and linear dynamic range was also investigated. Based on these two factors, the best line of each analyte was chosen. Chemical separation of the major matrix fowwoed by the analysis of the raffinate was the strategy adopted in the development of the method. To optimize the chemical separation procedure, TBP, TOPO and DHOA were used for prefential separation of the major matrix without loss of the analytes even at trace levels. The optimized method was validated using a synthetic sample which revealed that five contacts of 1.1 M TBP in dodecane was the ideal choice for separation and all of these analytes can be determined at the 1 mg L^{-1} level in a Zr-Nb matrix with a RSD less than 5%.

17. **TSCHAUNER O., HUANG S., GREENBERG E. et al. :** Ice-VII inclusions in diamonds : evidence for aqueous fluid in earth's deep mantle. *Science* 359(6380), 2018, 1136-1139. [olivert@physics.unlv.edu]

Water-rich regions in Earth's deeper mantle are suspected to play a key role in the global water budget and the mobility of heat-generating elements. We show that ice-VII occurs as inclusions in natural diamond and serves as an indicator for such water-rich regions. Ice-VII, the residue of aqueous fluid present during growth of diamond, crystallizes upon ascent of the host diamonds but remains at pressures as high as 24 gigapascals; it is now recognized as a mineral by the International Mineralogical Association. In particular, ice-VII in diamonds points toward fluid-rich locations in the upper transition zone and around the 660-kilometer boundary.

GEOMORPHOLOGY, QUATERNARY GEOLOGY

18. McMAHON William J. and DAVIES Neil S. : Evolution of alluvial mudrock forced by early land plants. *Science* 359(6379), 2018, 1022-1024. [nsd27@cam.ac.uk]

Mudrocks are a primary archive of Earth's history from the Archean eon to recent times, and their source-to-sink production and deposition play a central role in long-term ocean chemistry and climate regulation. Using original and published stratigraphic data from all 704 of Earth's known alluvial formations from the Archean eon (3.5 billion years ago) to the Carboniferous period (0.3 billion years ago), we prove contentions of an upsurge in the proportion of mud retained on land coeval with vegetation evolution. We constrain the onset of the upsurge to the Ordovician-Silurian and show that alluvium deposited after land plant evolution contains a proportion of mudrock that is, on average, 1.4 orders of magnitude greater than the proportion contained in alluvium from the preceding 90% of Earth's history. We attribute this shift to the ways in which vegetation revolutionized mud production and sediment flux from continental interiors.

GEOPHYSICS AND SOLID EARTH

19. COPLEY Alex : The Strength of earthquake generating faults. *J. Geol. Soc.* 175(1), 2018, 1-12. [acc41@cam.ac.uk]

This paper summarizes the observations and methods that have been used to study the strength of active earthquake-generating (seismogenic) faults. Indirect inferences based upon a range of geophysical and geological observations suggest that faults fail in earthquakes at shear stresses of less than *c.* 50 MPa, equivalent to effective coefficients of friction of less than 0.3, and possibly as low as 0.05. These low levels of effective friction are likely to be the result of a combination of high pore fluid pressures, which could be local or transient, and the frictional properties of phyllosilicate-rich fault rocks. The dip angles of new faults forming in oceanic outer rises imply that intrinsically low-friction fault rocks must control the fault strength in at least that setting. When combined with the much higher fault strengths inferred from borehole studies and some laboratory measurements, the observations are most consistent with weak faults embedded in strong surroundings, providing a clear reason for the prevalence of fault reactivation. However, the conditions required for the formation of new faults, and the reasons for an apparent wide variability in the degree of fault healing through time, remain unknown. Ever since the realization that faults accommodate the relative motions of parts of the Earth's

lithosphere, there has been controversy about their material properties. A major question that has received much attention concerns understanding the friction laws that determine why some parts of faults break in earthquakes whereas others slide aseismically, and equivalently what controls whether a slip event becomes an earthquake or a longer phase of transient aseismic creep (e.g. Dietrich 1979; Ruina 1983; Marone 1998; Scholz 1998). A component of this question involves establishing whether a given fault always behaves in the same manner. Observations from regions where suitably old markers of fault motion, or long historical records, give a view of multiple earthquake cycles suggest two important features. One is that at the scale of entire fault zones, some regions appear to be persistently seismic, and are locked and accumulating strain in the interseismic period, whereas others show little evidence of generating significant earthquakes (e.g. Ambraseys & Jackson 1998; Sieh *et al.* 2008; Chlieh *et al.* 2011). Such patterns exist on a larger scale than the dynamic propagation of seismic slip into creeping regions on the margins of individual slip patches, and the geometrical details around the boundaries between these regions are not well known. A second feature is that, with some exceptions, the slip areas and magnitudes of earthquakes usually appear to vary between sucessive seismic cycles on a given fault system, possibly as a result of stress perturbations from previous motions (e.g. Beck *et al.* 1998; Scholz 1999; Konca *et al.* 2008; Kozaci *et al.*2010). A second major question concerns the levels of stress that faults can support before moving by either seismic slip or aseismic creep. This paper focuses on this second question, and addresses the magnitude of differential stress required to cause earthquake-generating faults to slip. The particular focus on seismogenic faults, rather than creeping faults, is because a wealth of information revealed by studies of earthquakes can be incorporated into the analysis. Whereas a large body of work is devoted to the evolution of friction during the process of fault slip (e.g. Rice 2006; Reches & Lockner 2010; Di Toro *et al.*2011; Brown & Fialko 2012; Noda & Lapusta 2013, and references therein), this paper concentrates on the 'static' friction that needs to be overcome to begin the process of fault motion, and not the subsequent evolution of material properties during a seismic event. The level of differential stress required to begin the process of earthquake slip is often known as the fault 'strength'. The determination of fault strength has a number of wide-ranging implications. One of these relates to the rheology of the continental lithosphere, and its control on the locations and characteristics of deformation. There has been plentiful recent debate surrounding the relative magnitudes of the stresses transmitted through the brittle and ductile parts of the lithosphere, and how these stresses relate to the lateral variations of continental rheology that play a major role in controlling the geometry and rates of deformation (e.g. Watts & Burov 2003; Jackson *et al.* 2008; Burov 2010; Copley *et al.* 2011*a*). To fully address this question requires an understanding of the level of stress that can be supported by seismogenic faults. A second major implication of the strength of active faults relates to earthquake recurrence and hazard. Earthquake stress drops are commonly of the order of megapascals to tens of megapascals (e.g. Kanamori & Anderson 1975; Allmann & Shearer 2009). Opinion is divided as to whether or not these values represent the total pre-earthquake shear stress on fault planes (e.g. Kanamori 1994; McGarr 1999; Scholz 2000; Townend & Zoback 2000; Copley *et al.* 2011*a*). If earthquake stress drops do represent the release of the great majority of the

pre-event shear stresses on fault planes (so-called 'weak faults'), then a significant time interval will be required for stresses to build up again before an earthquake can nucleate on a previously ruptured fault segment. The tectonic loading rate is roughly constant and in the absence of interactions with other faults, this situation may lead to quasi-periodic ruptures on a given fault segment. If, however, earthquake stress drops represent only a small proportion of the pre-earthquake shear stresses on fault planes (so-called 'strong faults'), then unreleased shear stresses will be present following earthquakes, which could lead to events closely spaced in time. Understanding the stress state of faults therefore has significant implications for hazard assessment. This paper will begin by describing the range of methods that have been used to estimate the stress state at failure of active faults, and then combine these results into a coherent overall view of fault strength.

20. **VALLEE Martin, AMPUERO Jean Paul, JUHEL Kevin et al. :** Observations and modeling of the elastogravity signals preceeding direct seismic waves. *Science* 358(6367), 2017, 1164-1168. [vallee@ipgp.fr]

After an earthquake, the earliest deformation signals are not expected to be carried by the fastest (*P*) elastic waves but by the speed-of-light changes of the gravitational field. However, these perturbations are weak and, so far, their detection has not been accurate enough to fully understand their origins and to use them for a highly valuable rapid estimate of the earthquake magnitude. We show that gravity perturbations are particularly well observed with broadband seismometers at distances between 1000 and 2000 kilometers from the source of the 2011, moment magnitude 9.1, Tohoku earthquake. We can accurately model them by a new formalism, taking into account both the gravity changes and the gravity-induced motion. These prompt elastogravity signals open the window for minute time-scale magnitude determination for great earthquakes.

HYDROGEOLOGY

21. **TAO Wang and JIANSHENG Chen:** Overestimated ground water 14C ages triggered an inexpediency of water policy in China. *Curr. Sci.* 114(8), 2018, 1751-1755. [jschen@hhu.edu.cn]

Northern China has been facing a serious problem of groundwater scarcity. The government developed restrictive policies on groundwater extraction, and designed the South–North Water Transfer Project (SNWTP) to transfer water from the Yangtze River in southern China to the arid region in the north. However, contrary to expectation, groundwater levels in northern China have been rising significantly before completion of

the project. Due to misapplication of the ^{14}C dating method, the age of deep confined groundwater in arid northern China has been overestimated. This classifies the groundwater as palaeo-groundwater with little recharge, which results in the prohibition of groundwater extraction and SNWTP. Significant tritium concentrations recently reported in the so-called palaeo-groundwater, along with rising groundwater levels, imply recent groundwater recharge in arid northern China.

ISOTOPE GEOCHEMISTRY, GEOCHRONOLOGY

22. FRITSCHLE Tobias, DALY J. Stephen, WHITEHOUSE Martin J. et al. : Multiple intrusive phases in the Leinster Batholith, Ireland : geochronology, isotope geochemistry and constraints on the deformation history. *J. Geol. Soc.* 175(2), 2018, 229-246. [Tobi.Fritschle@gmx.de]

The formation of granite batholiths, commonly by incremental assembly of small magma batches, and their correlation with tectonic events, on both local and regional scales, is crucial to understanding the evolution of the Earth's continental crust. However, these correlations often rely on assumptions about the detailed relationship and timing of mapped units. Here we report how an integrated geochronological, structural and isotope geochemical study in only one key locality from the late Caledonian Leinster Batholith in SE Ireland provides the potential for unravelling essential questions on batholith petrogenesis. The Northern Unit of the Leinster Batholith intruded incrementally, as demonstrated by three crosscutting granite varieties at Glenmacnass Waterfall. The oldest, foliated granite, yielded a zircon U–Pb age of 417.4 ± 1.7 Ma. Following deformation, equigranular granite intruded at 409.8 ± 1.9 Ma and was cut by megacrystic granite at 404.9 ± 2.6 Ma. Hence, batholith formation lasted up to 16.8 myr, challenging the widely accepted 405 Ma age for the entire batholith. Multi-isotope geochemical investigations permit derivation of the three granites from the same sources, including both Mid- to Upper Ordovician peri-Gondwanan arc-related magmatic and Lower to Mid-Ordovician Ribband Group metasedimentary rocks. Zircon inheritance and Lu–Hf isotope geochemistry also reveal reprocessing of older granite wall rock in the younger magmas.

23. KORESHKOVA Marina, DOWNES Hilary, MILLAR Ian et al : Geochronology of metamorphic events in the Lower Crust beneath NW Russia : a xenoliths Hf isotope study. *J. Petrol.* 58(8), 2017, 1567-1590. [m.koreshkova@spbu.ru]

Hf isotope data for zircons and whole-rocks from lower crustal mafic granulite and pyroxenite xenoliths from NW Russia are presented together with the results of U–Pb zircon dating, Sm–Nd and Rb–Sr isotopic compositions of bulk-rocks and minerals, and trace element compositions of minerals. Most zircons preserve a record of only the youngest metamorphic events, but a few Grt-granulite xenoliths retain Archean magmatic zircons from their protolith. Metamorphic zircons have highly variable εHf(*t*) values from –25 to –4. The least radiogenic zircons were formed by recrystallization of primary magmatic Archean zircons. Zircons with the most radiogenic εHf grew before garnet or were contemporaneous with its formation. Zircons with εHf(*t*) from –15 to –9 formed by various mechanisms, including recrystallization of pre-existing metamorphic zircons, subsolidus growth in the presence of garnet and exsolution from rutile. They inherited their Hf isotopic composition from clinopyroxene, pargasite, rutile and earlier-formed zircon that had equilibrated with garnet. Subsolidus zircons were formed in response to a major change in mineral association (i.e. garnet- and zircon-producing reactions including partial melting). Recrystallized zircons date the onset of high-temperature conditions without a major change in mineral association. Age data for metamorphic zircons fall into five groups: >1·91 Ga, 1·81–1·86 Ga, 1·74–1·77 Ga, 1·64–1·67 Ga and <1·6 Ga. Most ages correlate with metamorphic events in the regional upper crust superimposed onto rocks of the Belomorian belt during formation of the Lapland Granulite Belt. Zircon formation and resetting at 1·64–1·67 Ga significantly postdates Lapland–Kola orogenic events and may relate to the onset of Mesoproterozoic rifting. The youngest ages (1·6–1·3 Ga) correspond to an event that affected only a few grains in some samples and can be explained by interaction with a localized fluid. The observed garnet-granulite associations were formed at 1·83 Ga in Arkhangelsk xenoliths and 1·74–1·76 Ga in most Kola xenoliths. By the end of the Lapland–Kola orogeny, the rocks were already assembled in the lower crust. However, no addition of juvenile material has been detected and preservation of pre-Lapland–Kola metamorphic zircon indicates that some xenoliths represent an older lower crust. Granulites, pyroxenites and Phl-rich rocks have a common metamorphic history since at least *c.* 1·75 Ga. At about 1·64 Ga metasomatic introduction of phlogopite took place; however, this was only one of several phlogopite-forming events in the lower crust.

24. MAIER Wolfgang D. and HANSKI Eero J. : Layered mafic-ultramafic intrusions of fennoscandia : Europe's treasure chest of magmatic metal deposits. *Elements* 13(6), 2017, 415-420. [maierw@cardiff.ac.uk]

Northeastern Fennoscandia hosts a rich diversity of mafic–ultramafic intrusions of variable shape and size, emplaced in different tectonic regimes over a period spanning ~600 million years (between 1.88 Ga and 2.5 Ga). Several of the bodies contain world-class ore deposits, notably the Kemi chromium deposit and the Pechenga nickel deposits. Other deposits include nickel and copper at Kevitsa, Kotalahti and Sakatti; vanadium at

Koillismaa; and platinum-group elements at Portimo and Penikat. These deposits constitute important resources that could shield Europe from potential future supply shortages of these key industrial metals.

25. **MATHEZ Edmond A. and KINZLER Rosamond J. :** Metasomatic chromitite seams in the Bushveld and Rum layered intrusions. *Elements* 13(6), 2017, 397-402. [mathez@amnh.org]

Millimeter–centimeter thick layers of chromite-rich rock (chromitites) are rare, but ubiquitous, features of the Bushveld (South Africa) and Rum (Scotland) layered intrusions. Despite their meager dimensions, the chromitites provide insight into processes that modify igneous layering and, in the Bushveld, the formation of the platinum-group element–rich Merensky Reef. The Merensky Reef chromitites represent reaction zones formed in a compositional gradient between hydrous silicate melt and a crystalline cumulate assemblage, analogous to reaction zones in metamorphic systems. At Rum, the chromitites formed at the melting front between newly injected magma and the magma chamber floor, an analogous process but one driven by thermal, rather than chemical, energy.

26. **O'DRICOLL Brian and VANTONGEREN Jill A. :** Layered intrusions : from petrological paradigms to precious metal repositories. *Elements* 13(6), 2017, 383-389. [brian.odriscoll@manchester.ac.uk.]

Layered mafic–ultramafic intrusions have occupied a position of central importance in the field of igneous petrology for almost a century. In addition to underpinning petrological paradigms such as cumulus theory, some layered intrusions are exceptionally enriched in base and precious metals, including the platinum-group elements. Technological advances are driving the current and future state-of-the-art in the study of layered intrusions and, looking forward, it is clear that these bodies will continue to inspire and challenge our understanding of magmatic systems and magma solidification for many years to come.

27. **PISAPIA Celine, DESCHAMPS Pierre, BATTANI Anne et al. :** U/Pb dating of geodic calcite : new insights on western Europe major tectonic events and associated diagenetic fluids. *J. Geol. Soc.* 175(1), 2018, 60-70. [celine.pisapia@gmail.com]

Abstract: This study presents the first application of the U/Pb dating method to highly Pb-depleted diagenetic geodic calcites of the Jurassic formations of the Paris Basin that leads to a reappraisal of the palaeohydrological history of this region. Composite U/Pb ages from multiple geodes, combined with δ18O analyses, reveal two main phases of diagenetic fluid circulations linked with major regional tectonic events. Dogger formations recorded a first diagenetic fluid episode at 147.8 ± 3.8 Ma, i.e. at the very beginning of the emersion of the basin during the Tithonian period and 30 Ma earlier than previously assumed. δ18O results confirmed that most of the calcitic cement phases that closed the porosity of these formations precipitated at the beginning of the Cretaceous period. Oxfordian formations recorded another major meteoric fluid circulation at 33.5 ± 2.8 Ma related to the initial stage of the European Cenozoic Rift System (ECRIS). Consequently, the porosity of the Mesozoic formations of the studied area may have been closed sooner than previously thought, before the main ECRIS rifting phase of Oligocene age. This study shows that U/Pb dating of secondary geodic calcite offers a new powerful way for reconstructing the coupled palaeohydrological and diagenetic history of sedimentary basins.

28. ZHANG Guobin, YANG Yanchen, VAKH Alexander S. et al. : Chronology and geochemistry of the Berezitovoe polymetallic gold deposit in eastern Siberia, Russia and its geological significance. *Acta Geol. Sinica* 91(5), 2017, 1733-1750. [zhangguobin000@163.com]

The Berezitovoe deposit is a large-sized Au–Ag–Zn–Pb deposit in the east of the Selenga–Stanovoi superterrane, Russia. Au–Ag orebodies are hosted by tourmaline-garnet-quartz-muscovite metasomatic rocks; Zn–Pb orebodies are hosted by granodiorites, porphyritic granites and tourmaline-garnet-quartz-muscovite metasomatic rocks. These orebodies are surrounded by wall rocks dominated by the Tukuringra Complex granodiorites, porphyritic granites, and gneissic granodiorites. The alteration includes silicification and garnet, sericitization chloritization, carbonatization and kaollinization. LA–ICP–MS U–Pb zircon dating indicates that the gold mineralization can be divided into two stages in the Berezitovoe polymetallic gold deposit (at 363.5 ± 1.5 Ma, and 133.4 ± 0.5). Hornblende–plagioclase gneisses of the Mogocha Group in the study area underwent Paleoproterozoic metamorphism (at 1870 ± 7.8 and 2400 ± 13 Ma), gneissic granodiorite of the Tukuringra Complex yields a late Paleozoic magmatic age (at 379.2 ± 1.1 Ma), and subalkaline porphyritic granitoid of the Amudzhikan Complex yield late Mesozoic magmatic ages (133–139 and 150–163 Ma). Granodiorites of the Tukuringra Complex in the study area have high concentrations of SiO2 (average of 60.9 wt%), are aluminum-oversaturated (average A/CNK of 1.49), are enriched in the large ion lithophile elements (e.g., K, Rb, and Ba), U, Th, and Pb, are depleted in high field strength elements (e.g., Ta, Nb, and Ti), and have slightly negative Eu and no Ce anomalies in chondrite-

normalized rare earth element diagrams. Fluid inclusions from quartz veins include three types: aqueous two-phase, CO2-bearing three-phase, and pure CO2. Aqueous two-phase inclusions homogenize at 167°C–249°C and have salinities of 4.32%–9.47% NaCl equivalent, densities of 0.86–0.95 g/cm3, and formed at depths of 0.52–0.94 km. In comparison, the CO2-bearing three-phase inclusions have homogenization temperatures of 265°C–346°C, salinities of 7.14%–11.57% NaCl equivalent, and total densities of 0.62–0.67 g/cm3. The geochemical and zircon U–Pb data and the regional tectonic evolution of the study area, show that the Berezitovoe polymetallic gold deposit formed in an island arc or active continental margin setting, most probably related to late Paleozoic subduction of Okhotsk Ocean crust beneath the Siberian Plate.

29. ZHANG Xiangxin, SU Zhen and GAO Yongfeng : Zircon U-Pb geochronology and geochemistry of the Early Cretaceous volcanic rocks from the Manitu Formation in the Hongol area, Northeastern Inner Mongolia. *Acta Geol. Sinica* 91(4), 2017, 1286-1304. [zhxiangxin@126.com]

We undertook zircon U–Pb dating and geochemical analyses of volcanic rocks from the Manitu Formation in the Hongol area, northeastern Inner Mongolia, to determine their age, petrogenesis and sources, which are important for understanding the Late Mesozoic tectonic evolution of the Great Xing'an Range. The volcanic rocks of the Manitu Formation from the Hongol area consist primarily of trachyandesite, based on their chemical compositions. The zircons from two of these trachyandesites are euhedral–subhedral in shape, display clear oscillatory growth zoning and have high Th/U ratios (0.31–1.15), indicating a magmatic origin. The results of LA-ICP-MS zircon U–Pb dating indicate that the volcanic rocks from the Manitu Formation in the Hongol area formed during the early Early Cretaceous with ages of 138.9–140.5 Ma. The volcanic rocks are high in alkali (Na2O + K2O = 6.22–8.26 wt%), potassium (K2O = 2.49–4.58 wt%) and aluminium (Al2O3 = 14.27–15.88 wt%), whereas they are low in iron (total Fe2O3 = 3.76–6.53 wt%) and titanium (TiO2 = 1.02–1.61 wt%). These volcanic rocks are obviously enriched in large ion lithophile elements, such as Rb, Ba, Th and U, and light rare earth elements, and are depleted in high field strength elements, such as Nb, Ta and Ti with pronounced negative anomalies. Their Sr–Nd–Pb isotopic compositions show positive ∈Nd(t) (+0.16‰ to+1.64‰) and low TDM(t) (694–767 Ma). The geochemical characteristics of these volcanic rocks suggest that they belong to a shoshonitic series and were likely generated from the partial melting of an enriched lithospheric mantle that was metasomatised by fluids released from a subducted slab during the closure of the Mongol–Okhotsk Ocean. Elemental and isotopic features reveal that fractional crystallization with the removal of ferromagnesian minerals, plagioclase, ilmenite, magnetite and apatite played an important role during the evolution of the magma. These shoshonitic rocks were produced by the partial melting of the enriched lithospheric mantle

in an extensional regime, which resulted from the gravitational collapse following the final closure of the Mongol–Okhotsk Ocean in the Middle–Late Jurassic.

MINERALOGY

30. CAVE Ben J., LARGE Ross R., WHITE Chris E. et al. : Does tungsten availability control the presence of tungsten in turbidite-hosted orogenic gold mineralization ? Evidence from the Meguma and Bendigo-Ballarat terraines. *Canadian Mineral.* 55(6), 2017, 973-999. [ben.james.cave@gmail.com]

Turbidite-hosted orogenic Au deposits are commonly enriched in W, along with a variety of other trace elements. A mineralogical source for W has recently been shown in the Otago Schist of southern New Zealand (Cave *et al*. 2016), with detrital rutile in the metasedimentary rocks recrystallizing to metamorphic titanite and making W available to be mobilized from the rock mass. In this study, we investigate the availability of W through prograde metamorphic mineral recrystallization in two additional turbidite-hosted orogenic Au provinces, one containing orogenic Au mineralization with associated subordinate W (Meguma Terrane, Canada), and the other containing orogenic Au mineralization without associated W (Bendigo-Ballarat Terrane, Australia). This was undertaken to assess whether W availability during prograde metamorphism is a key process in controlling the presence of W in turbidite-hosted orogenic Au mineralization. Like the Otago Schist, in both terranes detrital rutile is identified as being the most important host mineral for W in the lowest metamorphic grade rocks, and its prograde metamorphic recrystallization (to ilmenite) makes significant amounts of W available for mobilization (0.65 and 1.85 g of W per tonne of rock from the Goldenville and Halifax groups of the Meguma Terrane, respectively, and 0.16 g of W per tonne of rock from the Castlemaine Group of the Bendigo-Ballarat Terrane). This release of W in the Meguma Terrane is likely the source of W in these orogenic Au deposits. The lack of W in the orogenic Au deposits of the Bendigo-Ballarat Terrane suggests that W availability is not the only process controlling the presence of W minerals in turbidite-hosted orogenic Au mineralization. Alternatively, it might reflect a lower greenschist facies metasedimentary (Castlemaine Group) source for these deposits (*i.e*., a lower metamorphic grade source than the rutile to ilmenite conversion), as has been previously suggested.

31. ELMI Chiara, JIANGZHI Chen, GOLDSBY David et al. : Mineralogical and compositional features of rock fulgurites: a record of lightning effects on granite. *American Mineral.* 102(7), 2017, 1470-1481. [chiarael@sas.upenn.edu]

Fulgurites are a naturally occurring glass formed when sand, rock, or soil is struck by atmospheric electrical discharges (lightning). The aim of this paper is to provide insights into the conditions occurring in rocks during the lightning strike. Rock fulgurites collected from Mt. Mottarone, Baveno (Piedmont, Italy) have been investigated to assess the mineralogical and compositional changes occurring in granite due to a lightning strike. X-ray powder diffraction showed that the samples represent the dominant granitic rock type of the Baveno massif, the so-called "Pink Baveno." Fulgurite coats the surface of the granite as a brown-black, glassy to very fine-grained porous layer. Powder diffraction data for the fulgurite reveal the presence of cristobalite and quartz crystals in a glass matrix, suggesting that temperature exceeded ~1700 °C at near atmospheric conditions, assuming thermodynamic equilibrium. Electron probe microanalysis of the glass revealed that it is mainly composed of SiO_2 and Al_2O_3 and that it has a porosity of 5–7 area% in the studied zones. The presence of the amorphous phase indicates that the abrupt electrical (Joule) heating of the rock surface yielded high temperatures, producing a thin melt layer on the surface, which then cooled adiabatically. Idealized physical model was developed to simulate the effects of Joule heating and subsequent thermal conduction close to the rock surface during and after a lightning strike. The quantity of organic matter in the glass, obtained via Elemental Analyzer, suggests that rapid quenching of the melt trapped NO_x and CO_x gases produced during heating. Raman spectroscopy revealed the presence of polyaromatic hydrocarbon molecules, which, combined with the Elemental Analyzer data, suggest that organic matter was pyrolyzed at around 300–350 °C and then trapped in the glass matrix of the studied rock fulgurites.

32. KRUPP Katherine, BASKARAN Mark, BROWNLEE Sarah J. : Radon emanation coefficients of several minerals : how they vary with physical and mineralogical properties. *American Mineral.* 102(7), 2017, 1375-1383. [Baskaran@wayne.edu]

The escape rates of radon gas from rocks and minerals are of great relevance to many branches of geosciences, and it is, thus, important to understand the physical and mineralogical properties that control radon emanation rates. Mechanisms of radon loss from minerals have direct bearing on the reliability of U-Pb and U-Th-He geochronology. Fourteen minerals from three different mineral groups and with localities spanning three continents were selected for this study. The radon emanation coefficients (REC) for each mineral were measured as a function of grain size, temperature, ^{238}U and ^{232}Th activities, total absorbed α-dose, density, and mineral melting temperature. The measured ^{238}U and ^{232}Th activities ranged from 0.01 to 6487 Bq/g and from below detection limit to 776 Bq/g, respectively. The REC values for unheated, pulverized samples ranged from 0.083 to 7.0%, which is comparable to previously reported ranges (except for zircon). An inverse correlation between grain size and REC was observed. Full annealing of fission tracks resulted in an overall decrease in REC values, suggesting that nuclear tracks could

possibly act as conduits for radon release. While activity, α dose, density, and melting temperatures are not strongly correlated with REC values, it was observed that minerals with high melting points (≥1400 °C) have lower REC values, most likely due to inhibition of radon release by compact crystal-lattice structures. This is the first attempt, to our knowledge, to correlate REC values with melting temperature, and this study reports six minerals for which no REC values have been previously reported.

33. McHENRY Lindsay J., CARSON George L., DIXON Darian T. et al. : Secondary minerals associated with Lassen fumaroles and hot springs : implications for martian hydrothermal deposits. *American Mineral.* 102(7), 2017, 1418-1434. [lmchenry@uwm.edu]

The active hot springs, fumaroles, and mud pots of the southwestern Lassen hydrothermal system include various alteration environments, which produce a range of hydrothermal mineral assemblages. Analysis of water, mineral precipitates, altered sediment, and rock samples collected at and near these features at Sulphur Works, Bumpass Hell, Little Hot Springs Valley, and Growler and Morgan Hot Springs reveals conditions ranging from ~100 °C acid-sulfate fumaroles (e.g., Sulphur Works and Bumpass Hell) to near-neutral hot springs (e.g., Growler and Morgan), and includes both oxidizing and reducing conditions. Resulting hydrothermal minerals include a wide variety of sulfates (dominated by Al-sulfates, but also including Fe2+, Fe3+, Ca, Mg, and mixed-cation sulfates), sulfides (pyrite and marcasite), elemental sulfur, and smectite and kaolinite clays. Most altered samples contain at least one silica phase, most commonly quartz, but also including cristobalite, tridymite, and/or amorphous silica. Quartz and other silica phases are not as abundant in the less altered rock samples, thus their abundance in some hydrothermally altered sediment samples suggests a detrital origin, or formation by hydrothermal alteration (either modern or Pleistocene); this requires a high degree of diagenetic (or epigenetic) maturation. These results support a previously identified model that the Lassen hydrothermal system involves the de-coupling of a vapor phase (which becomes acidic as it oxidizes near the surface, producing acid-sulfate fumaroles at higher elevations at Sulphur Works and Bumpass Hell) from the residual near neutral thermal waters that emerge as hot springs at lower elevations (Growler and Morgan). Because both acid-sulfate fumarole and near-neutral sinter-producing hot springs have been invoked to explain the silica-rich deposits observed by the Mars Exploration Rover Spirit near Home Plate in the Columbia Hills on Mars, Lassen can serve as a useful terrestrial analog for comparison.

34. MORSE S. A. : Kiglapait mineralogy V : feldspars in a hot, dry magma. *American Mineral.* 102(10), 2017, 2084-2095. [tm@geo.umass.edu]

The lithology of the 1.305 Ga Kiglapait intrusion is dominated by a Lower Zone of troctolite, succeeded by an Upper Zone of olivine gabbro, ferrodiorite, and syenite with olivine composition of pure fayalite. The feldspar composition of the intrusion varies from An68 to An9 over a thickness of 8.4 km from the base to a sandwich horizon under an Upper Border Zone. The anhydrous nature of the Kiglapait syenites is shown by their high temperature, by the loss of minor biotite up-stratigraphy in the intrusion, and the absence of amphibole. The end-stage feldspar of the Kiglapait syenites is that of a solidus embedded in a solvus in a 3 kbar eutectic at 1000 °C. The end-member assemblage at temperature and pressure is invariant. The final bulk composition is relatively An-rich—An ~11%−with a composition of XOr = 1/3 when projected to the Ab-Or sideline. The experimental feldspar solvus when corrected for the effects of An and Ba and referred to 3 kbar penetrates the solidus and fits the experimental tie lines. These conditions precede a stage of local coarsening under subsolidus conditions that is found in colloform symplectites invading mesoperthite. The oligoclase-orthoclase symplectites are iso-compositional with their host mesoperthites. The coarsening is assumed to be related to a plausibly F-rich vapor phase that is locally consumed with time. The observed phase compositions indicate the end of exsolution at ~800 °C at 3 kbar on the binodal solvus.

35. MORSE Stearns A., DAVIDSON Jon P. and TEPLEY Frank J. III : Plagioclase zonation : an archive of trapped liquid and crustal contamination. *Elements* 13(6), 2017, 403-408. [tm@geo.umass.edu]

Many cumulates in layered intrusions contain plagioclase crystals that are compositionally zoned in terms of their major elements, and, less commonly, in their $^{87}Sr/^{86}Sr$ isotopic ratios. Major-element zoning in plagioclase is best explained by trapped liquid in the pore spaces between cumulus crystals, which is a result of the complex interplay between the rate of crystal growth and the cooling rate. Isotopic zoning in feldspars likely reflects crystal growth in a magma that is becoming, or has become, isotopically contaminated through wall rock partial melting and assimilation processes. Mineral-scale isotopic zoning, such as detected in plagioclase, can be used to infer the cooling rates of layered intrusions

36. PERCHIAZZI Natale, DEMITRI Nicola, FEHER Bela et al.: On the crystal-chemistry of rosasite and paradsasvarite. *Canadian Mineral.* 55(6), 2017, 1027-1040. [natale.perchiazzi@unipi.it]

We report the results of mineralogical and structural studies of parádsasvárite from Rudabánya, Hungary, and rosasite from Hayden, Arizona (USA). A preliminary investigation of the two minerals, which belong to the rosasite–malachite group, was conducted using Raman spectroscopy, X-ray diffraction, and EPMA. Parádsasvárite has the chemical formula $(Zn_{1.91}Cu_{0.06}Mg_{0.02})_{\Sigma 1.99}(CO_3)(OH)_2$, ideally $Zn_2(CO_3)(OH)_2$, and rosasite has the formula $(Cu_{1.14}Zn_{0.84}Mg_{0.02})_{\Sigma 2}(CO)_3(OH)_2$, matching the general formula $CuZn(CO_3)(OH)_2$. The first single-crystal full structural study of rosasite from Hayden, based on synchrotron X-ray data, is reported here and fully confirms the results obtained by Perchiazzi (2006) on the basis of X-ray powder data. The presence of structural disorder in Cu-Zn distribution in these minerals is indicated by the streaking of reflections along *c**. Rosasite is monoclinic, $P2_1/a$, *a*12.2436(29) Å, *b* 9.3555(19) Å, *c* 3.1535(6) Å, β = 98.69(3)°, and its crystal structure was refined to R_1 = 12.4%, wR_2 = 35.5%. The presence of Cu^{2+} causes a Jahn-Teller distortion of coordination polyhedra, a major feature of the rosasite crystal structure, particularly evident in the Me1 coordination polyhedron, which is fully occupied by Cu. A Rietveld study of parádsasvárite, based on synchrotron radiation data, shows it is isostructural with rosasite, monoclinic $P2_1/a$, *a* 12.253(4) Å, *b* 9.348(3) Å, *c* 3.167(1) Å, β = 97.700(4)°, and its crystal structure was refined to R_1 = 1.45%, wR_2 = 2.45%. The Me1 and Me2 coordination polyhedra in parádsasvárite, the former hosting Zn with a minor presence of Cu, the latter fully occupied by Zn, are as expected both more regular than the corresponding polyhedra in rosasite. Crystal-chemical considerations, based on literature chemical data for rosasite and Zn-rich malachite, indicate that a minimum Cu content of 0.4–0.5 *apfu* is necessary to stabilize the malachite-type structure.

37. SOROKINA Elena S., KARAMPELAS Stefanos, NISHANBAEV Tursun P. et al. : Sapphire megacrysts in syenite pegmatites from the Ilmen Mountains, South Urals, Russia : New mineralogical data. *Canadian Mineral.* 55(5), 2017, 823-843. [elensorokina@mail.ru]

Sapphires in the Ilmen Mountains of Russia's South Urals are found in syenite pegmatites where the mineral forms blue transparent to translucent megacrysts up to 6 cm in length. The corundum crystallized during the magmatic stage in equilibrium with columbite-(Fe), K-Na-feldspar, and ± perthite. There was a later metasomatic stage in which muscovite formed by the reaction corundum + orthoclase + H_2O ↔ muscovite and diaspore precipitated. Highly distributed syn- and post-tectonic brittle deformation of the host rocks is responsible for the polysynthetic twinning and parting of blue sapphires along the *r* face, which decreases the gem quality of the raw material. The formation of the corundum syenite pegmatites is associated with the intrusion of miascites in the Ilmenogorsky complex of alkaline rocks. Columbite-(Fe), zircon, and minerals from the alkali feldspar group were identified as syngenetic inclusions within the blue sapphire. Monazite-(Ce), sub-micron grains of uraninite, muscovite and diaspore, and exsolved

micron-sized needles of ilmenite were also found. The chemical composition of the sapphires fits well with those of magmatic sapphires from the literature with 10,000Ga/Al above 2.7, Ga/Mg > 29, Fe/Mg > 429, Cr/Ga < 0.074, and Fe/Ti > 19. Solid inclusions within the sapphires of the Ilmen syenite pegmatites, as well as their chemistry, provide possible genetic linkages with sapphires from alluvial and eluvial deposits of alkali basaltic terrains in Houai Sai (northern Laos) and several mines in Chantaburi province (Thailand).

38. TANER Mehmet F., DREVER Cameron, YAKYMCHUK Chris et al. : Origin of graphite in the southwestern Grenville Province. *Canadian Mineral.* 55(6), 2017, 1041-1055. [cyakymchuk@uwaterloo.ca]

Two graphite deposits in the southwestern Grenville Province are investigated to evaluate the origin of graphitic carbon and to test if the graphite mineralization is syngenetic or epigenetic. Graphite mineralization in the Bissett Creek deposit is characterized by homogeneously distributed and disseminated graphite flakes (approximately 1 to 5 mm in size and 2 to 10 vol.%) within graphitic gneisses. The graphite flakes are intergrown with metamorphic minerals, most notably biotite. The Montpellier graphite showing in Québec contains graphite concentrations of up to 20 vol.%. In contrast to the disseminated and homogenously distributed graphite in the Bissett Creek deposit, graphite mineralization at Montpellier forms lenses of variable sizes that occur at the top of a calc-silicate unit and as graphite-rich lenses in biotite-sillimanite-rich paragneiss. The $\delta^{13}C$ of graphite ranges from –29 to –17 ‰ at Bissett Creek and from –18 to –14 ‰ at Montpellier. Carbon isotope compositions of graphite from both deposits support a biogenic source for the carbon and the spread in $\delta^{13}C$ can be generated through Rayleigh fractionation. A minor contribution of inorganic carbon from the devolatilization of carbonate minerals is possible at Montpellier. Mineralization at Bissett Creek and Montpellier is interpreted to represent syngenetic graphite mineralization from organic-rich material during high-temperature metamorphism.

39. TRAN Linh K., STEPIEN Kathleen R., BOLLMEYER Melissan M. et al. : Substitution of sulphate in apatite. *American Mineral.* 102(10), 2017, 1971-1976. [cyoder@fandm.edu]

The substitution of sulfate in apatite is of potential importance in synthetic biomaterials used in bone repair and reconstruction. The counter ion (e.g., Na^+, K^+, Mg^{2+}, Sr^{2+}) in the sulfate reagent may also be used as a source of medically beneficial ions. An

understanding of the structural parameters controlling sulfate substitution is also important in expanding our knowledge beyond the substitution of carbonate in apatites. The incorporation of sulfate in calcium and strontium hydroxylapatites, prepared in aqueous solution at pH 9, was verified by combustion analysis of sulfate, infrared and Raman spectroscopy, and by determination of unit-cell parameters. Sulfate could not be incorporated into barium hydroxylapatite because of the preferential formation of $BaSO_4$. The amount of sulfate substituted in the apatite was affected by the mole ratio of sulfate to phosphate in the reaction mixture and by the nature of the counter ion in the sulfate reagent. When sodium is the counter ion in the sulfate reagent, the molar amounts of both sodium and sulfate in the product apatite can be explained by assuming charge compensation by sodium ions and sulfate displacement of phosphate and calcium. With lithium as the counter ion, a greater molar amount of lithium than sulfate is incorporated into the apatite, an observation that requires an additional charge-compensation mechanism. With potassium and rubidium as counter ions, less of the counter ion is incorporated than sulfate, probably a result of less favorable accommodation of the larger cation in the apatite structure. The maximum molar amount of sulfate incorporated in hydroxylapatite (prepared in the presence of Na^+) is more than three times lower than the maximum molar amount of carbonate that can be incorporated, a difference that can be explained by the relative solubilities of the substituted apatites. The unit-cell parameters determined for both sulfated calcium and strontium hydroxylapatites synthesized with the sodium counter ion show a slight increase in the *a*-axis length and a nearly constant *c*-axis length with increasing sulfate content. The difference in the variation of unit-cell parameters with anion content can be rationalized by the difference in size of the anion. The results indicate that sulfate can be incorporated into biomaterials such as apatite or in composites with calcium sulfate and that the design of new apatites and composites could include the use of medically desirable counter cations.

40. VILLIERS Johan P. R. de: How to sustain mineral resources: beneficiation and mineral engineering opportunities. *Elements* 13(5), 2017, 307-312. [Johan.deVilliers@up.ac.za]

The sustainability of a mineral resource depends, among other aspects, on what the mineral in question will be used for, price fluctuations, future resource requirements, and downstream manufacturing. A balance must be struck between the long-term commitment of developing a mineral deposit against the short-term threats of a changing commercial and social environment. Long-term resource sustainability is dependent both on increased efficiency, which improves profitability, and on revitalizing marginal mines. This is illustrated through breakthroughs in the processing of low-grade copper and refractory gold ores, as well as nickel laterite ores. Retreatment of mine wastes and tailings can also increase the sustainability of mining activity. Ongoing research and development is also helping to sustain mineral resource exploitation.

41. YU Zuxiang and WANG Hanggen : The Crystal structure of lisiguangite. *Acta Geol. Sinica* 91(4), 2017, 1270-1275. [yuzuxiang001@163.com]

The crystal structure of lisiguangite, CuPtBiS3, from Yanshan mountains, Chengde Prefecture, Hebei Province, China has been determined by single crystal X-ray diffraction. It belongs to orthorhombic space group P212121 with a = 7.7372(15) Å, b = 12.844(3) Å, c = 4.9062(10) Å, V = 487.57(17) Å3, Z = 4. The final full-matric least-square refinement on F2 converged with R1 = 0.0495 and wR2 = 0.0992 for 704 observed reflections [I≥2σ(I)]. Lisiguangite is the isomorph of known CuNiSbS3 and CuNiBiS3. Pt2+ and Bi3+ have the distorted octahedral coordination environments composed of two metal and four S and Cu+2 has a distorted tetrahedral coordination environment with four S atoms. Each S atom is surrounded by four metals to give a tetrahedral environment. The crystal structure is a complex 3 dimensional network.

PALEONTOLOGY

42. GUO Caiqing, YAO Jianxin, ZHANG Jianwei et al. : New fossil liverworts from the Lower Cretaceous of western Liaoning, China. *Acta Geol. Sinica* 91(5), 2017, 1542-1552. [lics@ibcas.ac.cn]

Sixteen liverwort specimens collected from the Lower Cretaceous Yixian Formation of Huangbanjigou Village, Liaoning Province, China are studied in this work. The plants are thalloid and preserved in brown arenaceous mudstone as impressions. Based on examinations, the liverworts are assigned to two new genera and five new species: Riccardiothallus palmata sp. nov., Pallaviciniites stricta sp. nov., Pellites latithallus gen. et sp. nov., Conocephalumites hexagonites gen. et sp. nov. and Metzgerites multifidus sp. nov., belonging to five families and five genera. The fossil research indicates that the divergence of families, Aneuraceae and Metzgeriaceae, Pallaviciniaceae and Hymenophytaceae, Pelliaceae and Fossombroniaceae, was in the Lower Cretaceous (125 Ma). The research provides significant additions to the fossil liverwort records in Western Liaoning and offers fossil evidence for studying the classification and evolution of extant liverworts.

43. LAOJUMPON Chalida, SUTEETHORN Varavuudh, CHANTHASIT Phornphen et al. : New evidence of Sauropod dinosaurs from the Early Jurassic period of Thailand. *Acta Geol. Sinica* 91(4), 2017, 1169-1178. [Ch.laojumpon@gmail.com]

The oldest dinosaur assemblages of Thailand deposit in continental sedimentary rocks of the Nam Phong Formation. Not only *Isanosaurus attavipatchi* was discovered but at least two more species of basal sauropods were found. A partial skeleton from Phu Hin Tan locality refers to sauropod taxon A. It is different from *Isanosaurus* and shares some characteristics with basal sauropods in the Early Jurassic. The sauropod taxon B was found in Non Sra Ard locality. Base on postcranial skeleton, sauropod taxon B shares some characteristics of the family Vulcanodontidae. Moreover, several fragments of the sauropods specimen are also found in Pha Khok Wang Yang and Phu Noi localities. All of the evidences above indicate that there are a highly diversity of sauropods in the Nam Phong Formation. At least three sauropod species (including *Isanosaurus)* were found in the Nam Phong formation. The issue about the age of the Nam Phong has been debated for a long time between the Triassic and Jurassic age. All of sauropodomorphs, in this study, are more likely the Early Jurassic period dinosaurs than the Triassic period dinosaurs. And they have deposited in the upper part of Nam Phong Formation.

44. **WANG Xiaolin, KELLNER Alexander W. A. JIANG Shunxing et al. :** Egg accumulation with 3D embryos provides insight in to the life history of a pterosaur. *Science* 358(6367), 2017, 1197-1201. [wangxiaolin@ivpp.ac.cn]

Fossil eggs and embryos that provide unique information about the reproduction and early growth of vertebrates are exceedingly rare, particularly for pterosaurs. Here we report on hundreds of three-dimensional (3D) eggs of the species *Hamipterus tianshanensis* from a Lower Cretaceous site in China, 16 of which contain embryonic remains. Computed tomography scanning, osteohistology, and micropreparation reveal that some bones lack extensive ossification in potentially late-term embryos, suggesting that hatchlings might have been flightless and less precocious than previously assumed. The geological context, including at least four levels with embryos and eggs, indicates that this deposit was formed by a rare combination of events, with storms acting on a nesting ground. This discovery supports colonial nesting behavior and potential nesting site fidelity in the Pterosauria.

PETROLOGY : IGNEOUS

45. **BEER C. H. de and MACEY P. H. :** Lithostratigraphy of the Mesoproterozoic garies granite. *South African J. Geol.* 119(4), 2016, 699-704. [cdebeer@geoscience.org.za]

The Garies Granite is a mesocratic to leucocratic, porphyritic post-tectonic member of the Spektakel Suite in the Mesoproterozoic Namaqua-Natal Belt of western

Namaqualand. It is a composite unit, showing a continuum of rock types from mesocratic porphyritic biotite granite with characteristic slender phenocrysts (Rooiberg-type) to coarse grained equigranular leucocratic granite (Karkams-type) with few or no phenocrysts at all. Metamict zircons prevented accurate dating, but field relationships suggest the Garies Granite is synchronous to slightly younger than the spatially associated Kliphoek Granite, which has recently been dated at 1078 ± 5 Ma and 1060 ± 9 Ma. The acidic, potassic and weakly peraluminous granite yielded ε values of between -1.39 and 0.61 and T values of between Nd DM 1579 and 1710 Ma indicating a significant contribution of older crustal material to the source magma.

46. CHEADLE Michael J. and GEE Jeffrey S. : Quantitative textural insights into the Formation of Gabbro in mafic intrusions. *Elements* 13(6), 2017, 409-414. [cheadle@uwyo.edu]

Rock textures provide a key to deciphering the physical processes by which gabbro forms in mafic intrusions. Development in both direct optical and crystallographic method as well as indirect magnetic fabric measurements, promise significant advances in understanding gabbroic textures. Here, we illustrate how bulk magnetic fabric data, particularly from intrusions with sparse silicate-hosted magnetite, may be used to extend direct crystallographic observations from thin sections. We also present a scheme for characterizing crystallographic foliation and lineation and use this to suggest that the strength of gabbro plagioclase foliations and lineations varies significantly with geodynamic environment.

47. FARBER K., DZIGGEL A., MEYER F. M. et al. : Petrology, geochemistry and fluid inclusion analysis of altered komatiites of the Mendon Formation in the BARB4 drill core, Barberton greenstone belt, South Africa. *South African J. Geol.* 119(4), 2016, 639-654. [farber@iml.rwth-aachen.de]

The 3.33 to 3.26 Ga Mendon Formation in the Palaeoarchaean Barberton greenstone belt, South Africa, forms the uppermost unit of the Onverwacht Group. It is dominated by ultramafic volcanic rocks interbedded with thin layers of cherty sediments that show pervasive alteration, including widespread serpentinisation, silicification and chert and quartz veining. The BARB4 drill core of the ICDP Barberton drilling project exposes a unique section through the Mendon Formation in the Manzimnyama Syncline. The komatiites are pervasively altered to an assemblage comprising quartz, chlorite,

carbonate, talc, biotite, and, locally, plagioclase, K-feldspar, muscovite, amphibole, stilpnomelane and ankerite. The overlying sediments are made up of banded iron formations and rare beds of siliciclastic rocks. Though the altered komatiites are pervasively silicified, SiO_2 contents do not exceed 58 wt.%, and their major and trace element geochemistry is similar to other komatiitic rocks of the Mendon Formation, particularly those of the M2v-member. Quartz veins and, less commonly, quartz-carbonate and quartz-carbonate-plagioclase veins are found throughout the core. Overall, composition and texture of the veins differ from primary and early diagenetic veins found in silicified komatiites elsewhere in the Barberton greenstone belt. In the BARB4 drill core, the veins are generally coarse-grained, and the immediate wall rocks are locally foliated along the vein margins. In addition, the $\delta^{18}O$ values of vein quartz range from 14.1 to 15.3‰, significantly lower than the values typically found in veins on the modern seafloor that formed during low temperature hydrothermal seafloor alteration (~22 to 32‰). Fluid inclusions in vein quartz are homogeneous two-phase (L+V) aqueous inclusions that occur in trans- and intragranular trails and clusters. Intragranular and isolated fluid inclusions have a similar homogenisation temperature (T_h) of 130 to 200°C, with most data ranging between 145 and 175°C. Salinities cluster in three different groups of high (20 to 27wt.% NaCl equiv.), medium (10 to 15wt.% NaCl equiv.) and low salinity (0.3 to 1.5wt.% NaCl equiv.). The composition and microthermometric characteristics of the fluid inclusions analysed within the drill core show similarities to those found in quartz veins in silicified komatiites of the Mendon Formation, which are interpreted to have been entrapped during metamorphism. P-T calculations based on fluid inclusion microthermometry reveal conditions of 230 to 400 MPa and 250 to 400°C. Similar conditions of 240 to 270°C have been obtained using oxygen isotope thermometry, assuming a metamorphic fluid with a $\delta^{18}O$ value of 6‰. Collectively, the $\delta^{18}O$ values, together with the texture and composition of the veins, are interpreted to indicate a metamorphic origin of the veins. The presence of high salinity inclusions indicates the occurrence of a highly saline fluid that locally mixed with the dominant lower salinity fluids. The high salinity might have been derived from fluid circulation through evaporites.

48. FRANZ Gerhard, KHOMENKO Vladimir, VISHNYEVSKYY Aleksei et al. : Biologically mediated crystallizations of buddingtonite in the Paleoproterozoic : organic-igneous interactions from the Volyn pegmatite, Ukraine. *American Mineral.* 102(10), 2017, 2119-2135. [Gerhard.franz@tu-berlin.de]

The Volyn pegmatites from Volodarsk-Volynskyi in the Zhytomyr Oblast, NW Ukraine, are associated with granites genetically related to the Paleoproterozoic Korosten pluton. Their late-stage evolution is characterized by the formation of opal-cemented breccia. A polymineralic pseudomorph after beryl within the breccia includes bertrandite (±euclase) + F-muscovite (with tobelite component) + buddingtonite + organic matter

(OM) + opal (+ traces of K-feldspar, albite, columbite, FeS_2, barite, REE-minerals). Sector-zoned and platy to fibrous buddingtonite has variable (K+Na)- vs. NH_4-contents (electron microprobe analyses) and some H_2O or H_3O^+, as indicated by microscope infrared spectroscopy. We suggest that ammonium was produced by decay of OM, which is partly preserved in the pseudomorph. Energy-dispersive electron microprobe data of the OM show with increasing O–decreasing C-N-content due to degassing; the OM contains the high field strength elements Zr (≤7 at%), Y (≤3 at%), Sc (≤0.8 at%), REE (≤0.3 at%), Th (≤0.2 at%), and U (≤1.25 at%), which increase with increasing O-content. Transmission electron microscopy of the OM confirms the presence of N; Zr, Si, and O (with other HFSE) are concentrated in nanometer-sized areas and at the transition from OM to opal in nanometer-sized platy Zr-Si-O crystals. C-rich areas are amorphous but show poorly developed lattice fringes. OM is present in the pseudomorph also as brown pigmentation of opal and in pegmatitic beryl from Volyn as a component in late stage fluid inclusions, identified by C-H vibrational bands in infrared spectra. Stable isotope investigations of C and N of buddingtonite, black opal and kerite (fibrous OM known from the literature to occur in the Volyn pegmatites and interpreted as microfossils) indicate a biogenic origin of the OM. We propose that OM in the pseudomorph is condensed kerite, which achieved the high concentrations of high field strength elements via fluid-pegmatite interaction. Although no age determination of minerals in the pseudomorph is available, textural arguments and phase equilibria indicate its formation in a late stage of the pegmatite evolution, at *P-T* conditions below ~100 MPa/150 °C. We favor a conceptual model for the formation of the Volyn buddingtonite in analogy to Phanerozoic occurrences of buddingtonite, where over and around the shallow anorthosite-granite Korosten pluton hydrothermal convection cells introduced N-bearing hydrocarbons and its precursors into the cooling igneous rocks. Due to the elevated temperature, the OM disintegrated into degassing volatile and non-volatile residual components analogous to petroleum maturation. Organic N, released as NH4, was then incorporated into buddingtonite.

49. GAGNEVIN Damien, HAUGHTON Peter D. W., WHITING Lewis et al. : Geological and geophysical evidence for a mafic igneous origin of the Porcupine Arch, offshore Ireland. *J. Geol. Soc.* 175(2), 2018, 210-228. [damien.gagnevin@icrag-centre.org]

Sedimentary basins west of Ireland contain a number of deep seismic structures that have been variously interpreted as fault blocks, serpentinite extrusions or igneous complexes. The Porcupine Arch (PA) is a deep-level (>11 km) domal 50 km wide seismic feature associated with a prominent free-air gravity anomaly high and high P-wave velocities. Detailed seismic mapping of igneous sill complexes in the Porcupine Basin suggests a possible connection with the PA. The sills form a thick (>5 km) interconnected

network extending from the PA into the flanking post-rift Cretaceous stratigraphy, suggesting that the PA may be the top of a large (ultra)mafic intrusion that fed the sills. An intrusive origin for the PA is in agreement with geophysical modelling (gravity and V_p), the seismic character of the Porcupine Arch structure and the primitive bulk composition of the Porcupine sills, and is consistent with documented regional Cenozoic uplift in the basin with the development of shallow water and the occurrence of Paleocene–Eocene deltaic depositional systems. Similar mafic–ultramafic intrusive complexes have been documented elsewhere on the northeastern Atlantic margin, including the Rockall Trough. These findings emphasize that higher heat flow in the early Cenozoic may have prevailed over the northern part of the Porcupine Basin.

50. HOLNESS M. B., NEUFELD J. A., GILBERT A. J. et al. : Orientation of tabular mafic intrusions controls convective vigour and crystallization style. *J. Petrol.* 58(10), 2017, 2035-2054. [marian@esc.cam.ac.uk]

The microstructure in basaltic dykes is significantly different from that in sills and lava lakes of the same bulk composition. For a given width of intrusion (or depth of lava lake), vertical tabular bodies are coarser grained than horizontal bodies, with an invariant plagioclase shape across the intrusion. When comparing samples from sills and dykes for which the average grain size is the same, the dyke samples contain fewer small grains and fewer large grains than the sill samples. In contrast, the variation of median clinopyroxene–plagioclase–plagioclase dihedral angles in dykes correlates precisely with that observed in sills and is a function of the rate of diffusive heat loss. These patterns can be accounted for if the early stages of crystallization in dykes primarily involve the growth of isolated grains suspended in a well-mixed convecting magma, with the final stage (during which dihedral angles form) occurring in a crystal-rich static magma in which heat loss is primarily diffusive. In contrast, crystallization in sills occurs predominantly in marginal solidification fronts, suggesting that any convective motions are insufficient to entrain crystals from the marginal mushy layers and to keep them suspended while they grow. An exception to this general pattern is provided by members of the Mull Solitary Dykes, which propagated 100–1000 km SE from the Mull Palaeogene Igneous Centre, Scotland, through the shallow crust. These dykes, where sampled >100 km from Mull, have a microstructure indistinguishable from that of a sill of comparable thickness. We suggest that sufficient nucleation and crystallization occurred in these dykes to increase the viscosity sufficiently to damp convection once unidirectional flow had ceased.

51. HOLNESS Marian B., NIELSEN Troels F. D. and TEGNER Chriatian : The skaergaard intrusion of east Freenland : paradigms, problems and new perspectives. *Elements* 13(6), 2017, 391-396. [marian@esc.cam.ac.uk]

The Skaergaard Intrusion of East Greenland is the quintessential example of low-pressure closed-system fractionation of basaltic magma. Field evidence of extensive layering and associated quasi-sedimentary structures, and the resultant 'cumulate' paradigm of crystal settling in magma chambers, has led to many long-standing controversies. Of particular significance is the lack of consensus about the microstructural record and the mechanisms by which interstitial liquid is expelled from solidifying crystal mushy zones. Skaergaard remains a cradle for new insights into igneous processes, with recent work highlighting the importance of separation of immiscible liquids on magma evolution.

52. JAIN A. K., SUSHMITA, SINGH Sandeep et al. : Migmatization, granite generation and melt accumulation in the Himalayan Orogenic Channel, Central and Eastern Bhutan. *Curr. Sci.* 114(9), 2018, 1903-1912. [himalfesgmail.com]

In Central and Eastern B hutan Himalaya, the Great Himalayan Sequence (GHS) reveals mesoscopic structures within the migmatite–leucogranite association due to crustal anataxis above the Main Central Thrust (MCT). The first phase of dominant melting generates stromatitic migmatite along the main foliation during high grade of metamorphism, possibly by dehydration melting. Subsequent ductile strike–slip shearing caused in situ melting in dilatational sites to produce structureless, non-foliated patchy leucogranite leucosome as well as in boudin necks and post-tectonic patches. In addition, melt-enhanced deformation caused doming of accumulated melt and subsidiary ductile shear zones on either margins of these domes. Surrounded by biotite-rich melanosome, leucosomes destroy the pre-existing foliation during new anatectic phase, which post-dates earlier stromatitic migmatite. These migmatites are the snapshot of mutual relations between newly-developed migmatite and leucogranite melt, and signify the transportation of Himalayan Orogenic Channel to the extreme south in Central and Eastern Bhutan over the Lesser Himalayan sedimentary belt along the MCT.

53. LATYPOV Rais, CHISTYAKOVA Sofya and MUKHERJEE Ria : A Novel hypothesis for origin of massive chromitites in the Bushveld Igneous Complex. *J. Petrol.* 58(10), 2017, 1899-1940. [Rais.Latypov@wits.ac.za]

The origin of chromitites in the Bushveld Complex has been attributed to two principal mechanisms: (1) gravity-controlled settling of chromite onto the chamber floor from magma that was saturated in chromite, either initially or owing to some internal process; or (2) gravity- and size-controlled separation of chromite from coexisting olivine and orthopyroxene within crystal-rich slurries, either formed directly within the chamber or brought into the chamber from some deep staging reservoirs. Here we present field observations from potholes, roughly circular structures in which footwall rocks were removed by magmatic erosion, that rule out both approaches. A key observation is that chromitites drape the irregular margins of potholes, even where they are vertical or overhanging. These relationships eliminate both early settling of chromite from the overlying magma and late mechanical segregation of chromite within cumulates as viable hypotheses. In addition, thick chromitites commonly consist of several texturally and compositionally distinct sublayers that are locally separated by thin partings of silicate rocks. The absence of thick sequences of intervening silicate rocks from which chromite may have been separated to form these sublayers refutes an origin from crystal slurries. Transgression of chromitite–orthopyroxenite units by hanging-wall rocks excludes the origin of chromitites from crystal slurries that intrude as late-stage sills into pre-existing cumulates. The field relationships appear to be compatible only with the emplacement of superheated, dense magma along the temporary base of the chamber that led to intense melting and dissolution of the pre-existing floor cumulates, followed by the *in situ* crystallization of chromite directly on the irregular chamber floor. Chromitites of differing thicknesses are produced, according to the volume of the multiple replenishments. This model involving *in situ* crystallization of basal layers of magmas, which are saturated with chromite on cooling in the chamber, can be extended to explain the origin of chromitites in other layered intrusions.

54. LAY Angela, GRAHAM Ian and COHEN David : Ophiolitc chromitites of Timor Leste : their composition, Platinum Group element geochemistry, mineralogy and evolution. *Canadian Mineral.* 55(5), 2017, 875-908. [angela.lay@unsw.edu.au]

Ultramafic rocks that crop-out as fault-bounded blocks within Hili Manu, ~50 km east of the capital Dili on the north coast of Timor Leste, have been a topic of considerable debate regarding their ophiolitic affiliation with the Banda Arc or Australian subcontinental lithosphere. Two discrete ultramafic massifs separated by amphibolite of undefined origin, Be Heda Hill and Kerogeol Hill in the east and Subao Highway in the west, have been identified and host tabular and vein-like chromitite morphologies, respectively. The chromitite bodies at Hili Manu occur as small lenses a few meters in size. This paper presents the first detailed investigation of the chromitites from the two massifs at Hili Manu, including their mineralogy, textures, and chemistry. Chemically, the primary chromites from the Hili Manu chromitites comprise both high-Cr type (Cr2O3

40.24-56.95 wt.% and Cr# [Cr/(Cr + Al)] > 0.6) that occur at Kerogeol Hill and Subao Highway and high-Al type (Cr2O3 35.70-37.38 wt.% and #Cr < 0.56) that are restricted to Be Heda Hill. Similarly, the accessory spinels of the enclosing wall rocks also show high-Cr (#Cr = 0.60-0.82) and high-Al varieties (#Cr = 0.17-0.48). Platinum-group minerals (PGM) such as laurite and possible erlichmanite-series minerals, silicates, base metal sulfides (BMS), and arsenides are found as inclusions and within fractures in the chromite or the serpentinite matrix. The platinum-group element (PGE) concentration of the Hili Manu chromitites and its immediate host peridotite at the three localities varies, with total PGE (Os + Ir + Ru + Rh + Pt + Pd) in the ranges 73.1-1295 ppb and 28.5-364 ppb, respectively. The total PGE content is higher and the Pd/Ir ratio is lower in the Cr-rich chromitites compared to the Al-rich ones. Most of the PGM are 3-10 μm in size and occur as primary or composite inclusions in IPGEbearing phases, particularly Os-rich laurite, within unaltered chromite grains. Host peridotite major- and trace-element geochemistry coupled with the chemistry of chrome-spinels for both the chromitites and host peridotites in this study show evidence of formation of the Hili Manu peridotite in an upper mantle in a supra-subduction zone setting, part of the young oceanic lithosphere from the Banda Arc.

55. MAIER Wolfgang D. and HANSKI Eero J. : Layered mafic-ultramafic intrusions of fennoscandia : Europe's treasure chest of magmatic metal deposits. *Elements* 13(5), 2017, 415-420. [maierw@cardiff.ac.uk]

Northeastern Fennoscandia hosts a rich diversity of mafic–ultramafic intrusions of variable shape and size, emplaced in different tectonic regimes over a period spanning ~600 million years (between 1.88 Ga and 2.5 Ga). Several of the bodies contain world-class ore deposits, notably the Kemi chromium deposit and the Pechenga nickel deposits. Other deposits include nickel and copper at Kevitsa, Kotalahti and Sakatti; vanadium at Koillismaa; and platinum-group elements at Portimo and Penikat. These deposits constitute important resources that could shield Europe from potential future supply shortages of these key industrial metals.

56. MATHEZ Edmond A. and KINZLER Rosamond J. : Metasomatic chromitite seams in the Bushveld and Rum layered intrusions. *Elements* 13(5), 2017, 397-402. [mathez@amnh.org]

Millimeter–centimeter thick layers of chromite-rich rock (chromitites) are rare, but ubiquitous, features of the Bushveld (South Africa) and Rum (Scotland) layered

intrusions. Despite their meager dimensions, the chromitites provide insight into processes that modify igneous layering and, in the Bushveld, the formation of the platinum-group element–rich Merensky Reef. The Merensky Reef chromitites represent reaction zones formed in a compositional gradient between hydrous silicate melt and a crystalline cumulate assemblage, analogous to reaction zones in metamorphic systems. At Rum, the chromitites formed at the melting front between newly injected magma and the magma chamber floor, an analogous process but one driven by thermal, rather than chemical, energy.

57. O'DRISCOLL Brian and VANTONGEREN Jill A. : Layered intrusions : from petrological paradigms to precious metal repositories. *Elements* 13(6), 2017, 383-389. [brian.odriscoll@manchester.ac.uk]

Layered mafic–ultramafic intrusions have occupied a position of central importance in the field of igneous petrology for almost a century. In addition to underpinning petrological paradigms such as cumulus theory, some layered intrusions are exceptionally enriched in base and precious metals, including the platinum-group elements. Technological advances are driving the current and future state-of-the-art in the study of layered intrusions and, looking forward, it is clear that these bodies will continue to inspire and challenge our understanding of magmatic systems and magma solidification for many years to come.

58. REHANUL Haq Siddiqui, M. QASIM Jan, MOHAMMAD Asif Khan et al. : Petrogenesis of the Late Cretaceous Tholeiitic volcanism and oceanic Island Arc affinity of the Chagai Arc, Western Pakistan. *Acta Geol. Sinica* 91(4), 2017, 1248-1263 [kakarmi.cemuob@gmail.com]

The Late Cretaceous Chagai arc outcrops in western Pakistan, southern Afghanistan and eastern Iran. It is in the Tethyan convergence zone, formed by northward subduction of the Arabian oceanic plate beneath the Afghan block. The oldest unit of the Chagai arc is the Late Cretaceous Sinjrani Volcanic Group. This is composed of porphyritic lava flows and volcaniclastic rocks, and subordinate shale, sandstone, limestone and chert. The flows are fractionated low-K tholeiitic basalts, basalticandesites, and andesites. Relative enrichment in their LILE and depletion in HFSE, and negative Nb and Ta and positive K, Ba and Sr anomalies point to a subduction-related origin. Compared to MORB, the least fractionated Chagai basalts have low Na_2O, $Fe_2O_3^T$, CaO,

Ti, Zr, Y and $^{87}Sr/^{86}Sr$. Rather than an Andean setting, these results suggest derivation from a highly depleted mantle in an intraoceanic arc formed by Late Cretaceous convergence in the Ceno-Tethys. The segmented subduction zone formed between Gondwana and a collage of small continental blocks (Iran, Afghan, Karakoram, Lhasa and Burma) was accompanied by a chain of oceanic island arcs and suprasubduction ophiolites including Semail, Zagros, Chagai-Raskoh, Kandahar, Muslim Bagh, Waziristan and Kohistan-Ladakh, Nidar, Nagaland and Manipur. These complexes accreted to the southern margin of Eurasia in the Late Cretaceous.

59. STALDER Roland, POTRAFKE Alexander, BILLSTROM Kjell et al. : OH defects in quartz as monitor for igneous, metamorphic and sedimentary processes. *American Mineral.* 102(9), 2017, 1832-1842. [roland.stalder@uibk.ac.at]

Oriented sections of more than 500 quartz grains from sediments, igneous, and metamorphic rocks from different localities in Sweden, Austria, Germany, and South Africa were analyzed by FTIR spectroscopy, and their OH defect content was determined with respect to the speciation and total defect water content. Systematic variations of defect speciation and statistical evaluation of total defect contents were used to evaluate the potential of FTIR spectroscopy on quartz as a thermometer in quartzite, as a tool for differentiation trends in granitic systems, and for provenance analysis of sedimentary rocks. In addition to the analyses of natural crystals, high-pressure annealing experiments at lower crustal conditions (1–3 kbar and 650–750 °C) were performed to document the effect of high-grade metamorphism on the defect chemistry. Results indicate that (1) quartz grains from unmetamorphosed granite bodies reveal interesting differentiation trends; (2) sediments and sedimentary rocks are valuable archives to preserve the pre-sedimentary OH defect chemistry, where individual signatures are preserved and can be traced back to potential source rocks; (3) OH defects are retained up to 300 °C over geological time scales; (4) long-term low-grade metamorphic overprint leads to a continuous annealing to lower defect water contents, where Al-specific OH defects survive best; and (5) middle to high-grade annealing drives toward a homogeneous defect partitioning from grain to grain, where the degree of attainment of equilibrium depends on temperature and duration of the thermal event. In summary, OH defects in quartz crystals monitor parts of their geological history, and the systematic investigation and statistical treatment of a large amount of grains can be applied as an analytical tool to study sedimentary, metamorphic, and igneous processes.

PETROLOGY: METAMORPHIC

60. MARTELAT Jean-Emmanuel, PAQUETTE Jean-Louis, BOSSE Valerie et al. : Chronological constraints on Tsavorite mineralizations and related metamorphic episodes in southeast Kenya. *Canadian Mineral.* 55(5), 2017, 845-865. [Univ. Lyon, Lab. Geol. Lyon, Cedex (FRA)]

Tsavorite is exclusively hosted in the Neoproterozoic Metamorphic Mozambique Belt (NMMB). The gemstone mines, widespread between Kalalani (Tanzania) and Mgama Ridge (Kenya), define a continuous corridor over a hundred kilometers in length. The tsavorite is hosted by a metasedimentary sequence defined as the Kurase tsavorite-bearing metasediments (Kurase-TB metasediments) that also hosts rubies. These metasediments underwent amphibolite-facies metamorphism and are surrounded by granulitic gneisses that are also of sedimentary origin (the Kurase high-temperature gneisses). All these rocks lie below the Kasigau Group, a unit dominated by granulite-facies metamagmatic rocks. To constrain the timing of events that led to this peculiar occurrence of tsavorite, we have performed geochronological analyses of thin sections and of separated grains of zircon, monazite, and rutile using LA-ICP-MS and ID-TIMS, as well as 40Ar/39Ar of muscovite and phlogopite from various lithologies. The results show that the different terranes were metamorphosed synchronously between 620–580 Ma but under different P-T strain conditions. The Kurase-HT gneisses and the rocks from the Kasigau Group are highly strained and underwent granulite-facies metamorphism with abundant partial melting and emplacement of felsic melts between 620 and 600 Ma. Textural observations also underlined a late regional water flux controlling the occurrence of V-free muscovite and monazite mineralizations at 585 Ma. The latter event can be related to the activity of the Galana shear zone, in the east. The Kurase-TB metasediments escaped strain and partial melting. They record amphibolite-facies conditions with static heating, since initial sedimentary structures were locally preserved. The age of the tsavorite mineralization was inferred at 600 Ma from metamorphic zircon rims and monazite from the closest host-rocks, sampled in the mines. Hence, tsavorite crystallization occurred statically at the end of the metamorphic event, probably when the temperature and the amount of volatiles were at maximum levels. Conversely, the ruby formed by local metasomatism of felsic dikes and isolated ultramafic bodies. The rubies are older and zircons and monazites from a ruby-bearing felsic dike (plumasite) were dated at 615 Ma. Finally, data from rutile and micas indicate a global cooling below 430°C of the whole region between 510 and 500 Ma.

61. PUTNIS Andrew, JAMTVEIT Bjorn and AUSTRHEIM Hakon : Metamorphic processes and seismicity : the Bergen Arcs as a Natural Laboratory. *J. Petrol.* 58(10), 2017, 1871-1898. [andrew.putnis@curtin.edu.au]

In the Bergen Arcs rocks that formed the root zone of the Caledonian mountain chain formed by the collision of Laurentia and Baltica at $400 Ma are exposed. They display a well-exposed, high-grade metamorphic terrane where Sveconorwegian granulites and Caledonian eclogite and amphibolite parageneses coexist spatially and provide challenging problems related to their interrelationships and their geodynamic settings. Some of the ideas that have been proposed for the formation of the granulites and the mechanism of their retrograde hydration during the Caledonian orogeny are reviewed. We make some preliminary microstructural observations on the earliest stages of retrogression and suggest that much progress in understanding metamorphism in terranes such as the Bergen Arcs could be made by greater attention to the relationship between seismicity and metamorphism. The Bergen Arcs provide a natural laboratory in which it should possible to elucidate the extent to which seismicity and cataclasis are a necessary precursor to fluid infiltration and metamorphism, the volume of rock processed by cataclasis during an orogenic event and the role of deviatoric stress in the metamorphic reactions.

PLANETS AND METEORITES

62. WARD Dustin, BISCHOFF Addi, ROSZJAR Julia et al. : Trace element inventory of meteoritic Ca-phosphates. *American Mineral.* 102(10), 2017, 1856-1880. [d.ward@uni-muenster.de]

The most common meteoritic phosphate species are apatite [Ca5(PO4)3(F,Cl,OH)] and merrillite [Ca9NaMg(PO4)7]. Both are important accessory phases in numerous meteorite classes which formed under varying conditions, such as oxidizing (e.g. martian meteorites) as well as reducing (e.g. winonaites) environments [1,2]. Both of them occur in varying abundances and their grain sizes range from µm to mm. Moreover, they are the dominating carrier phases for REEs as well as for halogens and therefore provide insight into the genesis and evolution of their host rocks. Nevertheless, their abundances, distribution and formation mechanisms – especially within the early Solar System – still remain poorly constrained [3-6].

PLATE TECTONICS

63. GREBER Nicolas D., DAUPHAS Nicolas, BEKKER Andrey et al. : Titanium isotopic evidence for felsic crust and plate tectonics 3.5 billion years age. *Science* 357(6357), 2017, 1271-1274. [nicolas.greber@unige.ch]

Earth exhibits a dichotomy in elevation and chemical composition between the continents and ocean floor. Reconstructing when this dichotomy arose is important for understanding when plate tectonics started and how the supply of nutrients to the oceans changed through time. We measured the titanium isotopic composition of shales to constrain the chemical composition of the continental crust exposed to weathering and found that shales of all ages have a uniform isotopic composition. This can only be explained if the emerged crust was predominantly felsic (silica-rich) since 3.5 billion years ago, requiring an early initiation of plate tectonics. We also observed a change in the abundance of biologically important nutrients phosphorus and nickel across the Archean-Proterozoic boundary, which might have helped trigger the rise in atmospheric oxygen.

SEDIMENTOLOGY

64. EIDE Christian Haug, SCHOFIELD Nick, LECOMTE Isabelle et al. : Seismic interpretation of sill complexes in sedimentary basins : implications for the sub-sill imaging problem. *J. Geol. Soc.* 175(2), 2018, 193-209. [christian.eide@uib.no]

Application of 3D-seismic reflection-data to igneous systems in sedimentary basins has led to a revolution in the understanding of mafic sill complexes. However, there is considerable uncertainty on how geometries and architecture of sill-complexes within the subsurface relates to those imaged in seismic reflection-data. To provide constraints on how sill complexes in seismic data should be interpreted, we present synthetic seismograms generated from a seismic-scale (22x0.25 km) outcrop in East Greenland constrained by abundant field-data. This study highlights how overlying igneous rocks adversely affect imaging of underlying intrusions and rocks by decreasing seismic amplitude, frequency and making steeply dipping features near-impossible to image. Furthermore, seismic modelling in this study shows that, because of the high impedance contrast between siliciclastic host-rock and dolerites, very thin (1-5 m) intrusions should in principle be imaged in reflection-seismic data at 3 km depth. However, comparison with actual seismic data with well-data shows significant amounts of unimaged sill intrusions, and this is likely due to limited seismic resolution, overburden complexity, inadequate velocity-models, and interference between reflections from closely spaced sills and sill-splays. Significant improvements to sill imaging and interpretation could be made by better predicting occurrence and geometry of sill intrusions and including these in velocity models.

SEISMOTECTONICS

65. HINCKS Thea, ASPINALL Willy, ROGER Cooke et al. : Oklahoma's induced seismicity strongly linked to wastewater injection depth. *Science* 359(6381), 2018, 1251-1255. [Thomas.gernon@noc.soton.ac.uk]

The sharp rise in Oklahoma seismicity since 2009 is due to wastewater injection. The role of injection depth is an open, complex issue, yet critical for hazard assessment and regulation. We developed an advanced Bayesian network to model joint conditional dependencies between spatial, operational, and seismicity parameters. We found that injection depth relative to crystalline basement most strongly correlates with seismic moment release. The joint effects of depth and volume are critical, as injection rate becomes more influential near the basement interface. Restricting injection depths to 200 to 500 meters above basement could reduce annual seismic moment release by a factor of 1.4 to 2.8. Our approach enables identification of subregions where targeted regulation may mitigate effects of induced earthquakes, aiding operators and regulators in wastewater disposal regions.

66. MEIER M. A., AMPUERO J. P. and HEATON T. H. : The hidden simplicity of subduction megathrust earthquakes. *Science* 357(6357), 2017, 1277-1281. [mmeier@caltech.edu]

The largest observed earthquakes occur on subduction interfaces and frequently cause widespread damage and loss of life. Understanding the rupture behavior of megathrust events is crucial for earthquake rupture physics, as well as for earthquake early-warning systems. However, the large variability in behavior between individual events seemingly defies a description with a simple unifying model. Here we use three source time function (STF) data sets for subduction zone earthquakes, with moment magnitude $M_w \geq 7$, and show that such large ruptures share a typical universal behavior. The median STF is scalable between events with different sizes, grows linearly, and is nearly triangular. The deviations from the median behavior are multiplicative and Gaussian—that is, they are proportionally larger for larger events. Our observations suggest that earthquake magnitudes cannot be predicted from the characteristics of rupture onsets.

STRATIGRAPHY

67. DEW Romana E. C., KING Rosalind, COLLINS Alan S. et al. : Stratigraphy of deformed Permian carbonate reefs in Saraburi Province, Thailand. *J. Geol. Soc.* 175(1), 2018, 163-175. [romana.dew@adelaide.edu.au]

Kilometre-scale thrusts affect the stratigraphic order of the sedimentary rocks that form the Khao Khwang Platform in central Thailand. The effect of these thrusts requires detailed analysis to unravel the original distribution of the sedimentary units and their associated facies. The Khao Khwang Platform comprises three carbonate-dominated units identified previously as the Phu Phe, Khao Khad and Khao Khwang Formations. These carbonates are intercalated with clastic, mixed siliciclastic and carbonate sequences: the Sap Bon, Pang Asok and Nong Pong Formations. The palaeogeography of the area prior to the Indosinian Orogeny is poorly known and has herein been investigated by combining structural reconstructions, microfacies and biostratigraphy in the Saraburi area. A stratigraphic model for the Yakhtashian-Midian carbonate platform palaeogeography using the well-developed exposed sections of the Khao Khwang Platform, located in the Saraburi Province of Thailand, is presented. This has revealed the presence of several separate carbonate platforms dominated by four major Middle Permian facies (peritidal, platform interior, algal reef and basin slope), which are dated using foraminifera and algae. This model integrates recent structural studies and considers their impact on the present-day distribution of the facies in terms of platform development using biostratigraphy and detailed microfacies analysis.

68. KLAUSEN Tore Grane, MULLER Reidar, SLAMA Jiri et al. : Depositional history of a condensed shallow marine reservoir succession : stratigraphy and detrital zircon geochronology of the Jurassic Sto Formation, Barents Sea. *J. Geol. Soc.* 175(1), 2018, 130-145. [tore.klausen@uib.no]

The Early to Middle Jurassic Stø Formation (Toarcian to Bajocian) was deposited in a relatively shallow (10 s of meter deep) epicontinental sea in northern Pangea and represents one of the most prolific reservoir intervals in the Barents Sea basin. It comprises a condensed, predominantly shallow marine succession characterized by long hiatuses and erosional reworking with several horizons of extraformational pebble grade conglomerate. Six distinct facies associations describe sedimentological environments ranging from transgressive, tidal, fluvial and regressive shoreface. Deposits are interpreted and correlated within three sequence stratigraphic units (SI to SIII) which reflect variations in relative sea-level during an overall transgression of the basin.

Interpreted depositional systems show subtle variations in petrographic character, but provenance analyses reveal different sedimentary sources. Thirteen core samples distributed geographically and stratigraphically were analysed for detrital zircon U–Pb geochronology. Data show that the Southwestern Barents Sea Basin (SWBSB) was dominated by mixing of reworked material and coarse grained sediment supply from extrabasinal source areas including a Caledonian provenance in the southwest and a Fennoscandian provenance to the southeast. Intra-basinal erosion of underlying strata with Triassic zircon grains dominate in northern parts of the basin.

69. QIAN Yuan, NAMUR Olivier, FISCHER Lennart Alexander et al.: Pulses of plagioclase-laden magmas and stratigraphic evolution in the Upper zone of the Bushveld Complex, South Africa. *J. Petrol.* 58(8), 2017, 1619-1643. [Lvxb_01@163.com]

Cumulate rocks of the Upper Main Zone and Upper Zone (UUMZ) of the Bushveld Complex, South Africa, contain the world's major resources of Fe–Ti–V ± P, hosted in Ti-magnetite and apatite, and are commonly considered as having crystallized from the last major injection of magma into the magma chamber. In this study, we present the petrography, modal proportions, whole-rock major element chemistry (260 samples), electron microprobe data (~10 000 analyses for plagioclase, olivine, and pyroxene), and compiled analyses of Cr in magnetite (239 samples) for the UUMZ sampled over 2·1 km of the Bierkraal drill cores in the western limb of the Complex. The UUMZ section exhibits a broad normal fractionation trend upwards, but a series of reversals to more primitive anorthite contents in plagioclase, Mg# in pyroxenes and olivine, Cr in whole-rocks and Cr in magnetite separates are observed, accompanied by the appearance or disappearance of various minerals. Anorthosite or leucogabbro layers are closely linked to these reversals; the reversals in An % of plagioclase are used as boundaries to divide the UUMZ into 18 cycles. These cycles are interpreted as indications of magma chamber replenishment by plagioclase-laden magmas (up to 20 vol. % plagioclase) and are also marked by spikes in Cr content. In addition, abundant Fe–Ti oxide-bearing plagioclase-rich rocks are identified in the lower half of the UUMZ. These have crystallized from a hybrid melt produced by the mixing of a new plagioclase-bearing magma batch and the resident magma. Further crystallization of this hybrid liquid may lead to the formation of magnetite layers in the lower part of the UUMZ. The Bushveld UUMZ therefore grew by multiple emplacements of crystal-laden magmas coming from deep-seated chambers. Slow cooling in a shallow chamber explains the systematic bottom-up compositional evolution in the cumulate pile within individual cycles. The residual melt reached silicate liquid immiscibility soon after the saturation of apatite. Thereafter, segregation of conjugate Fe-rich and Si-rich melts and crystallization of the paired melts produces cumulates with a smooth upward decrease in Fe–Ti oxides, whereas plagioclase mode

increases in each apatite-bearing cycle. A comparison of systematic geochemical analyses and a detailed lithological stratigraphy between the Bushveld limbs demonstrates the possible connectivity between the western and eastern Upper Zone but indicates notable differences from the Bellevue section of the northern limb.

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