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Protolith age and role in tectonic significance of the Eastern Ghats Domain, east India

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DECLARATION

I declare that the contents contained in this thesis are the result of my own research. It does not contain any previously published, written or produced material from another person except where referenced in the following text.

Signed……………………….

Date………………………….

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TABLE OF CONTENTS

FIGURE CAPTIONS

Figure 1.

Location map of towns and khondalite samples localities. From Google Earth 2010.

Figure 2.

Simpified geological map of the Eastern Ghats Mobile Belt showing terrains of significance. 1=Jeypore, 2=Rengali Province, 3=Ongole Domain, 4=Krishna Province, 5=Cuddapah Basin, 6=Nallamallai Fold Belt

Figure 3.

Fitzsimons (2000) model of East Gondwana at 500 Ma, showing three Grenville age provinces; The Maud, the Rayner and the Wilkes Provinces, all with different ages of high grade, collisional tectonism. These provinces are juxtaposed by two Pan African Orogens; 1. the East African Orogen, including Central Dronning Maud Land, with reworked Grenville aged crust at the margins of the orogen and 2. The Prydz-Denman-Darling Orogen, which includes the Pinjarra Orogen. The Pinjarra Orogen was included as Grenville age basement in previous East Gondwana models, but here Fitzsimons (2000) has grouped it with Pan African age.

Figure 4.

CL images of zircons from EG9_04:

a. An angular, oscillatory zoned, igneous zircon
b. A broken igneous zircon grain with oscillatory zoning
c. Top grain- meatomorphosed zircon with an oscillatory zoned igneous core. Sharp boundaries between the core and the rim; bottom grain- Dark metamorphic zircon with a slightly lighter core, showing sector zoning
d. Bright igneous grain with oscillatory zoning and rounded edges
e. Rounded metamorphic zircon, bright under CL
f. A broken, homogenous, igneous zircon with angular edges

Figure 5.

CL images of zircons from EG9_53:

a. Two igneous zircon grains; one with an oscillatory zoned core separated from darker metamorphic rims, by a sharp boundary; the other zircon grain is has a homogenous igneous core and lighter metamorphic rims, separated by a distinct boundary
b. A metamorphic zircon with a darker core and shows faint sector zoning

c. A sector zoned metamorphic zircon with a bright core with distinct, darker metamorphic rims
d. A metamorphic zircon of homogenous nature
e. A metamorphic zircon with dark sector zoning
f. A deformed metamorphic zircon grain with a dark core and bright rims with a distinct boundary separating them.

Figure 6

CL images of zircons from EG9_61:

a. A rounded, sector zoned metamorphic zircon with a dark core and distinct rims of alternating, contrasting brightness
b. A rounded metamorphic zircon with a bright distinct core and dull exterior
c. A fractured metamorphic zircon with a dark core and homogenous rim
d. A rounded metamorphic zircon with a dark core and sector zoned rims, separated by a distinct boundary
e. Half of a metamorphic zircon with a dark core and lighter rims, separated by distinct boundaries. This zircon is sector zoned
f. A homogenous, dull metamorphic zircon

Figure 6

CL images of zircons from EG9_61:

a. A rounded, sector zoned metamorphic zircon with a distinct dark core and lighter rims
b. Two metamorphic zircons with dark distinct cores and bright rims
c. A sector zoned metamorphic zircon with a dark core and contrasting rims
d. A sector zoned metamorphic zircon with a dark core and contrasting rims
e. A sector zoned metamorphic zircon with a bright core distinctly separated from the first dull rim which is encompassed by a bright rim

Figure 8.

EG9_04

a. U/Pb concordia plot for EG9_04
b. Relative probability density plot showing peak U/Pb ages at approximately 930 Ma and 800 Ma
c. 207Pb206/Pb relative probability plot showing zircon ages at approximately 890 Ma

Figure 9.

EG9_53

a. U/Pb concordia plot for EG9_61
b. Relative probability density plot showing peak U/Pb ages at approximately 930 Ma

Figure 10.

EG9_61

a. U/Pb concordia plot showing zircon growth at approximately 900Ma and lead loss recorded from this age onwards

Figure 11.

EG9_62

a. U/Pb concordia plot for EG9_62
b. Relative probability plot of 207Pb/206Pb ages show zircon ages at 840 Ma
c. Relative probability plot of U/Pb ages showing zircon crystallisation at 900-810 Ma

TABLES

Table 1.

Isotope concentrations from EG9_04, processed in Glitter an Excel.

Table 2.

Isotope concentrations from EG9_53 processed in Glitter an Excel.

Table 3.

Isotope concentrations from EG9_61, processed in Glitter an Excel.

Table 4.

Isotope concentrations from EG9_62, processed in Glitter an Excel.

ABSTRACT

U/Pb age analyses were conducted on detrital zircons from Khondalites in the Eastern Ghats Belt (EGB) in eastern peninsular India. This study was aimed at determining detrital ages to help understand the nature of the protolith to the meatasedimentary rocks. These khondalite terrains make up the most extensive terrains in the EGB yet they are poorly understood. They are important because they help constrain timing of tectonism in the Mesoproterozoic and the formation of Rodinia and Eastern Gondwana. There were very few detrital zircons in the samples collected from the EGB and age analyses could not be made from them. Metamorphic ages were recorded from metamorphic/metamorphically recrystallised zircons. The age of metamorphism recorded in these zircons is approximately 900 Ma. This age agrees with metamorphic ages predicted from previous studies. This metamorphism is a result of the collisional orogeny that amalgamated eastern India with eastern Antarctica in the Mesoproterozoic. A Pan-African overprint has been recorded in the zircon ages which range from 660-560 Ma. These are predicted to be from lead loss due to metamorphism and can be seen on the concordia plots for U/Pb age data.

1. INTRODUCTION

The Eastern Ghats Belt, eastern India evolved as one mobile belt system with the Rayner Province in east Antarctica in the Mesoproterozic (Dobmeier and Raith, 2003). These terrains have become a focus point of research as they show an evolutionary history of the amalgamation of Eastern Gondwana and Rodinia.

The aims of this study were to understand the origin of the protoliths in the metasedimentary rocks of the Eastern Ghats Belt and to determine the tectonic relationships in the Mesoproterozoic. Zircons from khondalites in the Eastern Ghats were harvested and U/Pb age dated for detrital ages. Unfortunately, detrital ages were not constrained. The khondalites of the Eastern Ghats underwent polyphase metamorphism throughout the Mesoproterozoic. The rocks in this terrain were metamorphosed to granulite facies metamorphism and underwent phases of ultra-high temperature and high temperature (UHT and HT) metamorphism (Boger *et al*., 2000). This destroyed a significant (if not a majority) of the detrital zircons present from the protolith. Detrital ages have been very limited from previous studies. One study has found detrital ages of the protolith have been predicted to be 2.5-1.8 Ga, from Nd model age data (*T*DM) and deposition occurred at 1.37 Ga (Simmat and Raith, 2008). Divakara *et al,* (1998) has stated that the provenance of these sediments must have been form an acidic source with a composition similar to tonalite-trondhjemite-granodiorite (TTG).

Zircon ages collected from the Eastern and Western Khondalite Zones in the Eastern Ghats Province showed a spread of metamorphic ages from 990-900 Ma. These ages have been correlated with other metamorphic ages from a number of studies that have determined the cause to be from the collisional orogeny between East Antarctica and East India (Boger *et al.,* 2000; Dobmeier and Raith, 2003; Fitzsimmons, 2000; Kovach *et al.,* 2001; Rickers *et al.,* 2001; Simmat and Raith, 2007). These ages were produced from metamorphism experienced during a collisional orogeny. Lead loss occurred at ca.650-560 Ma, showing a metamorphic Pan-African overprint.

2. AIMS AND SIGNIFICANCE

There is very little knowledge on the age, geochemistry and protolith of the khondalites in the Eastern Ghats Belt in East India, despite the fact that these metasedimentary rocks make up the most extensive terrains there. Understanding the origin of the protoliths of the metasedimentary rocks is very important in order to piece together the palaeogeography of Rodinia and understand the tectonic relationships during the Mesoproterozoic. Detrital zircons can be dated in sediments to determine their provenance. Zircons are the most appropriate minerals for U-Pb dating because of their robust structure and their retention of U in their crystal lattices (Attendorn and Bowen, 1997). Furthermore, the dating of detrital zircons in a metasediment can be used to determine the provenance of the protolith (Rollison, 1993). This study focuses primarily on determining the detrital age of zircons in the granulite facies metasedimentary rocks in the Western Khondalite Zone (WKZ) and the (EKZ) and the subsequent comparison of ages in adjacent terrains in order to constrain what could be the possible provenance of the khondalites in the Eastern Ghats Belt. It is also vital to look at previous research, which will help to correlate the age data and the nature of the metasediments with provenance and the tectonic significance of the age data. Uranium-lead age data and cathodoluminescence images were obtained to help unravel the mystery behind these elusive metamorphosed sediments.

3. GEOLOGICAL SETTING AND PREVIOUS RESEARCH

The Eastern Ghats Domain is a mobile belt system which trends NE-SW and is located on the eastern coast of peninsular India in the states of Orissa and Andhra Pradesh. It lies to the east of three Archaean cratons; The Dharwar Craton; the Bastar or Bhandara Craton; and the Singhbhum Craton. To the west of the Eastern Ghats Domain is the Bay of Bengal. The Eastern Ghats Belt (EGB) has been multiply deformed with thrusts and faults and metamorphosed during a long time period of orogenesis from the Proterozoic to the Cambrian (Battacharya, 1996; Dobemeier and Raith, 2003). During this period of extensive mountain building, a deep section through the Eastern Ghats Domain became exposed (Simmat and Raith, 2008).

3.1 TECTONIC EVOLUTION

The Eastern Ghats Belt formed as part of the Rayner Province in East Antarctica (Fitzsimmons, 2000). The EGB became juxtaposed onto the Indian Archaean Cratons (listed above) during arc-continent collision during the Neoproterozoic. This was during the amalgamation of Eastern Gondwana. Deformation and Granulite facies metamorphism occurred to the EGB/Rayner Complex at 990-900 Ma, at the same time as the arc-continent collision (Boger *et al.,* 2000). The final amalgamation of Eastern Gondwana occurred during the Pan-African Orogeny which saw the ocean closure along two suture zones; the East African Orogen, including Central Dronning Maud Land, with reworked “Grenville aged” crust at the margins of the orogen and The Prydz-Denman-Darling Orogen (Fitzsimmons, 2000). Pan-African metamorphic overprints are witnessed in the Eastern Ghats Domain (Simmat and Raith, 2008).

This paper sometimes refers to a “Grenvillian age” which has been adopted from another model which also describes the final amalgamation of Easten Gondwana. This Model is known as the Circum East Antarctic Orogen (CEAO) (Yoshida, 1992, 1995, 1996, 2006; Yoshida *et al.,* 2003). The Circum East Antarctic Orogen model suggests the South African, Indian and Australian plates formed one continuous mobile belt during their collision with East Antarctica. This however, is incorrect as the three plates formed three different aged orogenies and were separated by ocean during the Proterozoic (Fitzsimmons, 2000). Grenville Orogeny occurred at the same time as the hypothesised CEAO in Laurentia and they were connected (Yoshida, 1992, 1995, 1996, 2006).

3.2 ARCHAEAN AND PALAEOPROTEROZOIC TERRAINS

The Jeypore and Rengali Provices acted as the continental margin during the Archaean and mark the transition zone into the Eastern Ghats Province (Rickers *et al.,* 2001; Simmat and Raith, 2008). Calc-alkaline igneous intrusions suggest an Andean-type continental margin (from fieldwork). Granites intruded the province at 2.7 Ga (Kovach *et al.,* 2001). The Jeypore Province is exclusively made up ofgarnet bearing, granulite, metaigneous rocks and contains no metasediments. Evidence of ductile deformation is seen in the granulite rocks here. Unfoliated, fine grained mafic dykes cross cut the granulites and have a low grade metamorphic overprint.

The Ongole Domain, south-east of the Jeypore Province, is composed of metasedimentary rocks. Provenance of the sediments from the Ongole Domain is from the Dharwar Craton based on Nd model ages (TDM) of 2.8-2.6 Ga. These have been predicted to have a depositional age between 1.72 and 1.71 Ga (Kovach *et al.,* 2001; Simmat and Raith, 2008). Ultra high temperature (UHT) metamorphism occurred at 1.6 Ga (Simmat and Raith 2008). Mesoproterozoic rifting prompted retrogression at 1.45-1.39 Ga (Upadhyay, 2008).

The Krishna Province and the Cuddapah Basin are situated on top of the eastern portion of the Dharwar Craton and are composed of a volcano-sedimentary package which has been metamorphosed to greenschist /amphibolite facies in the eastern Krishna Province during the Neoproterozoic (Simmat and Raith, 2008). The Cuddapah Basin and the Krishna Province are separated by the Nallamallai Fold Belt, extending longitudinally approximately north-south. West to north-west directed deformation occurred later, during the Pan African Orogeny (Fitzsimmons, 2003).

3.3 GRENVILLIAN AGE TERRAINS

The Eastern Ghats Province is situated in the central and eastern parts of the Eastern Ghats Belt. According to Simmat and Raith (2008), sediments here were deposited at 1.37 Ga and have a Mesoproterozoic provenance. Nd model ages (*T*DM) have found protolith age to be 2.5-1.8 Ga (Rickers *et al*, 2001). The Eastern Ghats Province and the Rayner Province in East Antarctica are shown to have formed together as one continuous, Grenville aged mobile belt during the late Mesoproterozoic to Early Neoproterozoic (Fitzsimons, 2000; Rickers *et al*, 2001).The Eastern Ghats province has been thrusted onto the neighbouring cratons and separated by the Sileru Shear Zone, a transitional zone in between the

Eastern Ghats Belt and the Archean Cratons. The shear zone dips roughly 40-50˚ to the south east. Four major lithological units have been identified in the Eastern Ghats province and all run parallel to the orientation of the cratons to the west (Rickers *et al*, 2001).

- Western Charnockite Zone:

  The Western Charnockite Zone (WCZ) consists of basic granulites and enderbites with minor charnockites and metasedimentary, migmatitic enclaves (Rickers *et al*, 2001; Kovach *et al,* 2001). The WCZ is divided into a southern Palaeoproterozoic terrain and a northern, Archaean terrain, separated by the Godavari Rift (Rickers *et al*, 2001). Pegmatites cross cut previous structures at a later stage (Rickers *et al*, 2001).

- Western and Eastern Khondalite Zones:

  The Western Khondalite Zone (WKZ) and the Eastern Khondalite Zone (EKZ) areas are domininated by garnet-sillimanite gneisses, interlayered with quartzite and garnet rich quartzo-feldspathic gneisses (Simmat and Raith, 2008; Rickers *et al*, 2001). Lenses of calc-silicates and Mg-Al granulites are also present. UHT metamorphism occurred at approximately 1.1 Ga, where temperatures would have been increased to 1000˚C at 8-10 Kbar based on feldspar whole rock Pb-Pb data (Jarick, 1999). It subsequently cooled down to 800˚C and heated back up to 850˚C (HT metamorphism) at 8 K bar around 1000-950 Ma, according to U/Pb mineral data (Mezger and Cosca, 1999). Enderbites and charnockites intruded the supracrustal metasediments at 930-920 Ma (Simmat and Raith, 2008). Amphibolites facies metamorphism occurred as a result of retrogression and is shown as an overprint in areas affected by ductile or brittle deformation and fluids associated with Pan-African tectonism (Mezger and Cosca, 1999).

- Charnockite Migmatite Zone:

  The Charnockite Migmatite Zone (CMZ) separates the East and West Khondalite Zones and is the most heterogenous zone in the Eastern Ghats Province (Rickers *et al*, 2001). The CMZ is characterized by intensely migmatised, supracrustal garnet bearing granulites and leptynites (Rickers *et al*, 2001; Simmat and Raith, 2008). The area has been largely intruded by garnet, and orthopyroxene granitoids with large feldspar megacrysts (Dobmeier and Raith, 2003).

4. METHODS

4.1 Field work

Field work was conducted over a three week period in the Eastern Ghats Domain, East India. The Field study was concentrated between Visakhapatnam (Vizag), Andhra Pradesh and Koraput, Orissa. A rough transect was chosen along Highways NH43 and NH 5 and the Vizianagaram Road and the road from Vizag to Araku Valley (this road is simply titled “Way to Araku Valley”). These roads start inland, in the Jeypore Province, in the north-west and go through the Western Charnockite Zone, the Western Khondalite Zone, the Central Charnockite Migmatite Zone and finally through the Eastern Khondalite Zone towards the Bay of Bengal in the south-east. The aim of the field work was to collect and observe Khondalites and or other metasedimentary rocks as well as focusing on their relationships with adjacent rock types. A total of 80 field stops were made. Most of the Khondalite outcrops were significantly weathered and rarer than their charnockitic neighbours. This is due to the chemical instability of granulite facies garnet, sillimanite gneisses which have become exposed at the surface. The Eastern and Western Khondalite Zones are characterized by rounded small hills and fertile plains, mostly corrupted by farming and rice fields. Some of the granulites had become retrogressed to amphibolite facies, where remnant weathered garnets had been replaced with biotite and Fe oxides.

4.2 Sampling Procedure

Khondalite samples were taken along a rough transect in the Eastern Ghats Belt, India in May and June 2009. The transect started in Koraput, Orissa (the transects north-western end) and went south-west to Araku and Vishakhapatnam, both in Andhra Pradesh. The transect lies relatively perpendicular to the orientation of the central Eastern Ghats Belt (Eastern Ghats Belt orientation is south-west to north-east, the transect is from north-west to south-east). This orientation was chosen to show any zircon age differences moving away from the *Archaean* Cratons towards the coast and towards East Antarcticas former position in Rodinian times.

4.3 Sample Preparation

Of the 16 khondalite samples taken in the field, only four were chosen for CL and LA-ICPMS. Originally there were six samples chosen, however there were issues with mounting the zircons and CL imaging which were not rectified due to time constraints. EG9_04, EG9_53, EG9_61 and EG9_62 were chosen for analysis.

4.3.1 Sample crushing

The samples were crushed into powder so the zircons could be extracted. Rock samples were hit with a geological hammer on a clean surface, on top of newspaper until they were smashed into a smaller size with a diameter of roughly 10 – 15 cm. The samples were then placed into the rock crusher; which had been cleaned with compressed air and ethanol to ensure no contamination from previous samples. Newspaper was laid down underneath the crusher in the sample capture tray. At this stage the sample was a mixture of gravel and fine to medium grained powder. The rock crusher was cleaned once again, the same as detailed above, ready for the next sample to be placed in it. The crushed sample was then placed into the tungsten-carbide mill and was milled for approximately 10 seconds. Any further milling poses a risk on crushing the zircons. The samples were sieved into three different grain sizes; <75 µm, 75-400 µm and >400 µm. These three separate sizes were then placed into clean plastic sample bags. Anything smaller than 75 µm is too small for the LA-ICPMS and zircons of this size are likely to be damaged or over crushed and anything greater than 400 µm is unlikely to be a zircon.

4.3.2 Mineral separation

The 75-400 µm samples were then panned to remove the light, felsic material. The quartz and feldspars and other felsic material are washed out of the sample, leaving the heavier material in the pan. The heavier minerals from the pan were then dried and ready for mineral separation. The felsic grains were still dried and kept in case they need to be used at a later stage. A Neodymium magnet is then ran through the sample to remove heavy, mafic minerals, leaving behind zircons. If the sample still had a large quantity of light minerals, it was separated with heavy liquids.

4.3.3 Zircon mounting

The sample at this stage should contain mostly zircons. Two microscopes were used, one to pick zircons out of the sample and another to place them into rows, on double sided tape, attached to a slide. It is helpful to order zircons on the slide rather than placing them randomly over the tape, otherwise it is very difficult to find them when trying to CL image them and when using the LA-ICP-MS.

100 zircons were placed inside a small piece of poly pipe (1.5cm high, 2.5cm diameter) on the double sided tape, on a slide. Epoxy resin was mixed with hardener (carefully at a 5 resin: 1.1 hardener) poured carefully into the poly pipe. The mounts were left to set for 24 to 48 hours. The mounts had a 50% success rate. The resin did not set properly a number of times or there were ridges on the surface of the zircon mounts, rendering the mounts unfit for use. At this stage, the zircons had to be re-picked or the sample needed to be crushed and mineral separated again from the beginning.

Once successful mounts had been created, they were polished with fine sand paper on a turntable. This process exposes the zircons core through the resin and improves the surface, ready for CL imagery and LA-ICP-MS analysis.

4.4 Cathodoluminescence imaging (CL)

Cathodoluminescence imaging is used to detect structures and textures of a zircon grain which are difficult to examine under a transmitted light microscope (Muller, 2000). CL microscopy uses electron beams to excite the zircon grains and produce energies in the visible light spectrum. Zircons were first imaged with a Philips XL20 SEM with an attached Gatan CL detector at Adelaide Microscopy to obtain images of the structures of the zircons. Detrital cores, metamorphic overprinting, shape and size were the key features that were examined. These features dictate the position of the laser beam for uranium/lead isotope analyses, as the beam needs to be placed over the detrital core of the zircon and not on the metamorphic overprints. Zircon shapes and sizes are also of importance because they describe the nature of a zircons origin. Elongated, oscillatory zoned grains are of an igneous source or from a melt, where rounded, sometimes sector zoned, sometimes homogenous grains are from a metamorphic source or show recrystallised zones from metamorphism. These images also show any fractured or broken grains which are important to image, as these features can attribute to Pb loss, which can affect the age data collected after imagery.

4.5 Laser Ablation - Inductively Coupled Plasma Mass Spectrometry

Detrital zircons ages were obtained by using uranium/lead dating. Uranium/lead isotope ratios of zircon cores were analysed using laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS). A

30 µm laser beam was focused on the surface of a zircon core resulting in its ablation. The ablated material is then transported to the ICP-MS instrument via a carrier gas and becomes ionized and subsequently surveyed for uranium decay chain elements with mass spectrometry.

4.5.1 Uranium/Lead dating (U/Pb)

Zircons substitute uranium atoms into their crystal lattices, which over time decay down a decay chain from thorium and eventually to lead. Zircons retain U in their lattices better than any other mineral (Attendorn and Bowen, 1997). Average concentrations of U in a zircon are of 1330 and 560ppm respectively Thorium is not able to be substituted into the lattice because it is not compatible (Maas *et al.,* 1992). Therefore, any U series daughter products in a zircon must have decayed from Uranium.

Data was analysed using Glitter software and processed with Microsoft Excel Macro Isoplot/Ex, which generated concordia plots. The 207Pb/235U ages are plotted on the x-axis against 206Pb/238U ages on the y-axis. The concordant line is represented on the graph as a curved line and defines the locus of concordat ages for 235U and 238U decay (Rollison, 1993). The discordant array is plotted at a straight line which accounts for lead loss (during metamorphism and or deformation). The concordant and discordant lines show intercepts. The top intercept will provide the initial age estimate of zircon crystallisation from a melt (Rollison, 1993).The lower intercept is an age estimate of lead loss (Rollison, 1993). Lead loss is caused from the diffusion of lead from the zircon during metamorphism or chemical weathering (Attendorn and Bowen, 1997).

Standards were analysed with the unknown zircons from the Eastern Ghats to ensure data quality. These included GJ and two in house standards; BJWP and Plesovice.

5. RESULTS

Four samples from the Western and Eastern Khondalite Zones were collected. Outcrops of fresh khondalites are rare in the Eastern Ghats Province due to a high level of weathering and poor exposure. Three of the samples taken are from quartz, garnet, sillimanite gneisses (metapelitic/metapsammatic rock). The fourth sample is a leucogranite. These were classified both in and out of the field with a hand lens.

5.1 Sample EG9_04

Sample EG9_04 is from a quarry, 4 km NW of Nandapur, halfway in between Araku and Koraput in the Eastern Ghats Province. Sample EG9_04 is a quartz, feldspar, garnet leucogranite formed from the partial melting of metasedimentary rock. Zircons vary in colour from clear to light brown to light green. No detrital zircons are present.

5.1.1 Zircon features identified with CL imagery from EG9_04

- Elongated, igneous grains
    - Approximately 200µm in length
    - Most of these zircons have rounded ends, however some retain sharp ends
    - There are a number of zircons with broken ends
    - Most of the zircons have oscillatory zoning
    - There are a few homogenous grains with no zoning
    - Some zircons have new black zones (new cores)
    - Many zircons contain fractures or are broken or cracked
- Sub-rounded elongated grains
    - 100-150µm in length
    - Igneous cores with oscillatory zoning
    - Bright cores and dark, black metamorphic rims, varying in thickness
    - There is a sharp distinct nature in between the cores and the rims
- Rounded metamorphic grains
    - 75µm
    - Sector zoned
    - Dark in colour under CL

5.1.2 LA-ICPMS age data for EG9_04

68 zircons were mounted and analysed with LA-ICPMS, targeting their centres or cores (when present). Concordant zircon growth ages show crystallisation of new zircons from 976 ± 100 Ma (upper intercept) to approximately 870 Ma. This is the best estimate from the weighted mean of the 90-110% concordant analyses. The lower intercept from the 90-110% concordant analyses is 650 ± 150 Ma. The 90-110% probability density plots for zircon U/Pb age data show two age spikes. The oldest spike predicts zircon

crystallisation at 928 Ma. The second spike indicates zircon crystallisation at 813 Ma. This sample did not provide any detrital zircons from its protolith and therefore, provenance is unknown from this sample.

5.2 Sample EG9_53

Sample EG9_53 was collected from an outcrop on a hilltop in northern Visakhapatnam, Andhra Pradesh. This khondalite sample is a sillimanite, quartz gneiss with remnant, weathered garnets. Based on field and sample observations and mineralogy, this sample was metamorphosed to granulite facies metamorphism. Retrogression may have aided in the breakdown of the garnets, however, these khondalites from this area are highly weathered and it is difficult to distinguish based on field observations alone. Quartz veins with biotite concentrations have been observed in this sample. The concentrations of biotite in quartz veins suggest fluid alteration post deposition. Veining is parallel to foliation dipping at an angle of approximately 50° towards south-east.

5.2.1 Zircon features identified with CL imagery from EG9_53

- Metamorphic/metamorphically recrystallised zircons
    - Range from 70 to 150µm in size
    - Most of these zircons are sector zoned however there are a few that are homogenous with no zoning. This is typical of recrystallised zircons
    - Cores are present; some cores are dark under CL with distinct boundaries between the core and the lighter coloured metamorphic rims. Some zircons have light coloured cores under CL with darker metamorphic rims, separated by a distinct boundary also
    - Micro cracks are present in some zircons
- Metamorphosed, elongated, igneous zircons
    - 150µm in length
    - Some of these zircons show oscillatory zoning and some are homogenous
    - Metamorphic overgrowth encompasses the exterior of the igneous grains, with distinct boundaries
- One grain has had one of its ends broken away and looks highly deformed and therefore it is difficult to distinguish the nature of the zircon (metamorphic or igneous origin). It is likely to be a metamorphic zircon due to its sphericity, sector zoning (in the rims) and large metamorphic

overgrowth. There is a distinct boundary between the darker core and the light coloured metamorphic.

5.2.2 LA-ICPMS age data for EG9_53

18 zircon cores were analysed with LA-ICPMS of the 66 individual grains mounted in this sample. Only 18 cores were targeted due to the other material not being zircons (as initially thought during this samples preparation). The best age estimate for this sample is from a weighted mean of the 90-110% concordant analyses, giving a 207/206 age of 908 ±19 Ma. One older zircon gave a discordant U/Pb age of ca. 1.27 Ga, estimated from the weighted mean concordant analyses plot. This age could be from a detrital zircon. Ages from this concordia plot show concordant ages at ca. 800 and 900 Ma and moderate discordant ages from 1000 Ma. Intercepts are shown at 1071 ± 130 Ma (upper) and 563 ± 140 Ma (lower). Peak zircon crystallisation ages from the 90-110% density plot are ca. 910 Ma.

5.3 Sample EG9_61

Sample EG9_61 is a khondalite sample (metasedimentary gneiss), taken from a hinge zone in a syncline, from a quarry 1km south of Araku. This sample contains quartz, large amounts of sillimanite and remnant garnets. Fe oxides are also common in this sample. There are very few garnets still present in this sample, similar to sample EG9_53. This sample also appears to have been retrogressed to amphibolite facies and is highly weathered. Foliations and leucosomes are parallel to one another. Leucosomes separate layers with higher garnet concentrations.

5.3.1 Zircon features identified with CL imagery from EG9_61

- Metamorphic zircons with sector zoning
    - Rounded grains approximately 50µm in diameter
    - Most of these zircons contain dark cores under CL with alternating bright and dark rims. The boundaries between the rims and between the rims and the cores are distinct
    - Other zircons have bright cores with alternating dark and bright rims, also with sharp distinct boundaries between layers
    - A few zircons have secondary darker, retangular shaped cores of about 20µm in length and 10µm wide
    - There are a few broken and fractured grains present. These could attribute to the discordant data (see 4.3.2)

- Homogenous metamorphic zircons
    - Sub-rounded and sometimes sub-elongated grains 75-100µm in length
    - Dull under CL

5.3.2 LA-ICPMS age data for EG9_61

59 zircon cores were analysed in EG9_61. These produced metamorphic zircon ages of ca. 910 Ma. Crystallisation started at approximately 970 Ma. Results from approximately 900 Ma to approximately 700 Ma record discordant ages due to lead loss.

5.4. Sample EG9_62

Sample EG9_62 is a moderately fresh Khondalite sample taken from an outcrop a few kilometres north of Hukumpeta. This sample contains gneissic layers of garnet, sillimanite and quartz and is a granulite.

5.4.1 Zircon features identified with CL imagery from EG9_62

- Metamorphic zircons
    - Rounded grains approximately 75-100µm in diameter
    - Sector zoned
    - Dark and bright cores
    - Highly contrasting metamorphic rims
    - Some grains are broken and cracked

5.4.2 LA-ICPMS age data for EG9_62

The age data collected show a good spread of metamorphic ages from approximately 920-820 Ma, as demonstrated on the 206Pb-238U 95-105% probability density graph. There ages are concordant on the 90-110% concordia plot. Metamorphic zircons started forming at 906 ± 22 Ma, from the upper intercept of the 90-110% concordia plot. There is one possible, highly discordant grain with a predicted age of approximately 1010 Ma. Zircon ages become increasingly discordant as they decrease in age. This is interpreted as being due to lead loss. The lower intercept is at 562 ± 59 Ma. This is interpreted to be the age of lead loss from the zircons in this sample.

6. DISCUSSION

6.1. Detrital age of the protolith in the Eastern and Western Khondalite Zones

The primary goal of this research was to discover the age of the protolith of the khondalites/metasedimentary granulites in the Eastern Ghats Belt in eastern India. Unfortunately, there were very few detrital zircons found, not enough to constrain ages of the protolith and to make inferences on provenance. Highly discordant ages from the two detrital zircons are approximately 1.2 and 1.0 Ga. Discordant ages such as these do not suggest anything about the protoliths age because lead has been lost from the zircon grains and therefore gives false age data (Attendorn and Bowen, 1997).

Detrital ages of the protolith have been predicted to be 2.5-1.8 Ga, from Nd model age data (*T*DM) (Simmat and Raith, 2008). Deposition occurred at 1.37 Ga (Simmat and Raith, 2008), into diverse marine environments from shallow marine to a continental margin setting (Divakara *et al.,* 1998). This correlates well with metapelitic and metapsammatic rock descriptions. Divakara *et al.* (1998) have also found that the sediments have come from an acidic igneous source, with a composition similar to tonalite-trondhjemite-granodiorite (TTG). The source rocks and the depositional basins must have been in close proximity to one another, interpreted from the scatter in ferrous to ferric Fe ratios and low CaO (Divakara *et al.,* 1998).

It is highly likely that the protolith of the khondalites in the EGB are sediments deposited from the neighbouring Archaean cratons in the west. The Dharwar Craton has tonalite-trondjhemite-granodiorites present, as part of the Sargur Group (Dobmeier and Raith, 2003). The Dharwar Craton became stabilised at 3.4-2.5 Ga (Dobmeier and Raith, 2003). The Bhandara Craton has TTG gneisses and granitoids with protolith ages of 3.5 Ga and metamorphic ages of 2.65-2.41 (Sarkar *et al.*. 1993). The Singhbhum Craton contains tonalite intrusions from 3.44 Ga (Dobmeier and Raith, 2003). These cratons were in close proximity and adjacent to the mesoproterozoic depositional basins that accommodated the sediments that became the Eastern Ghats Belt and fit the criteria outlined by Divakara *et al.* (1998) in the above paragraph.

6.2 Metamorphic ages from U/Pb dating of zircons

All the zircons analysed with U/Pb dating methods recorded metamorphic ages. This is because the zircons sampled are all formed from metamorphic processes.

Leucogranites in sample EG9_04 are crustal derived, from garnet rich gneisses (metapelite/metapsammite). The leucogranites here were formed during crustal thickening during orogenic processes (Braun *et al.,* 1996). Leucogranite compositions are strongly influenced by their protolith and melts rich in garnet suggest an S-type melt (Braun *et al.,* 1996). Partial melting is common in granulite terrains. The granulite facies metamorphism here occurred at 976 ± 100 Ma, during the continental collision between East India and East Antarctica. Zircon ages from the leucogranites show “Grenvillian” ages (Yoshida 1992, 1995, 1996, 2006; Yoshida, et al 2003) and reflect partial melting and recrystallisation of melts produced during orogenesis and do not reflect any previous ages from the original protolith.

Metamorphic or metamorphically recrystallised zircons are found in samples EG9_53, EG9_61 and EG9_62. U/Pb ages recorded from the dating of the cores in these samples show peak crystallisation occurring from 910-906 Ma with upper intercepts from 1071 ± 130 Ma to 906 ± 22 Ma. These ages all coincide with the 990-900 Ma ages given for the amalgamation of eastern Antarctica and eastern India producing granulite facies metamorphism in the Eastern Ghats Belt/ Rayner Province (Boger *et al.,* 2000; Dobemeier and Raith, 2003; Fitzsimmons, 2000; Rickers *et al.,* 2001). Discordant analyses have predicted ages ranging from 900 – 560 Ma. These ages do not represent times of new metamorphic zircon growth or recrystallisation (Attendorn and Bowen, 1997). These analyses are from Pb loss from the zircon grain, the result of fracturing and breakage of the zircon crystals.

6.3 Pan-African ages recorded in metamorphic zircons

Discordant zircon ages from the four samples become increasingly discordant as they decrease in age. The simple explanation for this is when there are larger concentrations of Pb retained in a zircon, the ages will be closer to the concordant ages. As Pb is lost from a zircon, Glitter software will predict them as being younger than they really are (based on the U/Pb ratios provided from LA-ICPMS).

Lower intercept ages from the concordia plots show Pb loss ranging from 650 ± 150, 563 ± 140 and 562 ± 59. Pb is lost in zircons during metamorphism or recrystallisation. These ages can be correlated with the weak Pan-African metamorphism experienced in the Eastern Ghats Belt during the Neoproterozoic to early Phanerozoic (Dobmeier and Raith, 2003). This further supports the Pan-African model for Eastern Gondwanas final assembly instead of the Circum East Antarctic Orogen model (Collins and Pisarevsky, 2005; Dobmeier and Raith, 2003; Fitzsimmons, 2000 and 2003). Dobmeier and Raith (2003) has stated that there are sharp contacts between 3 separate crustal blocks with significantly different Nd isotope compositions, which became juxtaposed during the Pan-African Orogeny from the closure of suture zones. Dobmeier and Raith (2003) also describe a medium grade thermal overprint, experienced during the early Phanerozoic, from isotope data. This time also saw final thrusting of the Eastern Ghats Province onto the Bhandara Craton, creating metamorphic overprints that can be attributed to Pb loss (Dobmeier and Raith, 2003).

6.4 Detrital zircon dating in granulite terrains

There are very few previous studies with detrital zircon age data on the metasedimentary granulites (khondalites) in the Eastern Ghats. The reason for this is it is very difficult to find detrital zircons from a protolith in granulite terrains. Granulite metamorphism is high grade and induces partial melting, creating new zircons and new metamorphic zircons/ recrystallisation of metamorphic zircons. Different methods need to be adopted if protolith age is to be discovered of the khondalites in the Eastern Ghats.

7. CONCLUSION

Detrital zircon ages were not obtained from the analyses of zircons from the khondalites in the Eastern Ghats Province. Protolith age is still unknown from this research. But Divakara *et a.l* (1998) has suggested protolith to be 2.5-1.8 Ma. This is from Nd model ages. To determine the protolith ages futher, Nd models should be applied. Detrital zircon age studies are inappropriate in granulite terrains due to partial melting of the crust and recrystallisation of zircon; resetting the U/Pb concentrations in the crystal lattices.

Mesoproterozoic metamorphic ages were discovered from the U/Pb zircon dating. These ages agree with “Grenvillian” ages of metamorphism produced from the collisional orogeny between east India and East Antarctica ca. 990-900Ma. Pan-African events are also preserved in zircons and are demonstrated as Pb loss at 650-560 Ma in the concordia plots. This shows that the khondalites in the Eastern Ghats Belt have a weak Pan-African metamorphic overprint and became damaged at this time.

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FIGURES

Figure 1.

Figure 2.

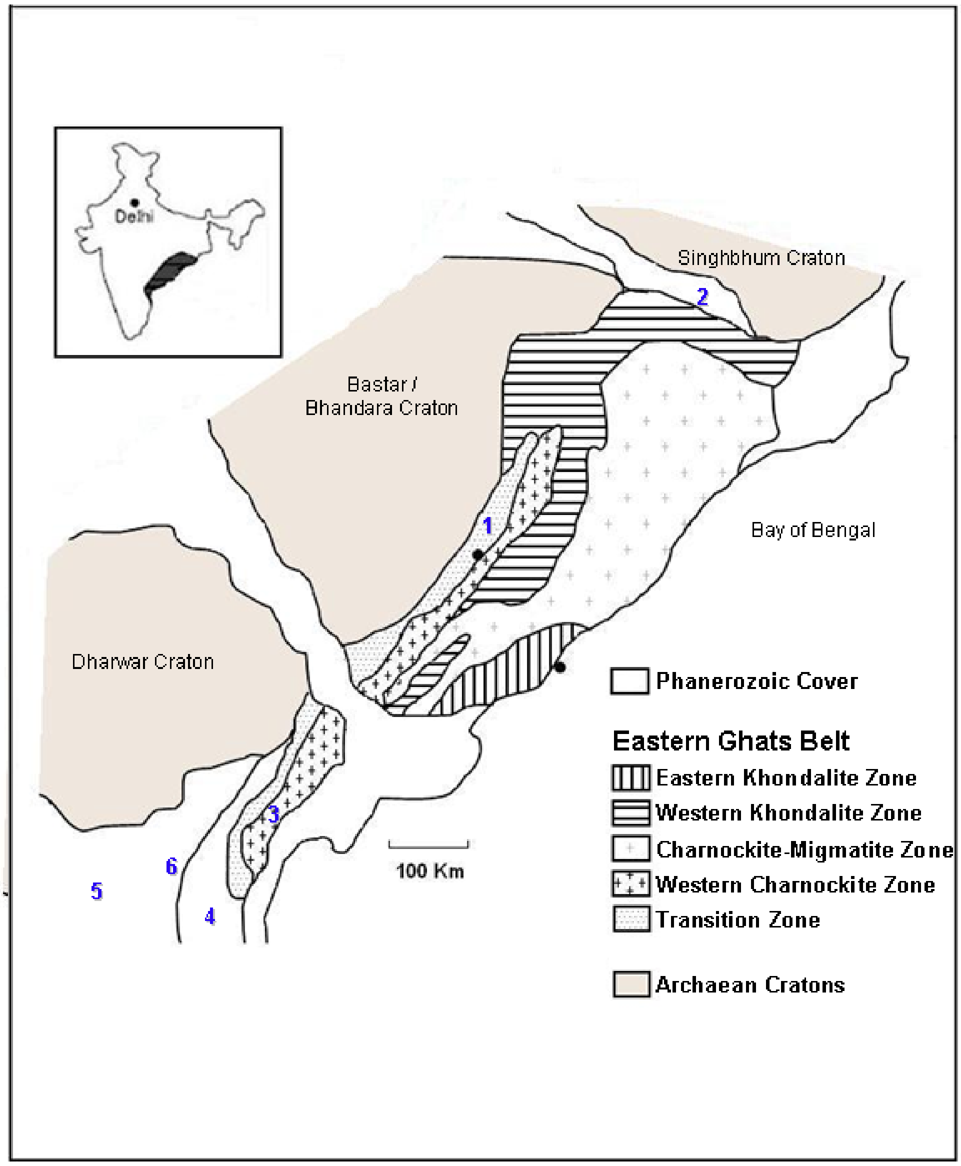
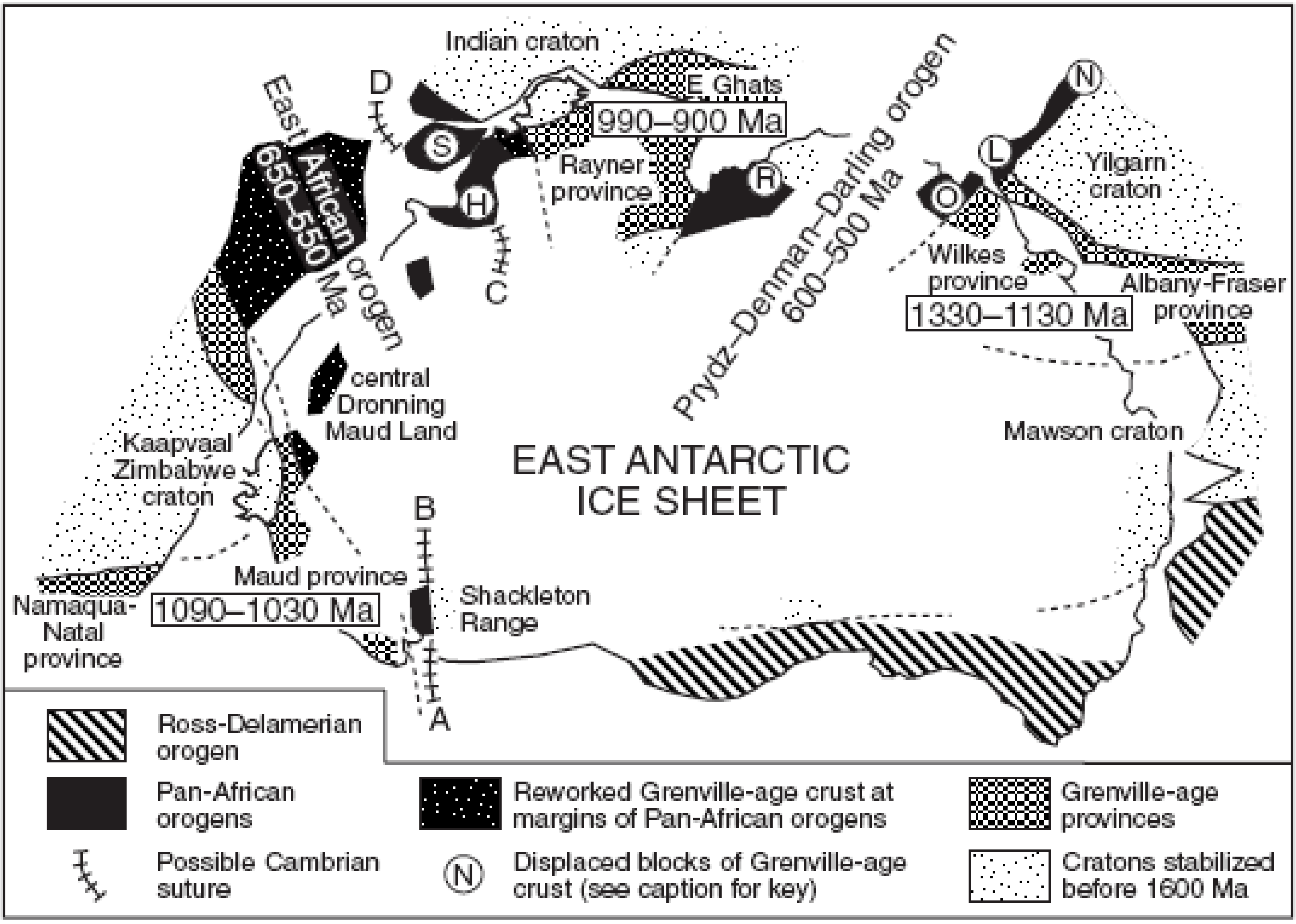

Delhi
Singhbhum Craton
Bastar / Bhandara Craton
Dharwar Craton
Bay of Bengal
1
2
3
4
5
6
100 Km
Phanerozoic Cover
Eastern Ghats Belt
Eastern Khondalite Zone
Western Khondalite Zone
Charnockite-Migmatite Zone
Western Charnockite Zone
Transition Zone
Archaean Cratons

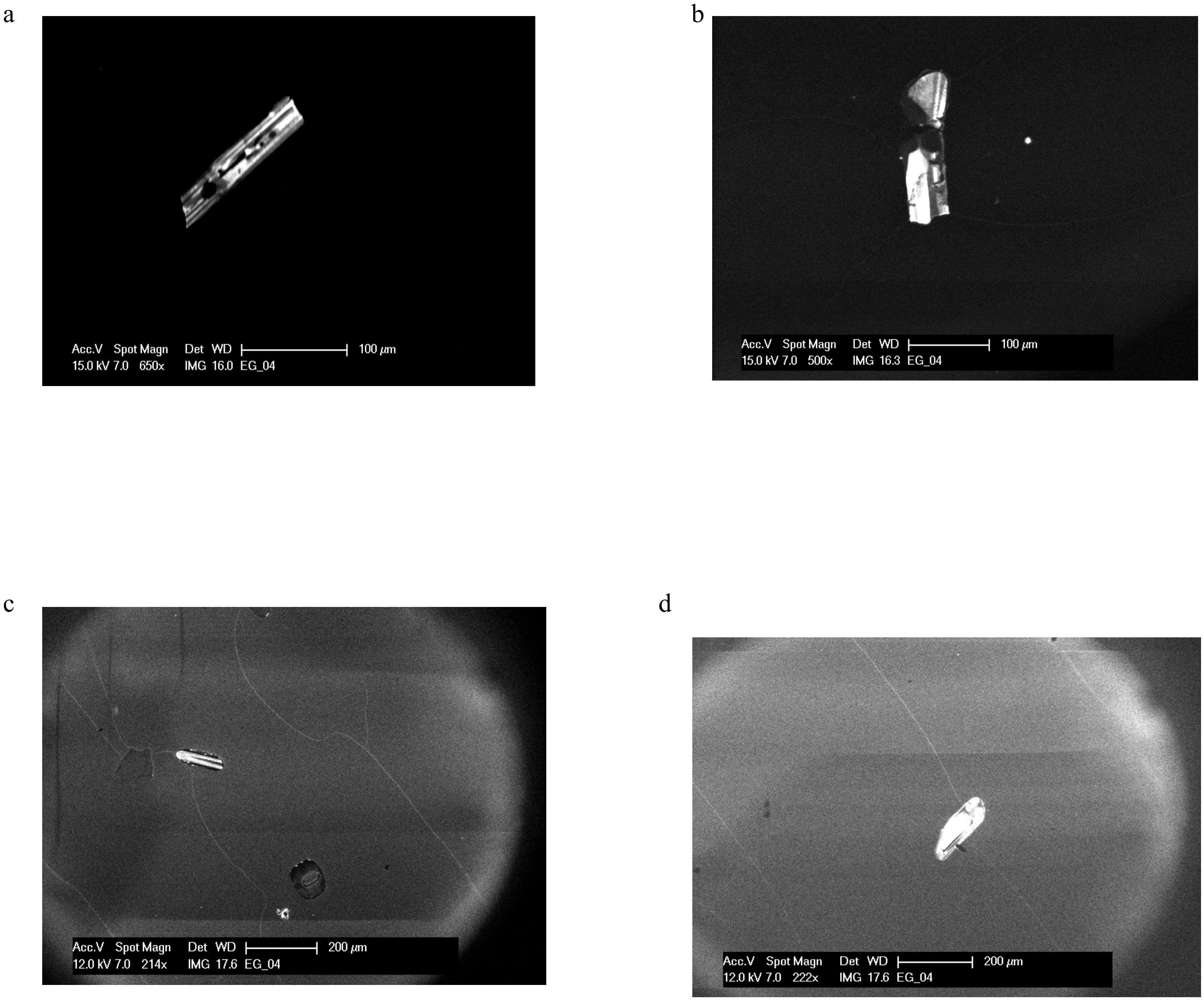
Figure 3.



Indian craton
E Ghats
990–900 Ma
Rayner province
D
S
H
C
R
East African orogen 650–550 Ma
Prydz–Denman–Darling orogen 600–500 Ma
N
L
O
Yilgarn craton
Wilkes province
Albany-Fraser province
1330–1130 Ma
Mawson craton
central Dronning Maud Land
EAST ANTARCTIC ICE SHEET
Kaapvaal Zimbabwe craton
B
Maud province
Shackleton Range
Namaqua-Natal province
1090–1030 Ma
A
Ross-Delamerian orogen
Pan-African orogens
Reworked Grenville-age crust at margins of Pan-African orogens
Grenville-age provinces
Possible Cambrian suture
Displaced blocks of Grenville-age crust (see caption for key)
Cratons stabilized before 1600 Ma

Figure 4.

EG9_04



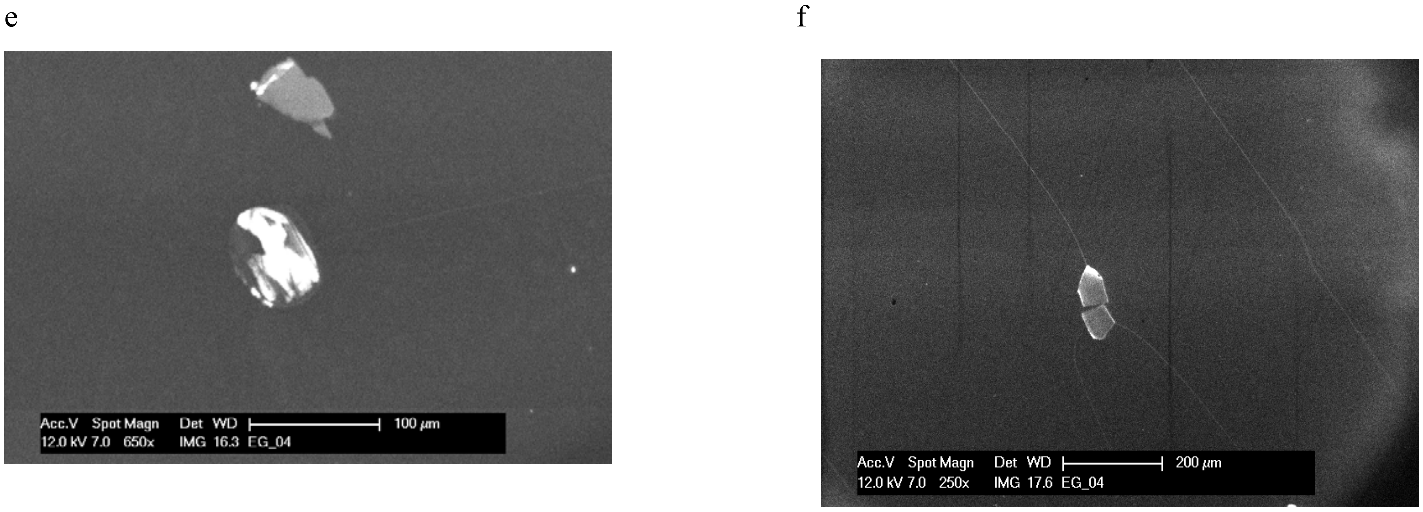
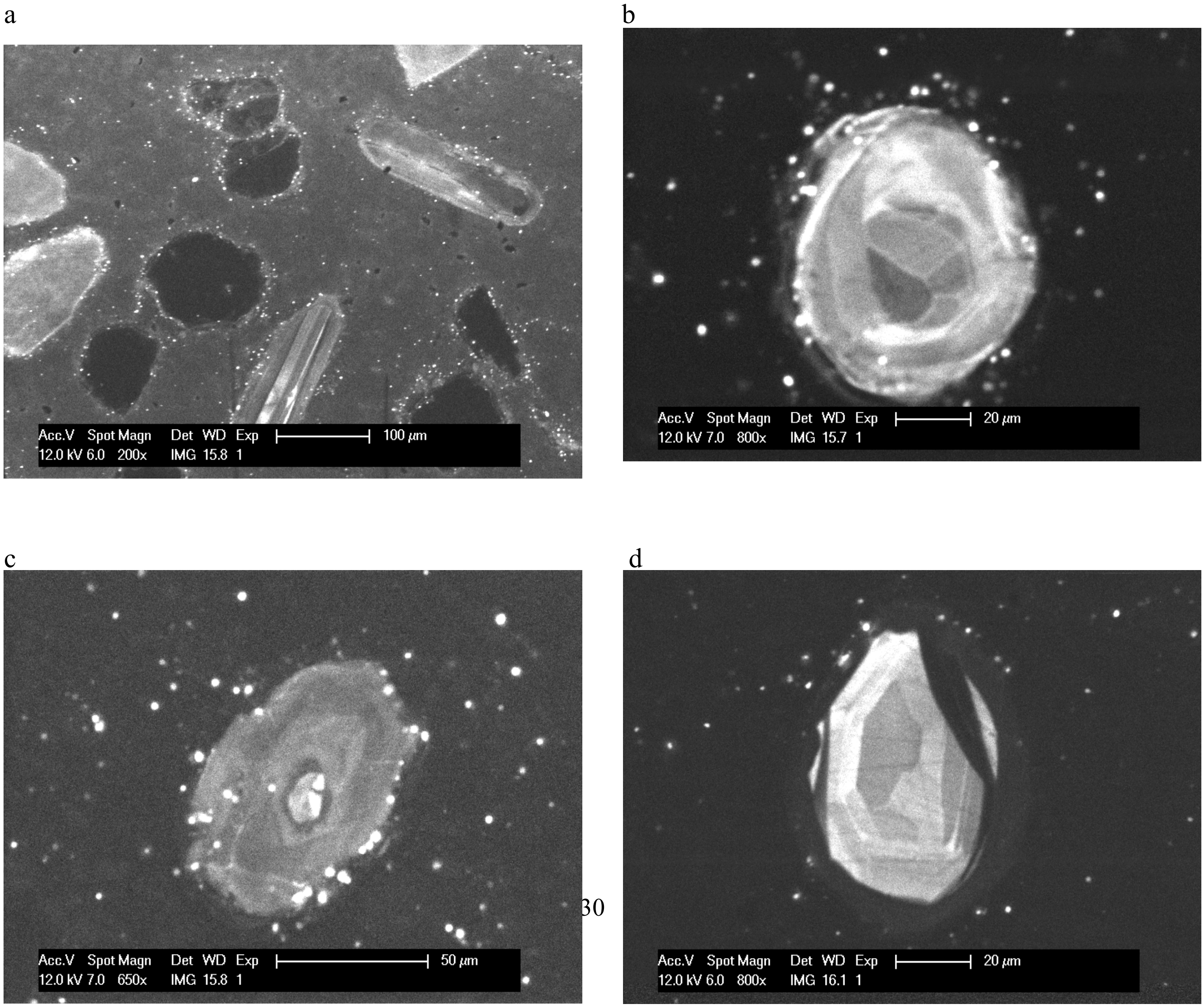
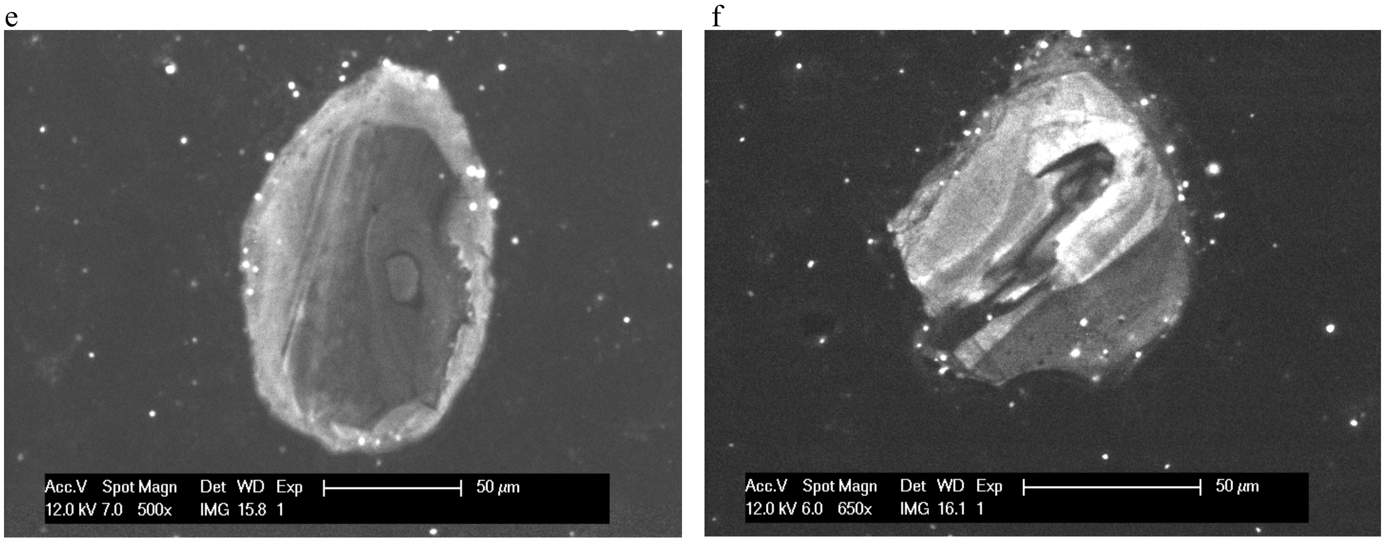


Figure 5.

EG9_53





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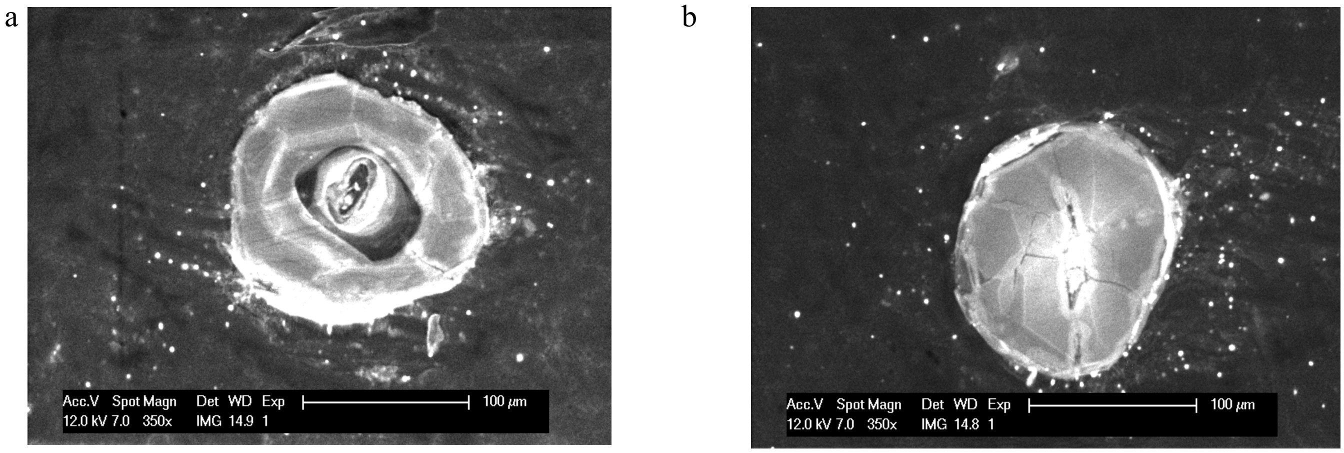
EG9_61



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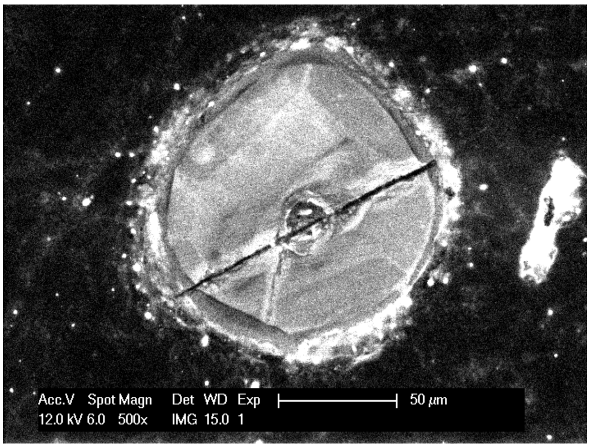
Acc.V Spot Magn Det WD Exp 50 µm
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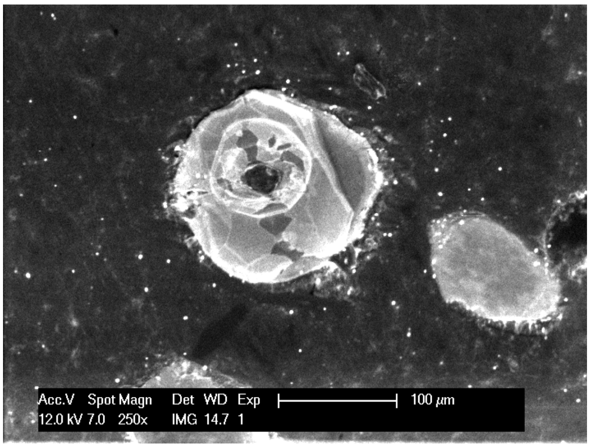
d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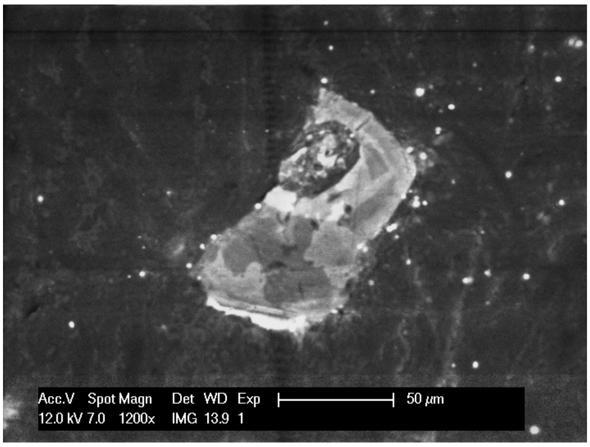
e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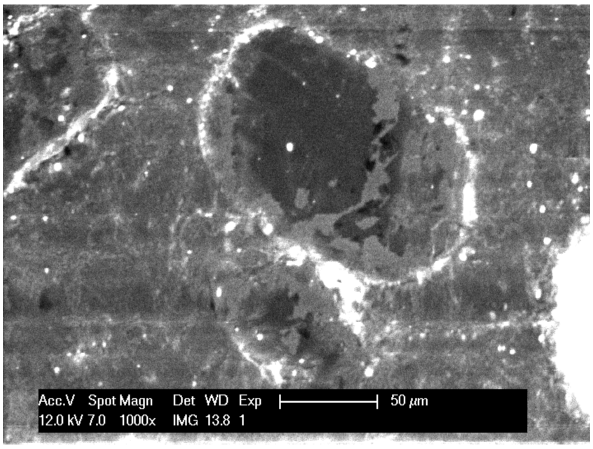
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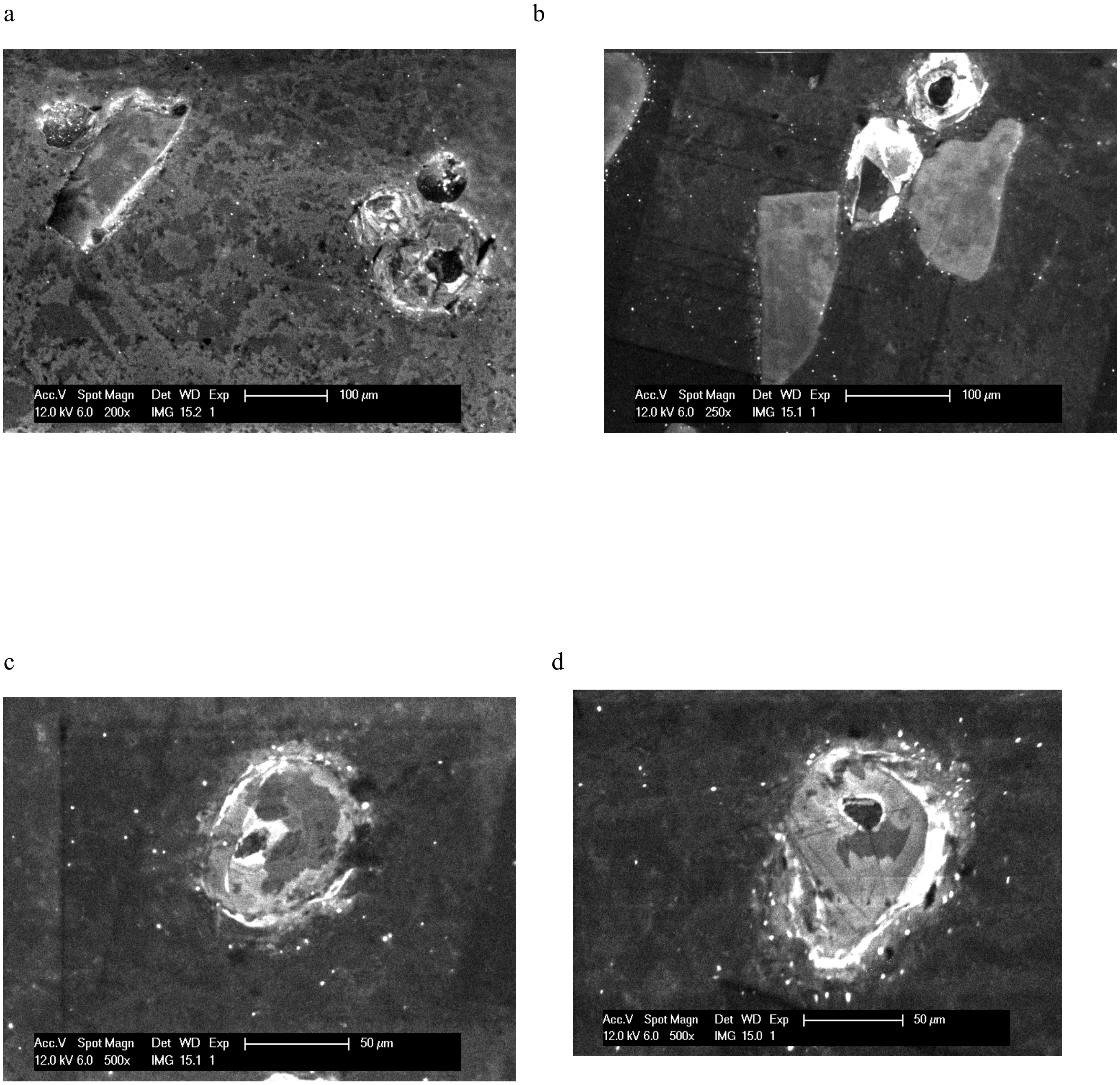
Figure 7.

EG9_62



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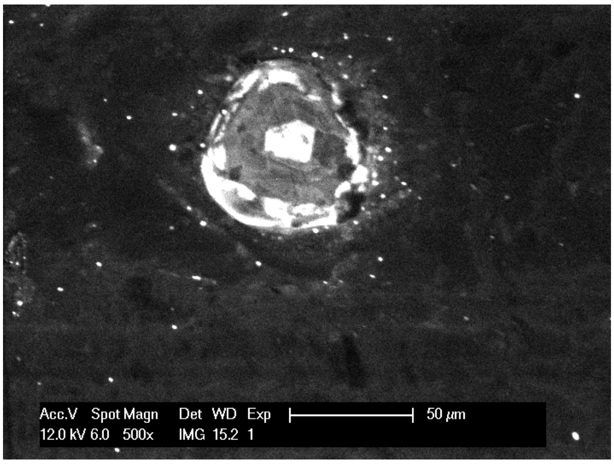
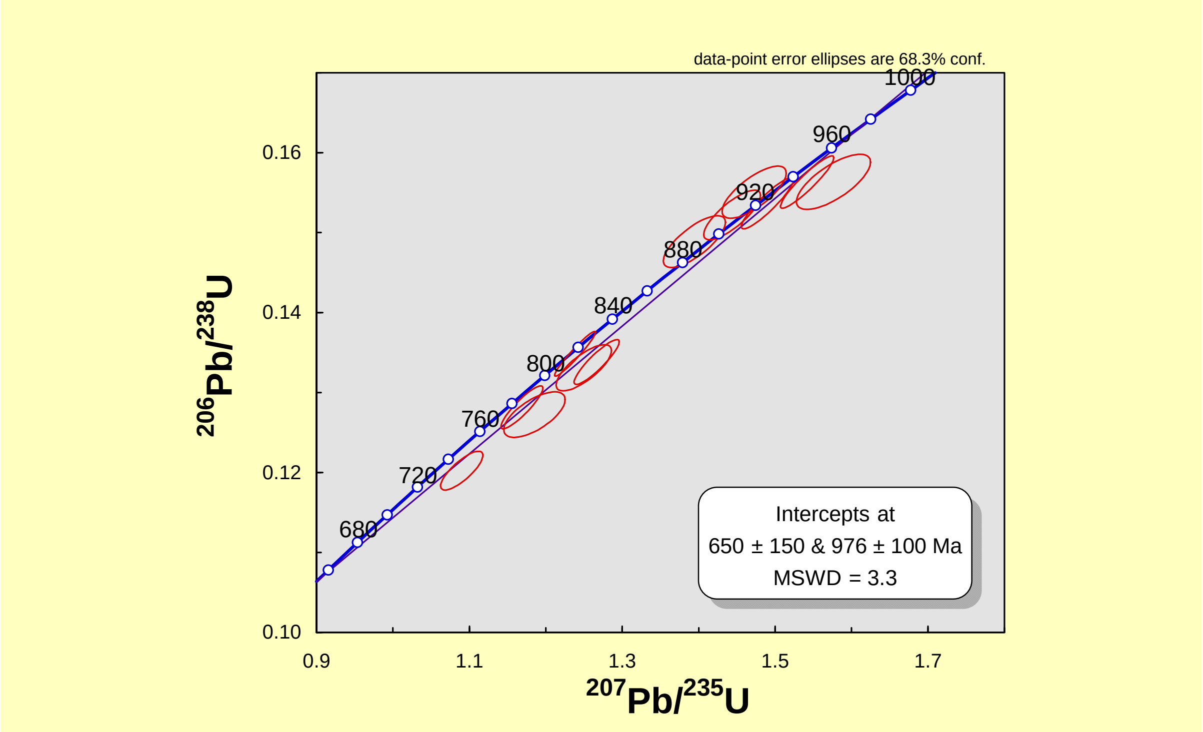


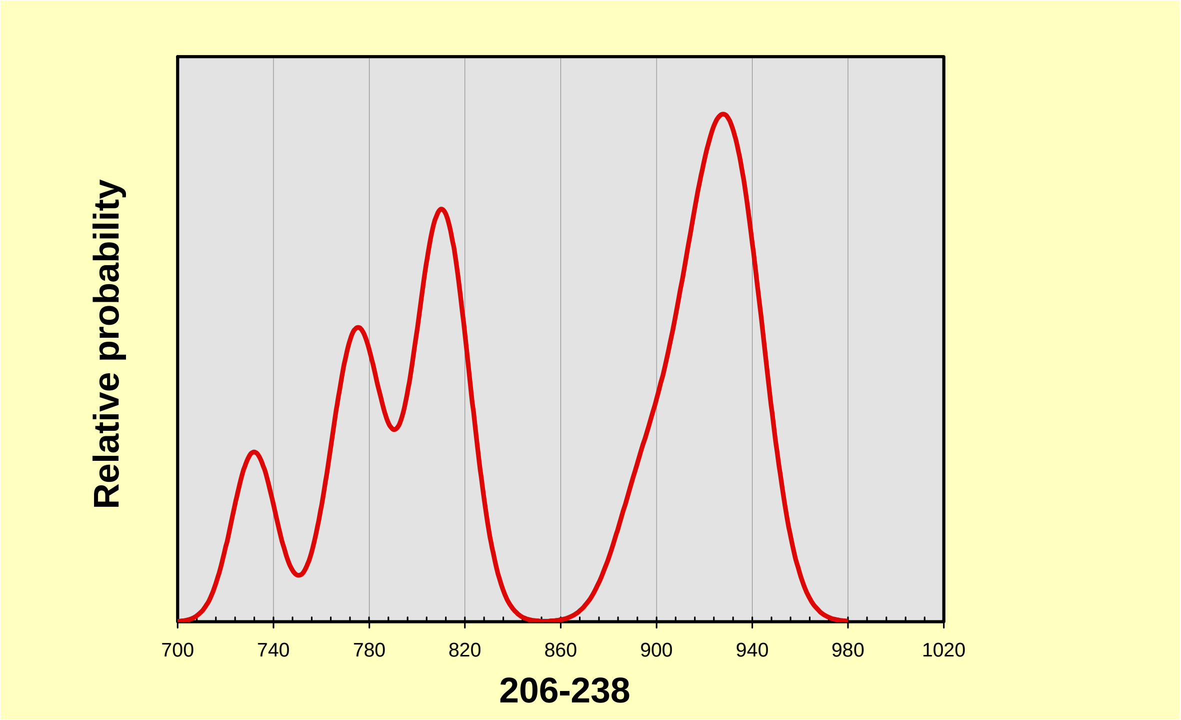
Figure 8.

EG9_04

a.



b.


Relative probability
700
740
780
820
860
900
940
980
1020
206-238

c.

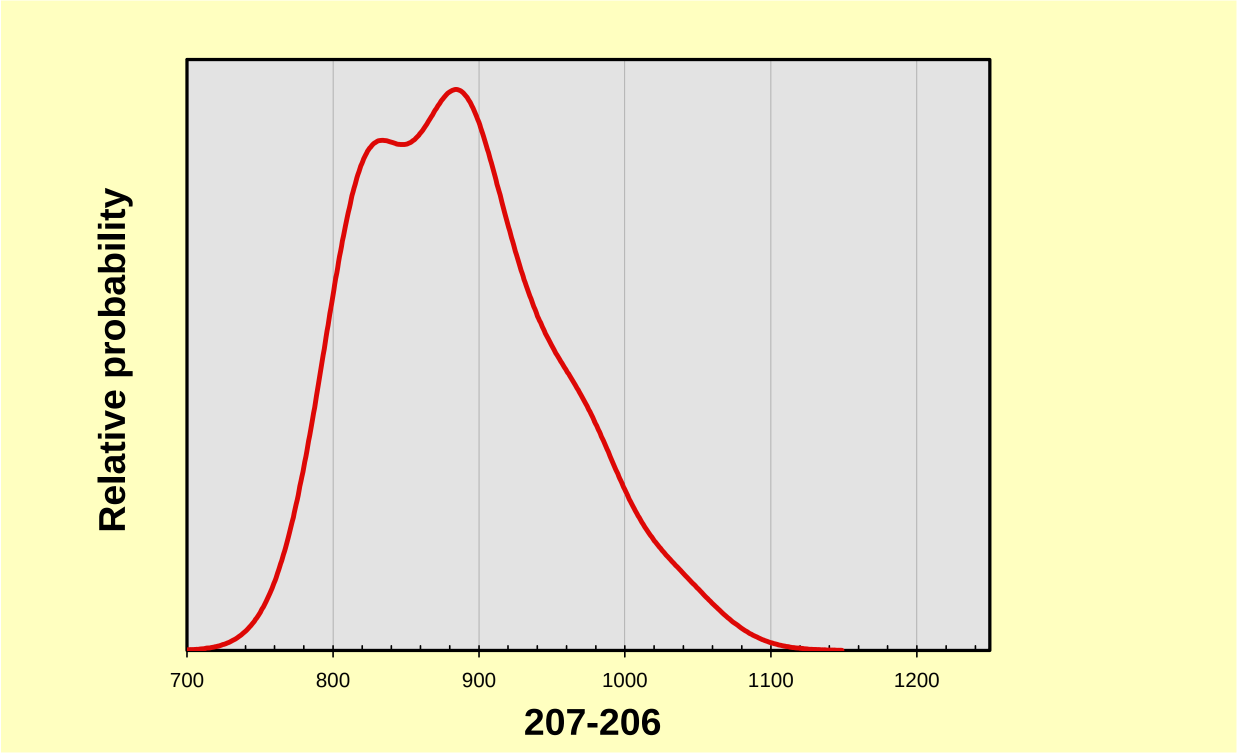
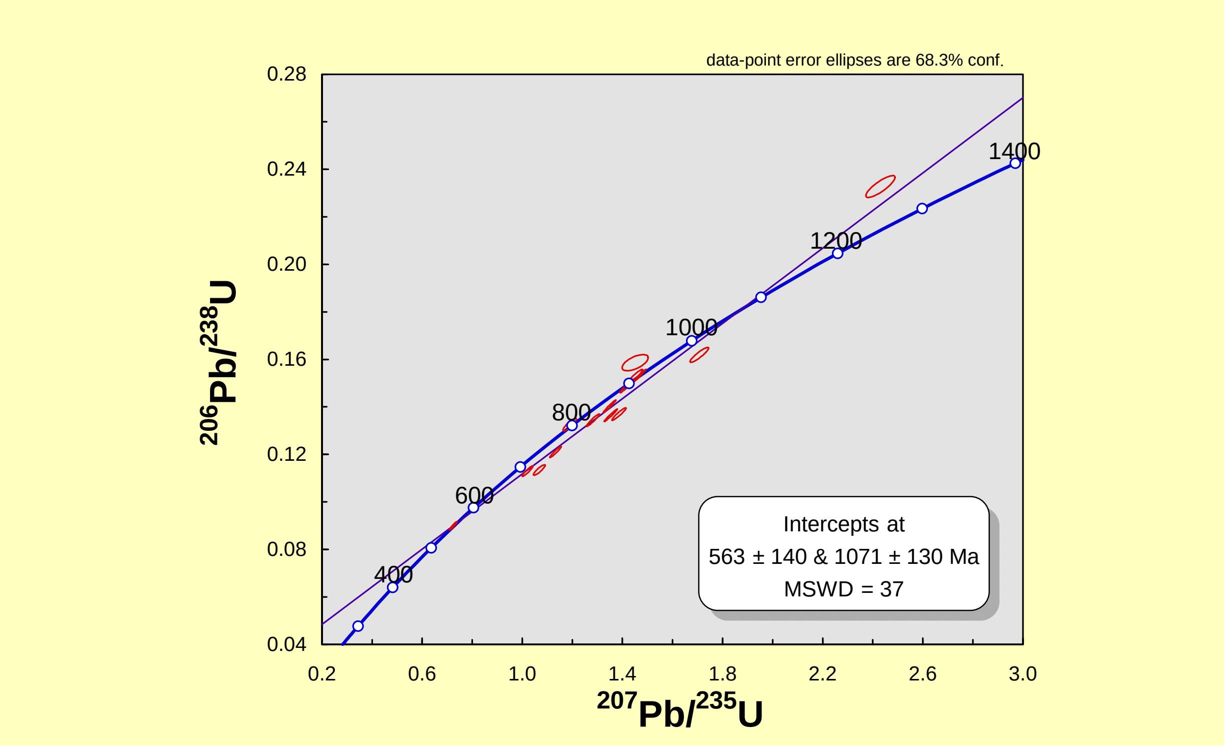

Relative probability
700
800
900
1000
1100
1200
207-206

Figure 9.

EG9_53

a.



b.

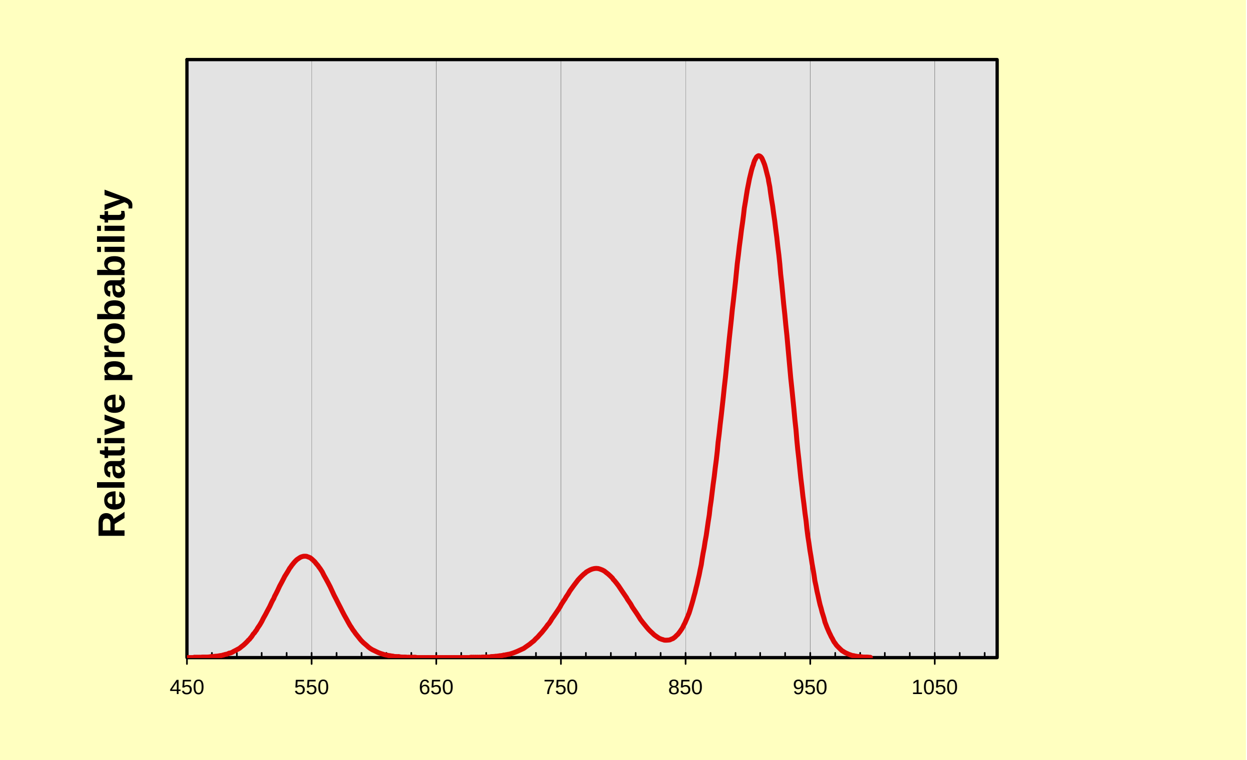


Figure 10.

EG9_61

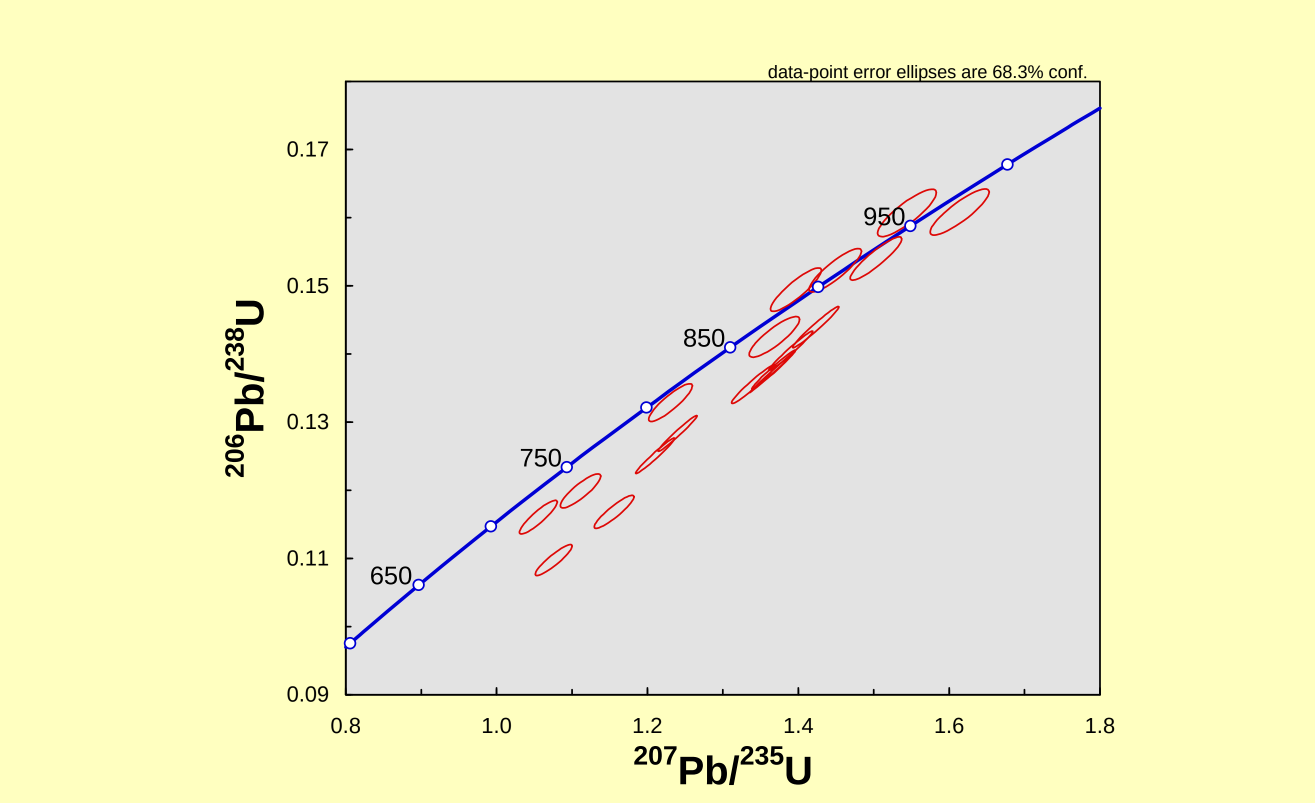
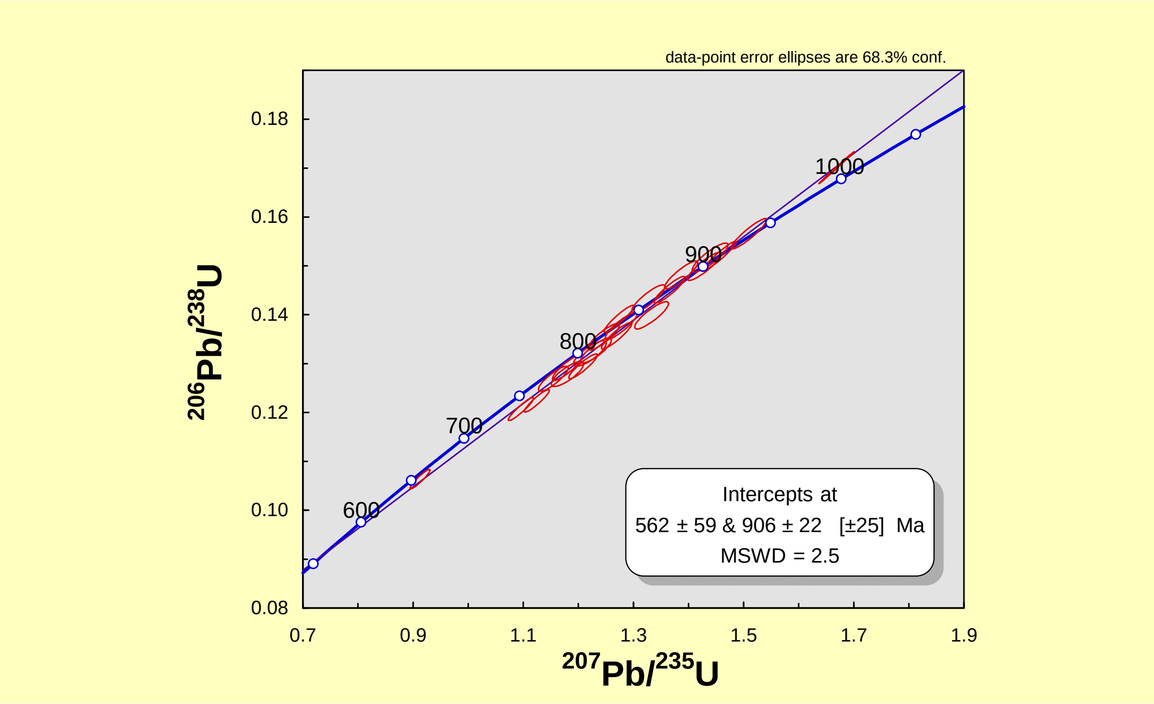


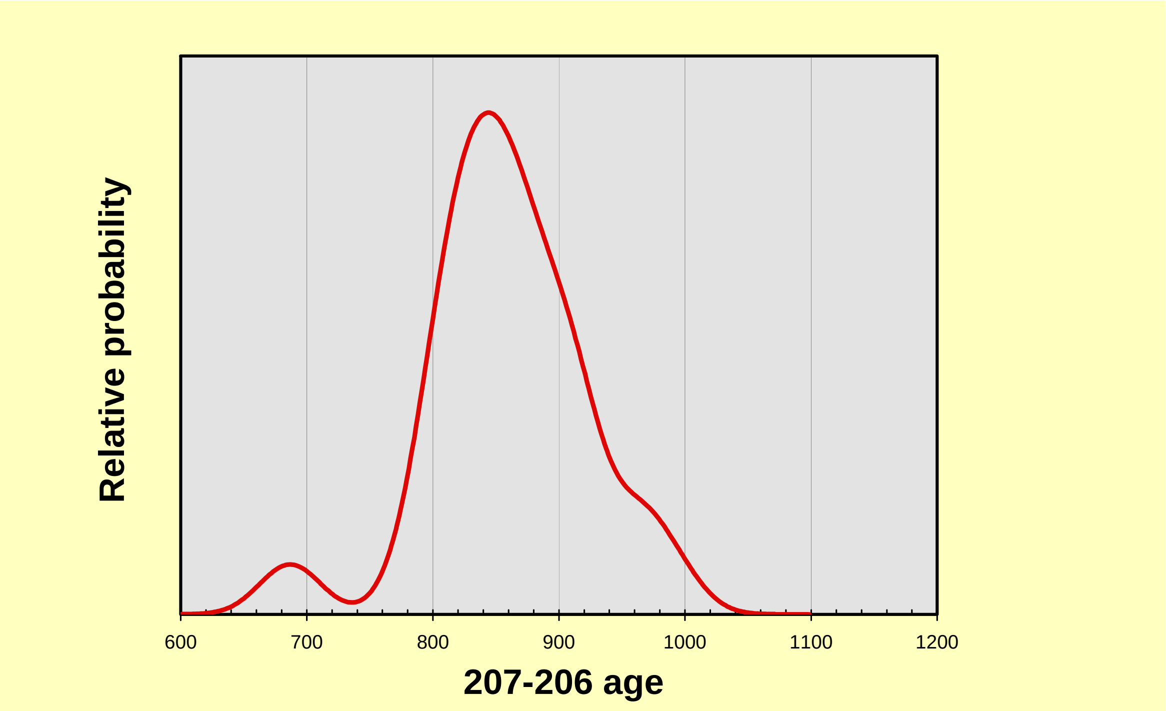
Figure 11.

EG9_62

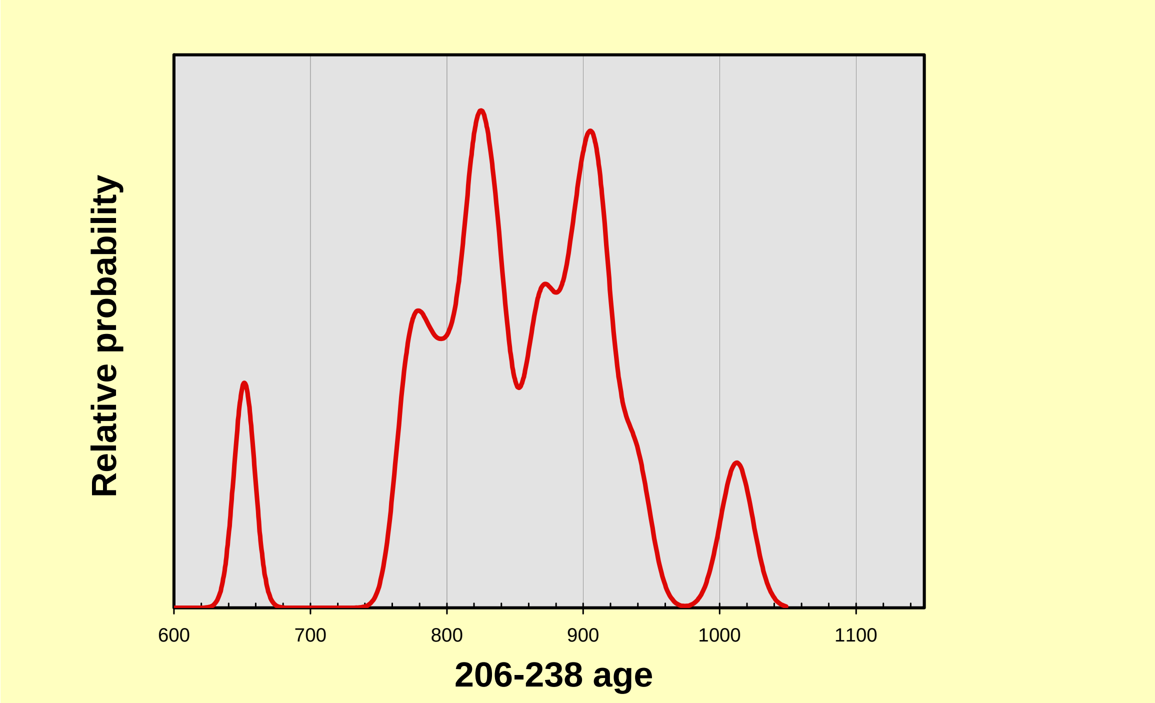
a.



b.


Relative probability
600
700
800
900
1000
1100
1200
207-206 age

c.


Relative probability
600
700
800
900
1000
1100
206-238 age

TABLES

Table 1.

EG9_04

Analysis_#	Concordancy	Pb207/Pb206	Pb206/U238
SPOT48	103	898	929.3
SPOT55	103	867.1	894.7
SPOT52	102	897.1	913.4
SPOT70	99	825.9	815.5
SPOT69	98	938.1	921.6
SPOT71	96	973.4	936.4
SPOT63	96	811.6	777.3
SPOT68	92	872.1	805.5
SPOT59	92	1018.1	936.5
SPOT62	91	888.6	809.7
SPOT53	91	803.6	731.9
SPOT66	90	855.6	772.1
SPOT50	89	816.2	724.4
SPOT65	87	851.4	743.8
SPOT56	83	1089.3	899
SPOT67	82	999.6	818.4
SPOT57	79	1242	984.3
SPOT58	77	1163.1	895.6
SPOT49	75	1105.9	828
SPOT61	74	1113.1	823.9
SPOT60	68	859.7	586.6
SPOT64	66	1306.2	859.9
SPOT51A	50	1697	852.1
SPOT57	79	1242	984.3
SPOT59	92	1018.1	936.5
SPOT71	96	973.4	936.4
SPOT48	103	898	929.3
SPOT69	98	938.1	921.6
SPOT52	102	897.1	913.4
SPOT56	83	1089.3	899

SPOT58	77	1163.1	895.6
SPOT55	103	867.1	894.7
SPOT64	66	1306.2	859.9
SPOT51A	50	1697	852.1
SPOT49	75	1105.9	828
SPOT61	74	1113.1	823.9
SPOT67	82	999.6	818.4
SPOT70	99	825.9	815.5
SPOT62	91	888.6	809.7
SPOT68	92	872.1	805.5
SPOT63	96	811.6	777.3
SPOT66	90	855.6	772.1
SPOT65	87	851.4	743.8
SPOT53	91	803.6	731.9
SPOT50	89	816.2	724.4
SPOT60	68	859.7	586.6

Table 2.

EG9_53

Analysis_#	**Concordancy**	**Pb207/Pb206**	**Pb206/U238**
SPOT16	124	1088.6	1348.9
spot3	116	817.5	949
SPOT17	103	778.2	802.1
SPOT10	103	894	916.6
SPOT13	102	544.5	555.2
spot1	100	915.4	917.2
SPOT8	99	901.9	894.4
SPOT18	92	921	846
spot5	90	904.7	812.8
spot4	87	1107.9	967.2
SPOT14	87	792.5	689.8
SPOT12	85	865	736.4
SPOT9	84	984.4	824.5
SPOT15	81	1025	827.5
spot6	79	876.9	692.6

SPOT11	49	1175	576.1
spot2	43	2046.8	882.1
SPOT7	23	2596.5	585.8

Table 3.

EG9_61

Analysis_#	Concordancy	Pb207/Pb206	Pb206/U238
61B41	97	951.9	923.4
61B42	70	960.4	671.3
61B43	94	918.3	858.8
61B44	86	844.8	730.1
61B45	73	979.2	712.3
61B46	95	1008.3	961.4
61B47	95	843.5	804.2
61B48	87	979.5	847.3
61B49	84	930.4	778.4
61B50	102	899.2	913.7
61B51	84	985.8	831.7
61B52	81	933.3	759.7
61B53	84	988.7	828.8
61B54	84	977.3	819.7
61B55	105	918.7	960.6
61B56	89	977.1	866.9
61B57	88	804.3	707.8
61B58	104	861.5	897.8
61B59	6186300	0.1	6186.3

Table 4.

EG9_62

Analysis_#	Concordancy	Pb207/Pb206	Pb206/U238
spot1	#VALUE!	1650.6	-NaN
spot10	81	993.9	804.5
spot11	103	868.5	890.5
spot12	78	1016.7	791.5
spot13	80	961.1	769.4

spot14	82	940.8	774.7
spot15	89	885.6	790.5
spot16	95	841.9	799.6
spot17	73	796.1	577.7
spot18	77	1455.2	1127.3
spot19	93	837.8	775.8
spot2	81	976.8	795.1
spot20	100	904.7	900.4
spot21	102	893.8	910.5
spot22	100	914	912.6
spot23	75	1193.2	895.6
spot24	111	942.4	1042.2
spot25	90	987.3	888.4
spot26	91	860.1	784.7
spot27	105	962	1012.5
spot28	82	839.3	689.1
spot29	92	801.1	734.5
spot3	87	891.6	775.5
spot30	102	843	863.1
spot31	73	921.7	673.9
spot32	98	845.1	831.6
spot33	99	826.3	819
spot34	94	899.9	844.1
spot35	96	803.4	770.2
spot36	82	1067.4	871.9
spot37	102	923.8	937.8
spot38	103	815.8	839.9
spot39	97	811.2	783.3
spot4	99	881.3	873.6
spot40	95	860.8	820.3
spot5	82	846.3	695.9
spot6	95	686.8	651.6
spot7	90	831.3	744.3
spot8	89	883.4	782.3
spot9	94	852.8	803.2
spot24	111	942.4	1042.2

spot27	105	962	1012.5
spot38	103	815.8	839.9
spot11	103	868.5	890.5
spot30	102	843	863.1
spot21	102	893.8	910.5
spot37	102	923.8	937.8
spot22	100	914	912.6
spot20	100	904.7	900.4
spot4	99	881.3	873.6
spot33	99	826.3	819
spot32	98	845.1	831.6
spot39	97	811.2	783.3
spot35	96	803.4	770.2
spot40	95	860.8	820.3
spot16	95	841.9	799.6
spot6	95	~~686.8~~	651.6
spot9	94	852.8	803.2
spot34	94	899.9	844.1
spot19	93	837.8	775.8
spot29	92	801.1	734.5
spot26	91	860.1	784.7
spot25	90	987.3	888.4
spot7	90	831.3	744.3
spot15	89	885.6	790.5
spot8	89	883.4	782.3
spot3	87	891.6	775.5
spot14	82	940.8	774.7
spot5	82	846.3	695.9
spot28	82	839.3	689.1
spot36	82	1067.4	871.9
spot2	81	976.8	795.1
spot10	81	993.9	804.5
spot13	80	961.1	769.4
spot12	78	1016.7	791.5
spot18	77	1455.2	1127.3
spot23	75	1193.2	895.6

spot31	73	921.7	673.9
spot17	73	796.1	577.7