Freemantle 2016 PhD Examination corrections.

Examiner 1

General:

1. Please refer to original submission for page and figure/table numbers that are listed in this document.
2. Applied sub-section numbering scheme to whole document as advised in examination appraisal.
3. Applied automatic Figure and Table numbering and cross-referencing throughout document.

Figure and Table movements from Examination Version to Final Version:

Figures

Moved Figure 2.2 to Figure 1.1

Moved Figure 3.1 to Figure 1.2

Moved Figure 3.3 to Figure 1.5

Tables

Moved Table 3.1 to Table 2.3

Moved Table 3.2 to Table 2.4

Moved Table 4.15 to Table 3.1 in response to Examiner 1 request for an annotated map showing the distribution of all the granites, which is not possible on an A3 size map sheet. The table provides an adequate summary of the leucogranite distributions at the deposits of the study.

Chapter 1

Examiner 1

General: cross-checked and cross-reference all Figure and Table Captions, corrected header and footer errors, addressed typos throughout Chapter

Page 1: Paragraph 2 spelling correction World Class; paragraph 2 grammar remove comma, lower case adjective

Page 2: Paragraph 1 grammar and spelling correction; Paragraph 3, changed sentence structure as advised, grammar correction insert period line 3; Paragraph 4, grammar corrections and sentence structure changes as advised.

Page 3: Paragraph 1 removed repetition with page 4; Paragraph 3 applied search and replace in whole document (whole rock replaced with whole-rock); Rephrased paragraph 1 of “Research Outline” section, applied grammar corrections as advised; Paragraph 4, changed sentence as advised.

Page 4: Search and replace “);” with “),” in reference citations, Removed last sentence; Removed paragraph 2; Rephrased paragraph 3 and included spelling and grammar corrections; Paragraph 4 rephrased last sentence.

Page 5: Sentence structure change line 2. Rephrased sentence starting in line 3; Removed repetition in paragraph 1 of “Exploration and Mining Interest; Paragraph 2 removed repetition, rephrased as advised; Paragraph 3 Paragraph 4, rephrased as advised.

Page 6: Paragraph 1, grammar corrections, ‘year’ reference line 4; Paragraph 2 adjusted to common noun line 4; Paragraph 3 changed year reference to 2014 (latest available from World Nuclear Association), changed ‘/a’ to ‘per annum’ applied global search and replace to document, rephrased explanation of uranium supply and demand deficit; Paragraph 4 apply changes as advised, but disagree with replacing “demands” with “needs”, Global document search and replace “GW” with “,000 MW”.

Page 7: Rephrased to remove repetition, updated numbers, and figures 1.1 and 1.2 on Page 8.

Page 9: Applied grammar changes, removed redundant phrase line 7; Paragraph 2 moved Figure 3.3 to section “Uranium Exploration in the Damara Orogen” section.

Page 10, Summary Section: Paragraph 1 grammar corrections; Paragraph 3 removed unnecessary words.

Chapter 2

Page 12: Paragraph 1 grammar Line 2 and line 6, Global search and replace “))” for “)” on citations.

Page 13: Changes to Figure 2.1 caption, Re-plotted Central Zone changed font styles and colours to be more visible.

Page 14: Moved Figure 2.2 to Figure 1.1 and made changes to Figure as advised.

Page 15: Paragraph 3 “Neoproterozoic”

Page 16: Paragraph 4 “Stratigraphic”

Page 17: Paragraph 1 rephrased last sentence “up-stratigraphy”, Changed ‘Damara Sequence’ to ‘Damara Super Group’, global search and replace “Arandis Member” as per Geological Survey of Namibia convention, Paragraph 2 spelling and grammar as advised.

Page 18: Paragraph 4 Clarified age dates of Sturtian and Maranoan Global ice ages, placed in stratigraphic and orogenic context, Paragraph 5 search and replace Arandis Formation to Arandis Member – global document change, Paragraph 6 placed Ghaub Diamictite into Table 2.1.

Page 19: Paragraph 1 spelling and grammar changes, Paragraph 2 grammar corrections, Inserted a reference to Figure 1.4 (Regional geological map 1:250 000 scale, Geol. Surv. Namibia coverage), Paragraph 3 grammar change, Paragraph 4 grammar changes onto Page 20.

Page 20: Paragraph 2 grammar change

Page 21: Paragraph 2 clarified Khan Dome vs. Khan Inlier references, grammar changes, Paragraph 3 insert new word line 1.

Page 22: Paragraph 1 moved Table 3.1 and Table 3.2 to Table 2.3 and Table 2.4, Paragraph 2

Page 23: Paragraph 1 rephrased "averages for felsic igneous rocks" inserted Taylor and McClennan, 1985 reference. Corrected Table 2.2 caption, corrected line 7 of Table 2.2, removed confidential cross-references.

Page 24: Carried over from page 23 rephrased second half of paragraph, Paragraph 3 elaborated on "pressure shadow" description,

Page 26: Paragraph 1 corrected typos, Figure 2.4 inserted scale by giving field of view scale as ~50 cm.

Page 27: reworded definition of alaskite carried from page 27, Paragraph 2 typo corrected, Paragraph 4 moved Figure 2.5 (now 2.4) corrected typos, rephrased sentence 2.

Page 28: Summary list 2 response- Ages of granitic intrusions and pf metamorphic events are outlined on previous pages (22 and 28) and in the tables moved from Chapter 3 (Tables 3.1 and 3.2), Last paragraph corrected last line

Page 29: Clarify metamorphic and magmatic ages of Goscombe et al., (2004a) and made corrections to figure caption (Figure 2.5)

Page 31: Paragraph 1 Reworded line 7 onwards and did same with paragraph 3, Paragraph 4

Page 32: Paragraph 1 Advised to mention the Matchless Belt as a way to summarise the Orogen, and elaborate on the setting as that of a complete ocean basin, Paragraph 2 referenced Miller (1983) for role of stratigraphy representing the history of Damaran sedimentation, Paragraph 3 expanded on the descriptions of structural controls at each deposit, referenced this study and work of others, Paragraph 4 rephrased line 1.

Page 33: reworded line 7.

Chapter 3

Examiner 1

General: cross-checked and cross-reference all Figure and Table Captions, corrected header and footer errors, addressed typos throughout Chapter

Page 34: No figure numbers on title images to Chapters. The intention of these pictures from Chapter 3 onwards is to give a preview of the content, as much as chapters 3-9 constitute the work of this study, while chapters 1 and 2 really introduce the geological setting. Paragraph 1 corrected Damaran to Damara. Paragraph 2 removed redundant words line 2.

Page 35: Removed paragraph 2, 3, 4, 5 and list as it is repetition from Chapter 2, as pointed out in Examiner 1 comments.

Page 35-36: Moved paragraph 1 and 2 and Figure 3.1 to Chapter 1.

Page 37-38: Removed ALL of repeated text as advised by Examiner 1.

Page 39: Adding all the granite outcrops to the map may make it too busy, but I have added the Salem outcrops as per Geologic Survey of Namibia.

Page 41: Clarified the A-F descriptions of NEX and the I, S, and A type classification of granites, Paragraph 5 clarified the naming of the leucogranite (replaced 'sheets' with sheeted leucogranite).

Page 42: Question "Where are your actual observations" Paragraph 5 on page 41 explains that detailed descriptions are in Chapter 4 for each deposit. Paragraph 2 rearranged paragraphs to bring the C-type sheeted leucogranite description forward.

Page 43: Removed paragraph 1

Page 44: Moved Figure 3.3 to Figure 1.5 (Chapter 1).

Page 45: Paragraph 1 inserted first references from the Rössing deposit that describe and quantify the reaction between the alaskites and the Khan and Rössing formations that are believed to contribute to the crystallisation of uraninite.

Page 46: Stratigraphic column will remain at the right of the diagram in Figure 3.4 (now Figure 3.3). Because it illustrates the positions of most deposits relative to the stratigraphy. Although the Etango deposit is hosted almost exclusively in the Khan Formation, the sheeted leucogranites, uraniferous and barren, transgress the entire Nosib Group.

Page 47: Moved Table 3.1 to Table 2.3

Page 48: Moved Table 3.2 to Table 2.4, added Briqueu ages for leucogranite and red granite

Page49-Page 51: changed 'laths' to xenoliths

Page 53: Paragraph 4 corrected the incorrect Figure reference

Chapter 4

Examiner X

Page 187: Paragraph 1, referred to example of partial melt in Chapter 3, Figure 3.44.

Page 191: Changed ‘cut’ to ‘overprint’ paragraph 2.

Page 203: Paragraph 2, Clarified difference between metasomatic and magmatic sub-solidus reactions.

Page 212: Paragraph 1, deleted ‘radioactive’ on line 4

Page 214: Moved caption below Figure 4.21.

Page 218: Paragraph 2, explained that the pyrite and pyrrhotite essentially represent two mineral that host oxidised and reduced Fe. Deleted repetitive paragraphs.

Page 219: Figure 4.23(a) changed description from framboidal to ‘clustered and cubic’

Page 220: Removed repetition in paragraph 2

Page 222: Examiner suggests that the thick conglomerate is more likely Chuos. I consulted with geologists at Bannerman Resources in 2015 to clarify this and obtained a set of photographs of the entire core of the DH025 drill hole. It appears to be Khan Formation. I also followed this up with Prof. Alex Kisters at the University of Stellenbosch who was supervising an MSc student at the Ida Dome in 2015. I have decided to keep the conglomerate within the Khan Formation based on these discussions and the photographic information.

Page 234: figure 4.29(a) corrected caption as advised.

Page 241: Figure 4.32 caption is moved to below the figure as advised

Page 242: Paragraph 1, agreed, the evidence of strain could also imply the intrusive was emplaced at the same time as deformation, which make a lot of sense given the dilation features that are associated with strain zones.

Page 254: Last paragraph, ;last line, agreed the context of the brannerite and betafite bearing leucogranite is not set until I discuss chemistry. I have removed the sentence.

Page 260: Last paragraph, erroneous sentence removed.

Page 265: Corrected formatting of Figure 4.45.

Page 274: response to comment of opening paragraph describing the opinion of previous workers. The paragraph is intended to give the opinions of previous workers to open the passage of discussion.

Response to request to move text from page 277-289 to the front of the discussion. I agree and have done so with minor changes.

Page 278: Adjusted Tourmaline granite opening paragraph to accommodate Tin and Lithium pegmatites as fractionation examples.

Chapter 5

Examiner X

Page 298: Response to FeO vs Fe2O3 query, yes Fe2O3 was reported by XRF, FeO was calculated using a typical Rhyolite ratio in the CIPW calculator macro of Prof. K. Hollocher, Union College, New York.

Page 299: Original data were reported in ppm with 1 place decimal. Analyses are inherently the result of multiple readings of the sample, and are themselves averages, with decimal fractions. The detection limit may be reported as a whole number, but the results are not reported as a multiple of that detection limit value. Decimals will remain.

Page 300: Inserted list of elements analysed by ICPMS.

Page 303: Removed Al as a comparative between Valencia and Rössing, Figure 5.2.

Page 307: Corrected caption 5.3(b) as advised.

Page 309: Paragraph 2, defined barren SLGs as weakly mineralised, with reference to uranium abundances of rocks described in Plant *et al*. (1999). Paragraph 2, clarified the distinction between the Valencia SLG types on Figure 5.5(b), and removed references to deposits that are not clear on the diagrams of Figure 5.5.

Page 316: Agreed, variation in ANOR is somewhat equivocal, there may be an element of Ca mobilisation in the surface samples that would not necessarily be present in samples from depth. Highly altered samples shown in Chapter 4 are variable on the Q-ANOR plots, as shown for the Ida Dome area.

Page 317: Clarified references to Husab samples in Figure 5.7(c).

Page 319. Paragraph 2, removed references to trends identified in figures that only appear in later sections of the Chapter.

Page 320: Paragraph 1, inserted Shand (1927) reference.

Page 322: Figure 5.9, added CaO wt.% to image.

Page 3.24: Paragraph 2, the CaCO3 content is equivocal, rocks may be degassed by High T and P prior to alaskite intrusion. However, there is little doubt as to the role of the skarns on mineralisation, whether there is a pH effect, which would be at lower T, and therefore a residual process, or if there really is a carbonate reaction taking place.

Page 329: Corrected the poorly presented FeO vs FeO_{tot} presentation of Fe data.

Page 338: I cannot comment on the merits of the different methods of classifying the SLGs as peraluminous or metaluminous, it seems that the cationic plots are better than the A-B diagrams of Debon and Le Fort, and there is a stronger, consistent metaluminous trend in the ASI Shand division.

Page 342: 100 ppm is used as a cut-off as it is very rare for a SLG to exceed this concentration of U, unless it is a distinctive D- or E-type. In fact, 50 ppm appears to be an equally effective cut-off.

However, from an economic point of view, the Husab mine currently stockpiles 100 ppm to 400 ppm ore as sub-economic, anything below 100 ppm eU_3O_8 is waste.

Page 343: Removed Figure 5.22

Page 347: Paragraph 2, Holland's Dome samples are labelled HD, now indicated in the caption.

Page 348: Garnet Valley and Holland's Dome samples are clearly marked by a polygon in Figure 5.25(c), now labelled 5.35.

Chapter 6

Page 414: Figure 6.11, response to query about analytical error. Sample GRA83 was submitted for analysis twice, as a control sample, each sample went in a different batch and had independent submission labels. The data are in Appendix E9.

Chapter 7

Examiner 1

General: cross-checked and cross-reference all Figure and Table Captions, corrected header and footer errors, addressed typos throughout Chapter

Page 436-437: Reduced length of introduction by removing paragraphs that deal with mining application to the introduction of Chapter 8. Reiterated the need to quantify mineralogy by giving the Rössing examples described in Herd (1996), Nex et al (2003), and Abraham (2009).

Page 478: Paragraph 1, referred to petrographic evidence of multiple generations of euhedral uraninite from Chapter 4.

Page 479: Paragraph 2, clarification of line 4 explaining which evidence indicates uranium was in solution after the host rocks crystallised. Paragraph 2, the role of Fe I agree is not quite so simple, in some cases, such as at Valencia magnetite has formed a rim, largely between uraninite and the host phase, implying a replacement of the alteration in the rim that surrounds uraninite (Figs 7.23-7.25). However, the role of Fe in the Goanikontes example is that of U replacing corroded magnetite as evidence by vermicular uraninite in magnetite (Figure 7.5). Also, at the Ida Dome uraninite appears to have formed a replacement rim around a magnetite grain (Figure 7.13).

Page 480: Paragraph 2, clarified the example of increased FeO content as a function of biotite alteration to chlorite. The purpose of the paragraph is to highlight that reduced Fe may be available to react with any dissolved U in the alaskites as well as in the chlorite-bearing pelites of the host Rössing Formation. Re-worded and included reference to similar observations of uraniferous leucogranites in the Namaqua Metamorphic Complex in Robb *et al.* (1986). Clarified that the Fe oxides that are a product of biotite to chlorite alteration may contain magnetite.

Page 481: Equation, corrected magnetite in general equation to Fe-Ti oxides as ilmenite is observed in some examples. The prevalence of magnetite and Fe-Ti phases is shown in Chapter 4, and is highlighted in the QEMSCAN images of Chapter 7, particularly in the mineral maps that contain chlorite. Paragraph 2, clarification, reworded sentence describing coffinite as being exclusively a replacement texture after uraninite.

Page 485: Paragraph 1, clarification that anhedral zircons with inclusions, which do not show pronounced zoning suggest that they are inherited. This is supported by the prominent -Eu in the alaskites that implies very low percentages of partial melt at source. Paragraph 2, deleted sections that do not adequately discuss the mineralisation model, as Examiner 1 suggests.

Page 487: Paragraph 1, added cross-reference, suggested that the reduced U in the uraninite reacts at the margins with dissolved Fe^{3+} to form magnetite-haematite and perhaps also hydroxides and carbonates depending on the compositons of the Fe-bearing solution(s). Paragraph 1, omitted the sentence “Betafite is intensely replacing brannerite…” reworded to clarify that betafite is actually crystallising along cleavage planes.

Paragraph 2, cannot read the full comment, I have re-type as Examiner 1 points out incorrect word usage ‘immiscible’.

Chapter 8

Examiner 1

Page 490: Paragraph 1, removed as redundant information already presented in previous chapters, Paragraph 2, rephrased to correct for colloquial language.

Page 491: Paragraph 1, applied all changes as required, Heading ‘Philosophy’ replaced with ‘Approach’. Rephrased the bullet points, omitted spurious statements.

Page 493: Moved opening paragraph of “Replacement…” sub-section, moved to discussion of Chapter 8. Paragraph 5, removed redundant list items.

Page 496: Response to comment: The use of EPMA analyser in the determination of uranium composition not only gives a quantification of the relative U:Th in unaltered primary uraninite (based on empirical observations in BSE and traditional petrographic microscopy) but also tests for compositional variation within the numerous examples of secondary uraninite such as the replacement of cavities within magnetite at Goanikontes (Etango), on the rims of magnetite at Ida Dome, and also between clearly metal deficient rims of altered uraninite, such as at the Husab Deposit. It is also very clear that the total U content of the uraninite at each deposit varies considerably, as a result of alteration, but also as a representation of differing conditions of initial formation.

Page 497: Paragraph 1, removed second clause of sentence deemed ‘unnecessary’.

Page 563: Replaced U vs Pb to include the data from Cross et al. 2011 with a comment in the preceding text.

Page 564: Cross et al. (2011) did not use Rössing uraninite, it is in fact Rössing South uraninite, which changed names to the Husab deposit in 2012, as elaborated on in Chapter 3. The uraninite age appears young, Pb is within the range expected for uraninite in the CZ, and is must be assumed that some leaching of Pb and UO3 has taken place given the fracture nature and considerable alteration overprint prevalent in the alaskites, throughout the region.

Page 567: Paragraph 1, removed excessive detail as advised.

Response to comment on paragenetic sequence: "It would be difficult, and subject to warranted criticism, to present an 'attempt' at describing a paragenetic sequence without presenting ALL the observations, data, and interpretations thereof in the preceding Chapters and sections of Chapter 8."

Page 568: Paragraph 1, added evidence of multiple generations of uranium mineralisation. Using U:Pb is crude, however, samples with the lowest U:Pb should be older than the samples with higher U:Pb. U:Pb of coffinite is considerably higher than in uraninite, suggesting it is a much younger mineral.

Response to "imprecise" assertion that incompatible elements should concentrate in the last-to-crystallise and therefore last to site of granite emplacement. The initial mineralisation should therefore have comparable U:Th to the initial melt, all things being equal.

Page 569: The Dalonshan granite example is given because it illustrates the significant episodes of uranium mineralisation that post-dates granite crystallisation. This has application in the interpretation of younger uraninite ages than the chemical ages of the alaskites given in the U=Pb ages of zircon.

Page 570: Sub-section heading font corrected, replaced image of paragenetic sequence with one that addresses the concerns of the examiner. Citing references, changing colours of boxes and fonts. I have left out the uraninite age of Cross et al. (2011).

Page 572: Paragraph 1: It is quite obvious that the zircon in the image 8.23 has experienced growth sequences, as it is zoned, and must have rims that formed in the magmatic process, it is euhedral after all. It is completely surrounded by the betafite crystal, which is itself located between quartz and feldspar. It does have corroded edges, but the position within the matrix of quartz and feldspar suggests it formed within the granite too. I do not understand the Examiner's question, as the evidence is some 25 pages back in this chapter. Last paragraph, clarify that although brannerite is present in many samples, abundant brannerite is prevalent in the alaskites that invade the upper Rössing Formation.

Chapter 9

Examiner 1

Page 595: Corrected to page 628.

Page 615: Figure number is correct as Figure 9.8, figure 9.7 Is in two parts, ‘a’ and ‘b’. Magnetite rims were left of of the image.

Page 618: Added a paragraph to the start of the Mineralisation sub-section to better clarifiy the intention, that Fe is the key reducing element in the mineralisation sequence, as it is ubiquitous to the deposits.

Response to Examiner 1 comment top of Page 618: The textural evidence of magnetite and other Fe oxide reactions is abundant. It is very rare to find a euhedral Fe-oxide in the QEMSCAN textural analysis, suggesting some corrosion has taken place.

Second bullet point: Clarified tha difference in Fe-oxide reactions between the Valencia and Goanikontes deposits.

UO_3:UO_2 is variable, and is perhaps a combination of the initial REDOX and also subsequent alteration as the examiner points out. Statement added to be more agreeable with the Examiner’s assertion.

Page 619: Paragraph 1: clarified the role of alteration over prints, where contact metamorphism of the metasediment is the result of the alaskite intrusions, and alteration within the alaskites is driven internally, though contamination from the metasediment has played a critical role in promoting uraninite crystallisation. Final bullet point added, agree with assertion that the refractory mineral U deportment is enhanced by the preferential leaching of soluble U from uraninite.

Page 620: Removed Ellis and Mahon (1977) reference and comparison. Clarify, Husab is Rossing South, as described in Chapter 1, Chapter 2, and Chapter 3. Paragraph 2 corrections as advised inserted ‘orogen’.

Page 622: Paragraph 1, Clarified the Kaoko Zone as the site of post orogenic granites, Paragraph 2, Changed the second ‘sentence’ into a list of items.

Page 623: Response – the ‘petrographic’ items that are alluded to are not necessarily petrographic observations. The point of the passage is to illustrate that the metamorphic grades in the Namaqua province, where the uraniferous granites occur is perhaps insufficient to have released U from typical accessory minerals such as monazite and zircon.

Page 624: Clarification of the comparison between the Trans Hudson low-U pegmatite with the low U SLGs of the Damara. Added a sentence to complete the passage stating that the evidence of this study (REE analyses) are in agreement with the assertions of previous authors, that the alaskites are products of a lower degree of partial melt than the SLGs with low U enrichment.

Page 626: Response to point 1, it is clearly presented in the preceding sections that the uraniferous granites coincide with peak metamorphism, within error, and that this peak metamorphism may explain why there is abundant uranium available to the melts, more so than before because at granulite facies conditions monazite and zircon are may be in equilibrium, at least more so than at lower metamorphic grades.

Corrected error in point 2, Point 3: added Rössing and Goanikontes references as comparative models for CZ mineralisation. Cuney does not state that the carbonates are a fundamental seal, however the presence of CO_2 is interpreted by Cuney, among others, to have a fundamental role in the crystallisation of complex U^{6+} minerals such as betafite.

Page 627: Point 4, corrected grammar as advised, final sentence, the uraniferous sheets are distinct from the earlier sheets on terms of REE and other chemical traits, and also distinct from examples of anorogenic granites described elsewhere in the CZ, such as those described in McDermott et al. (2000).

Point 5, clarified that reduced Fe is found in pyrite and pyrrhotite which are the most abundant sulphides in association with uranium mineralisation. Removed spurious claims about biotite fenitisation as questioned by examiner, clarified that Fe seems to deposit on uraninite rims too. Final sentence stating that reduced conditions within the alaskites themselves would also result in sulphide and Fe oxides forming in the granites, independent of uranium mineralisation.

Page 628: Response, there is some degree of certainty about the discovery of new large uranium deposits in the Central Zone, the combination of basement dome structure with the suitable sequence of unconformable Damaran sediments is rare and occurs in a few locations. Whether more of these lie buried beneath the sands remains to be seen, but aeromagnetic indications within the region suggest not

Page 629: Constrained the age of uraninite with Cross et al. (2011) uraninite age, and the low Pb content of coffinite.