GEO4-1403 Petrological and Geochemical Evolution of the Earth

EXAM ANSWERS in blue

Thursday 08 November 2018, 09.00-12.00, Ruppertgebouw WIT

1. (a) Explain what is meant by mass independent fractionation in the oxygen isotope system (b) How can variations in multiple oxygen isotopes (^{16}O, ^{17}O, ^{18}O) be used to help determine the distance from the sun at which meteorites formed in the solar system? (c) Do differences in oxygen isotope ratios exist between the Moon and Earth and what does this tell us about the origin of the moon?

   (a) Stable isotope ratios should behave in a predictable way based upon their relative mass (e.g. $\delta^{18}O$ is approximately twice the $\delta^{17}O$ value for a mass-dependent process). This can be represented by the terrestrial mass fractionation line. Any deviations from this line are termed mass-independent effects and can be measured using Δ terminology ($\Delta^{17}O = \delta^{17}O - 0.52\ \delta^{18}O$).
   (b) Mass-independent fractionation typically occurs during the interaction of high energy UV light with gaseous compounds containing the element in question. Photochemical dissociation of C-O in the early solar nebula created variable gradients in $C^{17}O$ and $C^{18}O$ with corresponding variations in the mass fractionation line based upon distance of precipitation from the sun. Plot to show how this varies for different terrestrial planets and the asteroid belt is useful here.
   (c) Small differences in $\Delta^{17}O$ have been observed between basaltic rock samples from the surface of the Moon and the Earth. These variations can be explained by mixing between the proto-Earth and the impactor (Theia) that may have formed in slightly different parts of the early solar nebula. More recent work has shown that the differences initially found in $\Delta^{17}O$ are probably not real and due to analytical error.

2. **(a)** Mineral evolution is a relatively new approach of studying the formation and appearance of minerals. In this approach the mineral history is divided into three eras based on formation mechanism. What are these eras, from when till when did they span, and what are the mechanisms associated with each era?

   1. Era of Planetary Accretion (<4.55 Ga): the progressive separation and concentration of the elements from their original relatively uniform distribution in the pre-solar nebula

   2. Era of Crustal and Mantle Reworking (4.55-2.5 Ga): an increase in range of intensive variables such as pressure, temperature, and the activities of H_2O, CO_2, and O_2

   3. Era of Biological Mediated Mineralogy (>2.5 Ga): the generation of far-from-equilibrium conditions by living systems

(b) Meteorites are classified based on their mineralogy and petrology. What can you tell about the processing (and related to that, the relative age) of a meteorite if the meteorite contains

(b1) chondrules,

Chondrules are considered to be the oldest material in the Solar System. If found in a meteorite this means that the meteorite has undergone little change since its parent body has formed and stems from the beginning of the Solar System (4.5-4 billion years).

(b2) phyllosilicates,

The meteorite has undergone aqueous alteration - reaction with water

(b3) ringwoodite.

The meteorite has been subjected to shocks - for example during collisions early on n the solar system, during asteroid formation.

(c) What can you tell about the processing of a rocky body or planet if you find the following mineral groups on the surface

(c1) serpentine

Liquid water must have been present at some point in the bodies history

(c2) granitoids?

Planet possesses sufficient inner heat to remelt its initial basaltic crust

3. Describe how magmatic/volcanic rock types found in Archean greenstone belts were distinctive to those found on the modern Earth. Give examples of (a) mafic and (b) felsic rocks in your answer. What were their main compositional, textural and geochemical features and how were they linked to differences in tectonics, melting and crystallization processes.

   (a) Mafic= komatiite ultramafic rocks. High MgO from 18 to 30 wt%. Variably interpreted to reflect hotter mantle in Archean with high degrees partial melting, or wet mantle. Possible plume origin. Spinifex textures are common- skeletal olivine or pyroxene crystals grew under high cooling rates (1-3^{o}C/h) with diffusion slower than crystal growth rate. Archean mantle was less depleted than modern mantle and mafic and ultramafic rock geochemistry reflected this.

   (b) Felsic= predominantly TTG (tonalite-trondhjemite-granodiorite) plutonic suite. Intrusive rocks that lack K-feldspar. Depleted HFSE and enriched LILE indicate wet melting. Strong LREE/HREE fractionation indicates garnet in the source region during melting. Trace elements show similarities with high silica adakites with high Na_2O/K_2O ratios. Role has been suggested for subduction or sagduction in their genesis.

4. (a) Describe three different approaches in geology or geochemistry that can be used to determine the appearance of the first life in the geological record. Give the advantages and disadvantages of each approach.

   (b) Using these approaches describe the point in the geological record when you would argue that the first robust evidence for life becomes available. At what age did this happen? Give an example of a location and the types of rocks where this was found.

   (a) 1-Stromatolite/ microfossil data. Biologically produced layers (after microbial mats) plus spherical and rod-like fossil microbes lithified into chert. Advantage- Morphological evidence is direct. Disadvantage- microbial and abiotic morphologies are very similar making identification problematic.
   2-Biomarker data. Distinct organic molecules only produced by biological processes. Advantage- Presence of molecules directly linked to life and supports different metabolic processes. Disadvantage- preservation compromised by metamorphism. Prone to modern contamination.
   3-Stable isotope data. Isotopes of elements with metabolic role (e.g. C,N,S,Fe) can be fractionated during biological processing and then incorporated into and recorded in minerals. Advantage- Good preservation in ancient rocks, different metabolic processes identified. Disadvantage- Biological and abiotic processes can fractionate stable isotopes to similar degrees. Environment of deposition and post-depositional history of rock must be well-known for accurate interpretation

   (b) First point where multiple lines of evidence converge is Strelley Pool Chert at 3430 Ma in the Pilbara Block of Western Australia. Excellent preservation of stromatolites with 7 different styles, including large complex cones. Consistent with C isotope data and multiple S isotope data from rocks of similar age. Supported by inferred depositional environment. No biomarker data is available at this time due to the metamorphosed nature of the rocks. Prior to this in the Eoarchean there is no similar convergence in approaches and data to support early life and many more assumptions are required.

5. (a) Describe the main lines of geological and geochemical evidence that suggest that the near-surface environment of the Earth transitioned from fully anoxic conditions in the Archean to partially oxygenated after the Great Oxygenation Event.

(b) Which geochemical evidence can be used to apply quantitative constraints on the increase in pO_2 levels in the ancient atmosphere. Describe in as much detail as you can how this proxy works.

(a) Detrital pyrite, siderite, uraninite
Red beds (Fe2+, Fe3+)
Banded iron formation record
Lack of sulfate minerals
Mn deposits
Lack of a Ce anomaly in chemical sediments
Multiple S isotopes
Cr isotope record
Mo isotope record
N isotope record

(b) Multiple S isotopes (32S, 33S, 34S, 36S) provide the strongest evidence as they are only readily fractionated at a PAL O2 level of $<10^{-5}$. Significant MIF-S variability is lost in rocks <2.32 Ga

6. (a) What is a large igneous province (LIP)? Give the most important characteristics that define an event as a LIP and briefly describe its relationship to global tectonic processes.

   (b) How would you distinguish geochemically between the role of impactors and mass volcanism as causes for mass extinction events?

(a) Large volume of magmatic or volcanic rock (0.3-4 M Km3) erupted over a very short period (<1 Ma) in a single province. Often accompanied by large-scale crustal doming, evidence for underlying mantle plume activity, large scale volatile production (e.g. CO2, SO2), often but not always occurring together with mass extinction events.

(b) PGE (Ir) anomalies, Ni poisoning- impactor origin
Cr isotope anomalies due to impactor
Os isotope variability in marine sediments- impactor
Evidence for and dating of an impact crater coeval to the mass extinction
Presence of large volume magmatic/volcanic rock coeval with the event
Ca isotope shifts reflecting ocean acidification- volcanism
$\delta^{18}O$ shifts in marine foraminifera or mutagenesis of pollen track global temperature changes- longer term climate changes support volcanism
Ocean anoxic events linked to volcanic nutrient input

7. (a) When did crust-mantle separation first begin on Earth and what geochemical evidence can be used to most strongly support this?

   (b) What lines of evidence can be used to argue that plate tectonics was distinctive on the early Earth when compared to what we observe today?

   (a) Rb-Sr, Sm-Nd and Lu-Hf isotope systems have all been used to date crust-mantle separation. A diagram here showing how this systems work and a short explanation is required in the answer. Each isotope system gives a slightly different age (between 3.8 and 4.5 Ga). The Lu-Hf system is compromised by a lack of knowledge of the decay constant for this system, Rb-Sr data are compromised by poor preservation in the rock record.

   (b) Archean:
   Greenstone Belts
   TTGs
   BIF
   Ores rich in PGEs, Cr, Ni, Co, Au
   Late Archean sedimentary basins
   Continental-scale dykes
   Thick lithospheric mantle keels

   Modern (not present in Archean):
   Oceans- MORB, transforms, plumes, LIPs, arcs
   UHP rocks in subduction settings
   Abundant granite
   Kimberlites in continents
   Collisional plateaus

8. (a) Describe in as much detail as you can how you would distinguish the igneous rock type *blueschist* in hand specimen and under the optical microscope. (b) Blueschists are indicative of a particular type of geological setting. What is this? and why are blueschists only found in rocks of Neoproterozoic age and younger?

   (a) Minerals present: glaucophane + (lawsonite or epidote) +/- jadeite +/- albite or chlorite +/- garnet +/- muscovite in a rock of roughly basaltic composition. Textures can be lepidoblastic, nematoblastic or schistose. Grain size typically fine and rock appears blue, grey or blue-green in hand specimen.

   (b) Subduction settings where ultra high pressure/ low temperature metamorphism is distinctive. Conditions in a subducted slab are not easily mimicked in other tectonic settings on Earth. Downgoing plate is cool and rapidly reaches high pressure with relatively little heating. Blueschists only appear in rocks younger than Neoproterozoic- could indicate late onset of subduction/modern style plate tectonics. But presence of blueschists controlled, at least in part, by composition. More ultramafic oceanic crust does not readily form the mineral assemblages seen in a typical blueschist