# THE SEDIMENTOLOGY OF THE JACOVEC CAVERN, STERKFONTEIN

**Silindokuhle Siyabonga Mavuso**

Student number 461219

Supervised by

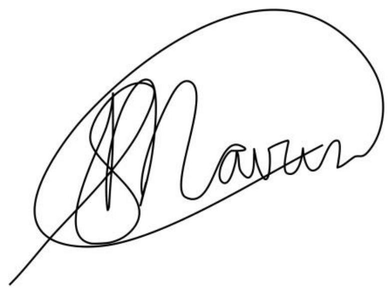
**Dr. Dominic Stratford and Dr. Christine Steininger**

**A dissertation submitted to the School of Geosciences, Faculty of Science University of the Witwatersrand, Johannesburg for the degree of Master of Science.**

**March 2017**

## Declaration

I, **Silindokuhle Siyabonga Mavuso**, hereby declare that this thesis is my own work and has not been submitted for a MSc at any other university.



## Abstract

Since the first fossil discovery in the late 1800s Sterkfontein has become one of the most productive palaeoanthropological sites in the world. This cave network has produced abundant fossil material that has provided insight to Plio-Pleistocene ecology, environments and hominid behaviour. Although the site is rich in fossil material, various post-depositional processes that occurred over time have made the deposits very complex and difficult to decipher. At the centre of understanding this complex site, extensive geological work has been done to place the fossil material in the best possible context. This has led to the establishment of a cave stratigraphic framework, namely the Sterkfontein Formation, which has arranged fossiliferous deposits from some of the chambers in the Sterkfontein Cave System. However, some of the lowerlying chambers were not included within this stratigraphic framework and thus required investigation. After the discovery of a partial cranium of *Australopithecus* sp. in this cavern, the primary research focus was on taphonomy, palaeoecology, biostratigraphy as well as chronostratigraphy; minimal sedimentological work was undertaken. This research involved a sedimentological facies analysis in a lesser known chamber of the cave network, the Jacovec Cavern, which is one of the deepest caverns in the Sterkfontein Cave System. The examinations of the sediment yielded a detailed depositional history as well as provided the opportunity to test previously proposed karstification models. This provides a better comprehension for the formation and development of the Jacovec Cavern and its relation to the entire Sterkfontein Cave System.

The observation of sediment halt (blockage from a palaeo-karst wall) suggested the presence of two depositionally independent chambers, namely the north western Main Jacovec Chamber and the newly-differentiated eastern (sediment-rich) Thulasizwe Chamber. Work in the Thulasizwe Chamber helped revise the proposed stratigraphy by identifying four distinct units and reconciling the previously-proposed reverse stratigraphy of the upper brecciated (Brown and Orange breccia) units. These four units begin with a basal slackwater (laminated) unit overlain by a debris flow unit followed by a fossiliferous Brown Breccia and, finally, a channel-derived Orange Breccia. The Main Jacovec Chamber contains two small sedimentary units whose depositional histories are harder to decipher. These sediments have been subject to a large degree of alteration (from both biotic and abiotic factors), which has led to the identification of cave access and phreatic stages. The lithology of the sediments (especially the presence of a distinct tuff seam) in both chambers has assisted in restricting the provenance of the sediments to localized deposits most likely coming from the south-southeast of the cave system. Furthermore, the presence of ghost rock remnants proved useful in providing a detailed karstification model (which suggests a long-lived stage of chemical dissolution before mechanical erosion and removal of cave earth) for the chamber and supports early works by Wilkinson (1985) of a deep phreatic network. This has implications for the stratigraphic interpretations on the cave system and sequence of filling.

## Acknowledgements

I would like for thank my supervisors, Dr. Dominic Stratford and Dr. Christine Steininger for their guidance and support throughout the entire duration of my masters; it is highly valued and appreciated. Dr. Stratford, your guidance, training and mentoring has been such a big factor in the skills I now possess as a scientist, and I am eternally thankful for that. I am grateful to Dr. Job Kibii for his advice on the Jacovec Cavern. I would also like to thank Prof Richard Maire and Dr. Laurent Bruxelles for teaching me about micromorphology and karst environments respectively. I wish to also thank the technicians of Sterkfontein who have made conducting research at Sterkfontein much easier. I would also like to thank my parents and siblings for their patience and support throughout my Masters. I am also privileged to be surrounded by a loving group of friends who were willing to assist me in my research as either field assistants, academic and emotional support, namely Rosa Moll, Joe Eppel, Refiloe Dhladla, Pia Viglietti, Cameron Penn-Clarke, Kelita Shadrach, Peter Morissey, Kimberleigh Tommy and the many others at Wits. I would also like to thank Kgotso Mampa and the Institute of Digital Education Africa who have provided graphics and use of their equipment for 3D imaging of the Jacovec Cavern. Lastly, I am thankful for financial support from the DST-NRF Centre of Excellence for Palaeosciences, the University of the Witwatersrand Postgraduate Merit Award, the National Research Foundation, Palaeontological Scientific Trust (PAST) and Erasmus Mundus AESOP programme who have allowed me to not only conduct this research but to share it with the world.

To my brother Thulasizwe Mavuso, I dedicate this work to you. Ngwane.

# Contents

**Declaration** I
**Abstract** II
**Acknowledgements** IV

**1.1. Dissertation Overview** **1**
**1.2. Introduction** **3**

**2. Literature Review** **7**
2.1. Geological setting 7
2.2. Geomorphology 11
2.3. Cave Formation and development 11
2.4. Sterkfontein Stratigraphy 19
2.5. Lower Cave deposits 27
2.6. The Jacovec Cavern 28
2.6. 1. Jacovec Cavern Deposits 28
2.6.2. Palaeontology 31
2.6.3. Stratigraphic positioning 32
2.7. Project aim and objectives 33

**3. Materials and Methodology** **34**
3.1. Sedimentary Facies analysis 34
3.2. Lithological descriptions of in situ exposure 36
3.3. Mineralogy and geochemistry 35
3.3.1. Sample Collection 36
3.3.2. Petrographic light microscopy 37
3.3.3. X-Ray Fluorescence analysis 38

**4. Results** **40**
4.1. Sedimentary facies analysis 40
*4.1.1. Facies* 46
*Clast supported massive breccia, uncemented - Gcm (u)* 46
*Clast supported massive breccia, partially cemented - Gcm (c)* 49
*Matrix supported massive breccia - Gmm* 56
*Massive Clay/silt and sand - Fm* 60
*Horizontally bedded sands - Sh* 62
*Horizontally laminated fines - Fl* 64
*Flowstone facies - P* 70
*4.1.2. Cave facies associations* 70
*Slackwater facies* 70
*Diamicton facies* 71

*Channel facies* 73
*Breccia facies association* 74
*Flowstone facies - P* 75
4.1.3. Geochemistry (X-Ray) of facies associations 76
4.1.4. Summary 78
**5. Discussion** **79**
5.1. Cave input, provenance and accumulation dynamics 79
5.2. Deposit alteration 81
5.3. The stratigraphy of the Jacovec Cavern 81
5.4. Stratigraphic positioning of the Jacovec Cavern in the Sterkfontein Formation 85
5.5. Ghost rock presence and karstification models 86
5.6. The depositional evolution at the Jacovec Cavern 87
5.7. Conclusions 89
**References** 90

## List of Figures

*Figure 1. 1. Plan view of the Jacovec Cavern showing chambers. Thulasizwe Chamber is from Partridge et al. (2003).* 2

*Figure 1. 2. Map showing the position of Sterkfontein in the Cradle of Humankind (right) in South Africa (left) and a map of the Sterkfontein underground cave network (Pickering and Kramers, 2010).* 4

*Figure 1. 3. Schematic drawing showing the position of the Jacovec Cavern in relation to the Silberberg Grotto (Grine, 2013, from Clarke, 2008).* 6

*Figure 2. 1. The lithostratigraphy, chronology tectonic setting and palaenvironments and inferred basin-level changes for the Transvaal Supergroup highlighting the stratigraphic position of the Malmani Subgroup. From: Catuneanu and Eriksson (2002).* 8

*Figure 2. 2. Map highlighting the geology around Sterkfontein, unpublished courtesy of Paul Dirks.* 10

*Figure 2. 3. Schematic drawing of the hyperphreatic model for Sterkfontein (Martini et al., 2003).* 14

*Figure 2. 4. Stages of sediment accumulation and removal in Sterkfontein (Wilkinson, 1985).* 16

*Figure 2. 5. Stratigraphic profile of the Sterkfontein caves showing location of various Members (indicated in numbers) (Ogola, 2009, adjusted from Clarke, 2008).* 21

*Figure 2. 6. Diagram showing the Sterkfontein Formation (Clarke, 2006).* 23

*Figure 2. 7. Schematic diagram and cross section of the eastern section of the Thulasizwe Chamber in the Jacovec Cavern (Partridge et al., 2003).* 30

*Figure 4.1. The eastern section of the Thulasizwe chamber showing the most continuous sedimentary exposure in the Jacovec Cavern.* 41

*Figure 4.2. Sedimentary log of the Thulasizwe Chamber showing lithofacies, lithofacies associations and sampling of thin sections.* 42

*Figure 4.3a. Section A-B in the Main Jacovec Chamber.* 44

Figure 4.3b. Section C-D in the Main Jacovec Chamber. 45

*Figure 4.4. Facies Gcm (u) facies in the Thulasizwe Chamber.* 47

*Figure 4.5. Photomicrograph (XPL - cross polarized light) of Facies Gcm (u) showing poorly sorted immature sediments with high chert and quartz abundance. Sample MM3.* 48

*Figure 4.6. Photomicrograph (XPL) of facies Gmm (u) showing Fe rimming of a polycrystalline quartz (centre) and ferrobacteria (bottom left ).* 49

*Figure 4.7. Facies Gcm (u) facies showing large clasts in the greyish brown unit, Thulasizwe Chamber.* 50

*Figure 4.8. Photomicrograph (XPL) of facies Gcm (c) showing cementation with subrounded grains and Fe rimming (bottom left grain of quartz).* 51

*Figure 4.9. Photomicrograph (XPL) of facies Gcm (c) showing fossil bone shaft (indicated with arrow) with calcite filling in the yellowish red unit.* 52

*Figure 4.10. Photomicrograph (XPL and PPL - plane polarized light) of facies Gcm (c) showing calcitic growth in skeletal elements (elongate structures).* 54

*Figure 4.11. Photomicrograph (XPL and PPL) of facies Gcm (c) showing calcitic growth in void spaces.* 55

*Figure 4.12. Facies Gmm facies in the Thulasizwe Chamber.* 57

*Figure 4.13. Photomicrograph (XPL and PPL) of facies Gmm showing mud clast in matrix of silt unit.* 58

*Figure 4.14. Photomicrograph (XPL and PPL) of facies Gmm showing ferric rimming around angular quartz grain.* 59

*Figure 4.15. Facies Fm in the Thulasizwe Chamber.* 61

*Figure 4.16. Photomicrograph (XPL) of Facies Fm large infrequent clasts in a massive sediment.* 62

*Figure 4.17. Facies Sh in the Thulasizwe Chamber.* 63

*Figure 4.18. Photomicrograph Facies Sh in Main Jacovec Chamber.* 64

*Figure 4.19 Facies Fl with turbation (microfaulting).* 66

*Figure 4.20. Photomicrograph (XPL) of facies Fl showings sandy/silty-mud interlaminae.* 69

*Figure 4.21. Photomicrograph (XPL and PPL) of facies Fl showing tabular micas depicting depositional orientation.* 68

*Figure 4.22. Photomicrograph (XPL and PPL) of facies Fl showing agglomerated ferrobacteria.* 69

*Figure 4.19 Facies Fl with turbation (microfaulting).* 66

*Figure 4.20. Photomicrograph (XPL) of facies Fl showings sandy/silty-mud interlaminae.* 67

*Figure 4.21. Photomicrograph (XPL and PPL) of facies Fl showing tabular micas depicting depositional orientation.* 68

*Figure 4.22. Photomicrograph (XPL and PPL) of facies Fl showing agglomerated ferrobacteria.* 69

*Figure 4.23. Erosional contact between basal thinly-bedded clay-silt and Gravelly Unit.* 72

*Figure 4.24. Graph showing major element chemical proportions of each facies unit.* 77

*Figure 5.1. Schematic showing tuff extrapolation in relation to Jacovec Cavern for sourcing direction (not drawn to scale)* 81

*Figure 5.2. Termination of sediment on wall (left).* 84

*Figure 5.3. Orange breccia 'inclusions' in Brown breccia from a redeposited sediment on the west exposure of the Thulasizwe Chamber.* 85

# List of tables

*Table 2. 2. Sediment and rock types from the Jacovec Cavern breccia (Kibii, 2000).* 29

*Table 4.1. Classification of the sedimentary facies in the Jacovec cavern. Adapted from Bosch (2015), using Miall (1996) facies codes convention.* 78

## 1.1. Dissertation Overview

This dissertation presents a sedimentological investigation into the deposits of one of the lesser known caverns in the Sterkfontein Cave System, the Jacovec Cavern. For clarity in this dissertation, the Jacovec Cavern is referred to by its constituting chambers, namely the Main Jacovec Chamber near the entrance, and the newly-differentiated (eastern) Thulasizwe Chamber (see Figure 1. 1; Figure 1.3 for relative location to the Main Jacovec Chamber). Chapter 1 outlines the history of Sterkfontein. Chapter 2 reviews the literature pertaining to the Sterkfontein Cave system, including the geology, geomorphology, cave formation models and stratigraphy. This is followed by a review of past work in the Jacovec Cavern, namely the deposits, palaeontology and stratigraphic positioning of the Jacovec Cavern within the Sterkfontein Cave system. This chapter then outlines project aims and objectives.

Chapter 3 describes methods that were applied to achieve these aims and objectives. Chapter 4 presents the results of this sedimentological investigation, including the sedimentary facies analysis, petrography and X- Ray Fluorescence (XRF).

Chapter 5 discusses the findings and their implications to the site. This includes a revision of the stratigraphy, the depositional evolution of the Jacovec Cavern, provenance and accumulation dynamics, sediment alteration, stratigraphic positioning of the Jacovec cavern in the Sterkfontein Cave system, and the presence of ghost rock and karstification models.

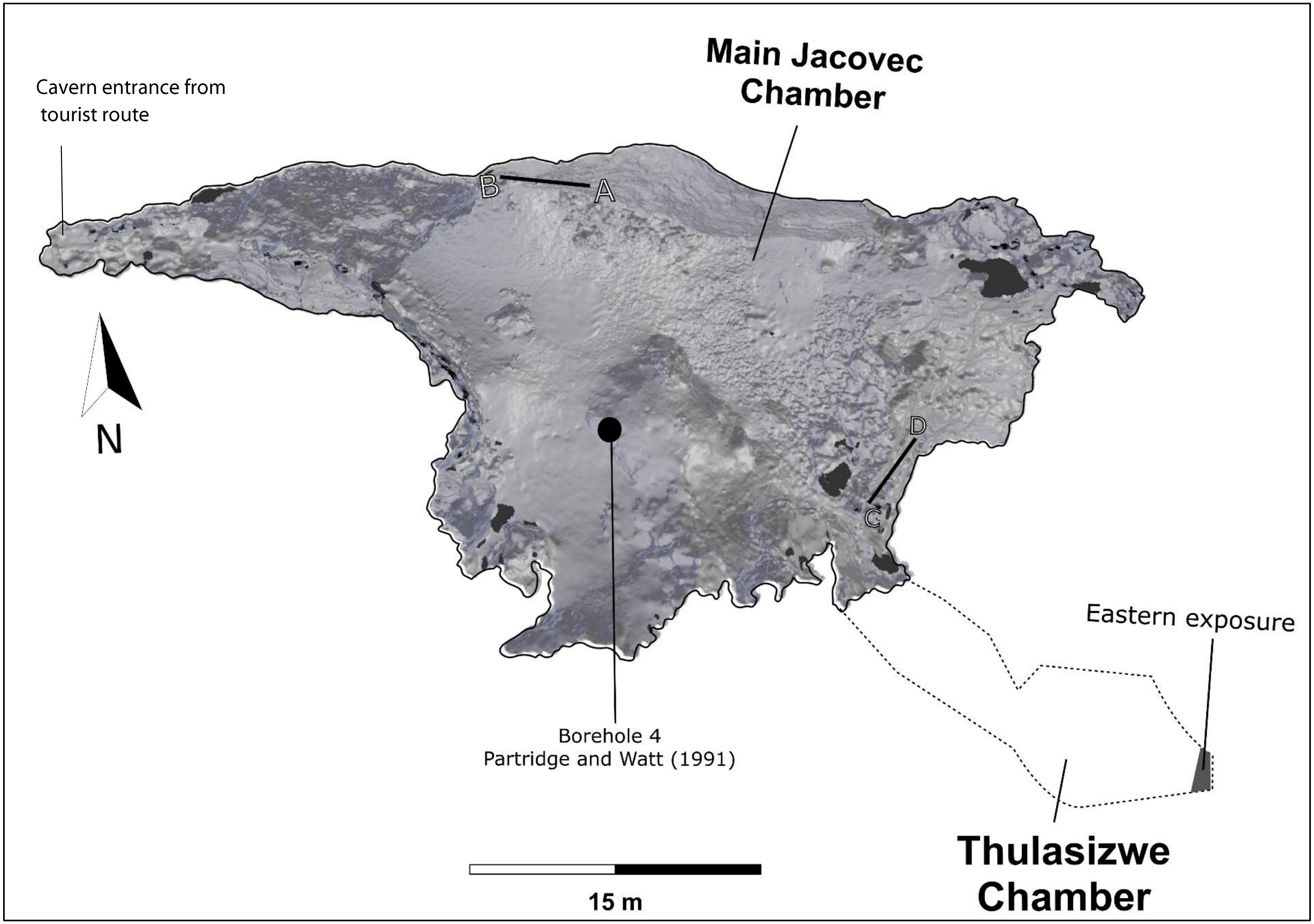



*Figure 1. 1. Plan view of the Jacovec Cavern showing chambers. Thulasizwe Chamber is from Partridge et al. (2003).*

## 1.2. Introduction

Sterkfontein, located in the Cradle of Humankind World Heritage Site (Gauteng Province, South Africa; Figure 1. 2), represents one of the most productive palaeoanthropological and archaeological cave sites in the world (Kuman and Clarke, 2000). Sterkfontein was first reported on at the first Geological Society of South Africa meeting in 1895 and described as "fossiliferous deposits of cave-filled breccia and flowstone deposits in the Transvaal Dolomite" (Draper, 1896; Martini et al., 2003). Brain (1981) asserted that this report was referring to the outcropping cave deposits found on the Sterkfontein Hill. It was Mr. G. Martinaglia who discovered the main cave opening from an exposed calcite flowstone on Sterkfontein Hill (Martini et al., 2003). This attracted a lot of public and academic attention of what was then termed the "wondergat" with more ensuing exploration of the flowstones. In 1898 plans were made by Draper to preserve the then already damaged cave for public interest. But the endeavour failed as there was additional damage between 1918 and 1920 by explosives under the mining permit held by Mr. Nolan (Martini et al., 2003). Later this cave was extensively exploited for calcitic flowstone, which was used in the gold mine and construction industry.

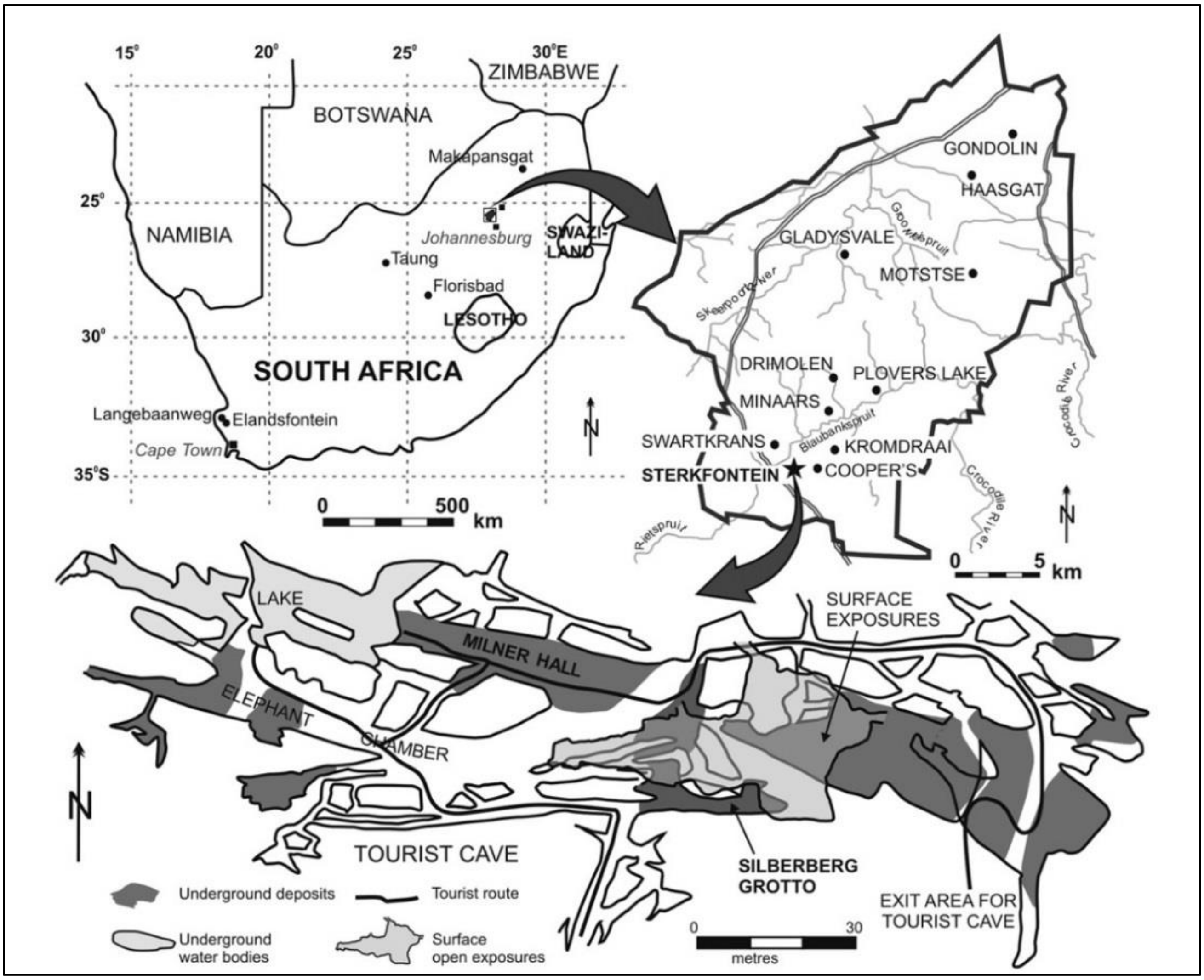



*Figure 1. 2. Map showing the position of Sterkfontein in the Cradle of Humankind (right) in South Africa (left) and a map of the Sterkfontein underground cave network (Pickering and Kramers, 2010). See figure 1.3 for location of Jacovec Cavern.*

In 1935, Dr. Robert Broom was conducting excavations in the Gladysvale and Skurweberg area when he was presented with fossil baboon material from Sterkfontein (Martini et al., 2003). He thereafter made several visits to Sterkfontein with two of Raymond Dart's students who had found well-preserved primate cranial fossils in the mining dumps. On Broom's third visit he discovered the cranium, endocast and partial dentition of the first adult *Australopithecus* (Broom, 1936). At this time, it was described as a new species, *Australopithecus transvaalensis*

(Broom, 1936) but later reclassified into the genus *Plesianthropus* (Broom, 1947), which was subsequently reclassified as *Australopithecus africanus* (Robinson, 1962). In 1947, Sts 5 (commonly referred to as Mrs Ples), the then most complete adult hominid cranium was discovered at Sterkfontein (Broom et al., 1950). Later that year, Sts 14 (then termed *Plesianthropus* partial skeleton) was discovered by Broom and Robinson (1947). Since these discoveries, excavations at Sterkfontein have produced over 700 hominid specimens that may represent up to five distinct species (*Australopithecus africanus, Australopithecus sp., Paranthropus robustus, Homo habilis, Homo ergaster).* Besides the rich diversity of hominid material, Sterkfontein is rich in other faunal material, which includes*:* ten non-hominid primate species, over 70 species of mammals and several bird and reptile species (Vrba, 1975, 1976; 1980; Turner 1987, 1997; Clarke, 1988; Pickering, 1999; Pickering et al., 2000). Two plant species are known based on the only fossil wood found in the cave sites in the Cradle of Humankind (Bamford, 1999). In addition, the site has produced a large Early Stone Age (ESA) tool assemblage (Kuman, 1996; Field, 1999; Kuman and Clarke, 2000, Kuman and Field, 2009).

Sterkfontein continues to yield new fossil material. In August 1995 the discovery of an *in situ* hominid partial cranium (StW 578, later classified as *Australopithecus sp.*) prompted investigation of the Jacovec Cavern where the cranium was found. This specimen was recovered in the Orange breccia in the ceiling of the eastern end of the cave (Partridge et al., 2003; Clarke, 2006; Clarke, 2013). To place the new fossils in context, this dissertation focuses on the Jacovec Cavern that represents one of the deepest areas in the Sterkfontein cave network and contains the deepest fossiliferous deposits at around 1452.5 m above sea level or 30 m from the ground surface (Reynolds and Kibii, 2011) (Figure 1. *3*).

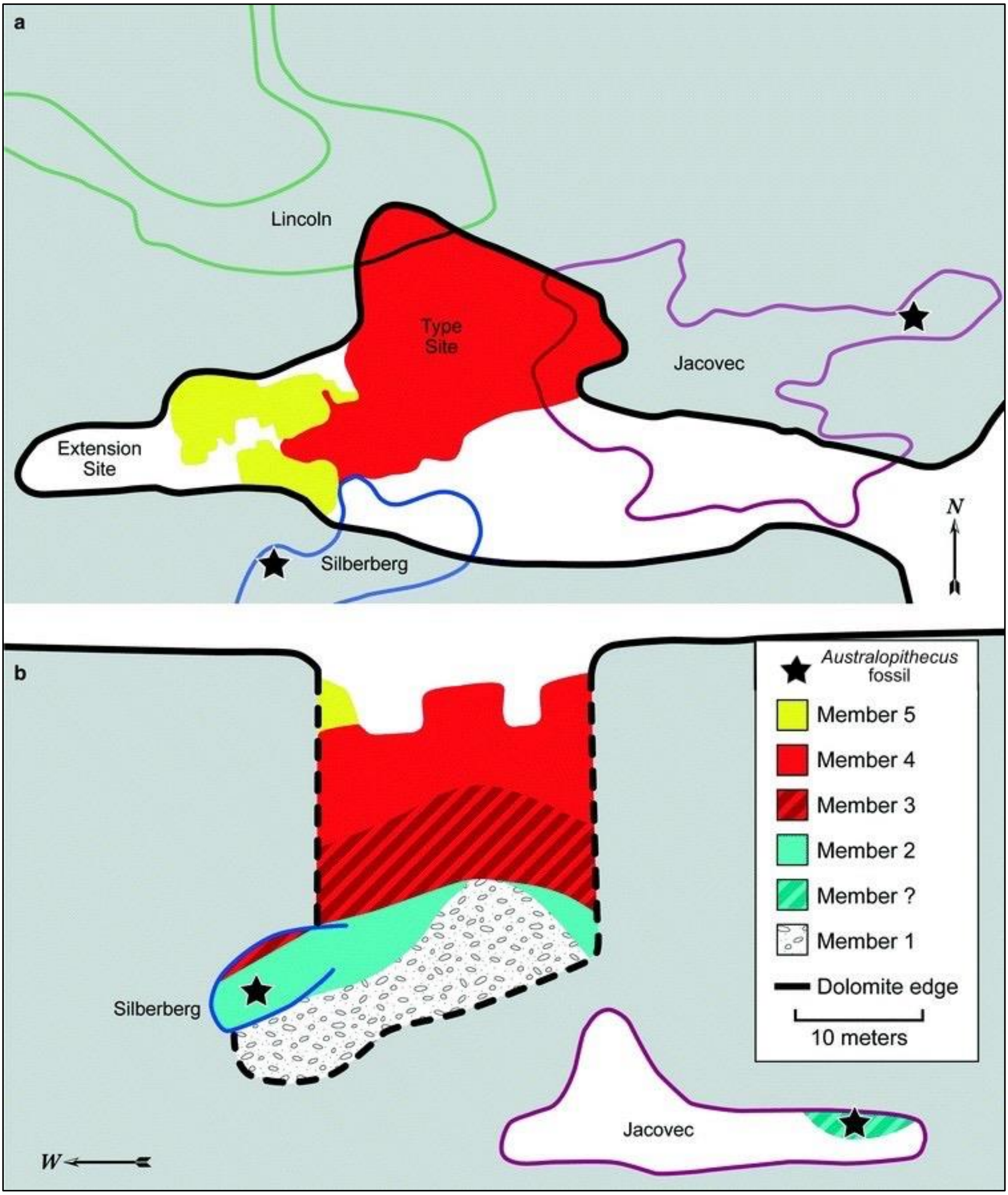



*Figure 1. 3. Schematic drawing showing the position of the Jacovec Cavern in relation to the Silberberg Grotto (insert a adjusted from Grine, 2013, insert b adjusted from Clarke, 2008).*

# 2. Literature Review

## 2.1. Geological setting

The host rocks of the Sterkfontein caves are stromatolitic dolomites of the Transvaal Supergroup (Chuniespoort Group, Malmani Subgroup) which during the late Archaean at around 2.5-2.6 Ga (Brink and Partridge, 1965; Martini et al., 2003). The Chuniespoort Group consists of a basal Malmani Subgroup which grades up to the Penge Banded Iron Formation (BIF) (Eriksson and Reczko, 1995; Eriksson and Altermann, 1998) (Figure 2.1). The basal part of this group is represented by the Malmani Supergroup which consists of five formations (Oaktree, Monte Cristo, Lyttelton, Eccles, Frisco) comprising mostly stromatolitic dolomites with some subordinate limestones, interbedded cherts and (to a lesser extent) mudrocks of chert-shale breccias. The stratigraphic assignment of different dolomite formations is based on the presence and relative abundances of the above mentioned lithologies, as well as shallow dipping unconformities (Button, 1973; Clendenin, 1989; Eriksson et al., 2001) (Figure 2. 1). The Malmani Subgroup, in the Transvaal structural basin, is a constituent of a much larger carbonate platform whose remaining parts are found in the Griqualand West and Kanye basins in the western part of the Kaapvaal Craton (Eriksson et al., 2001).

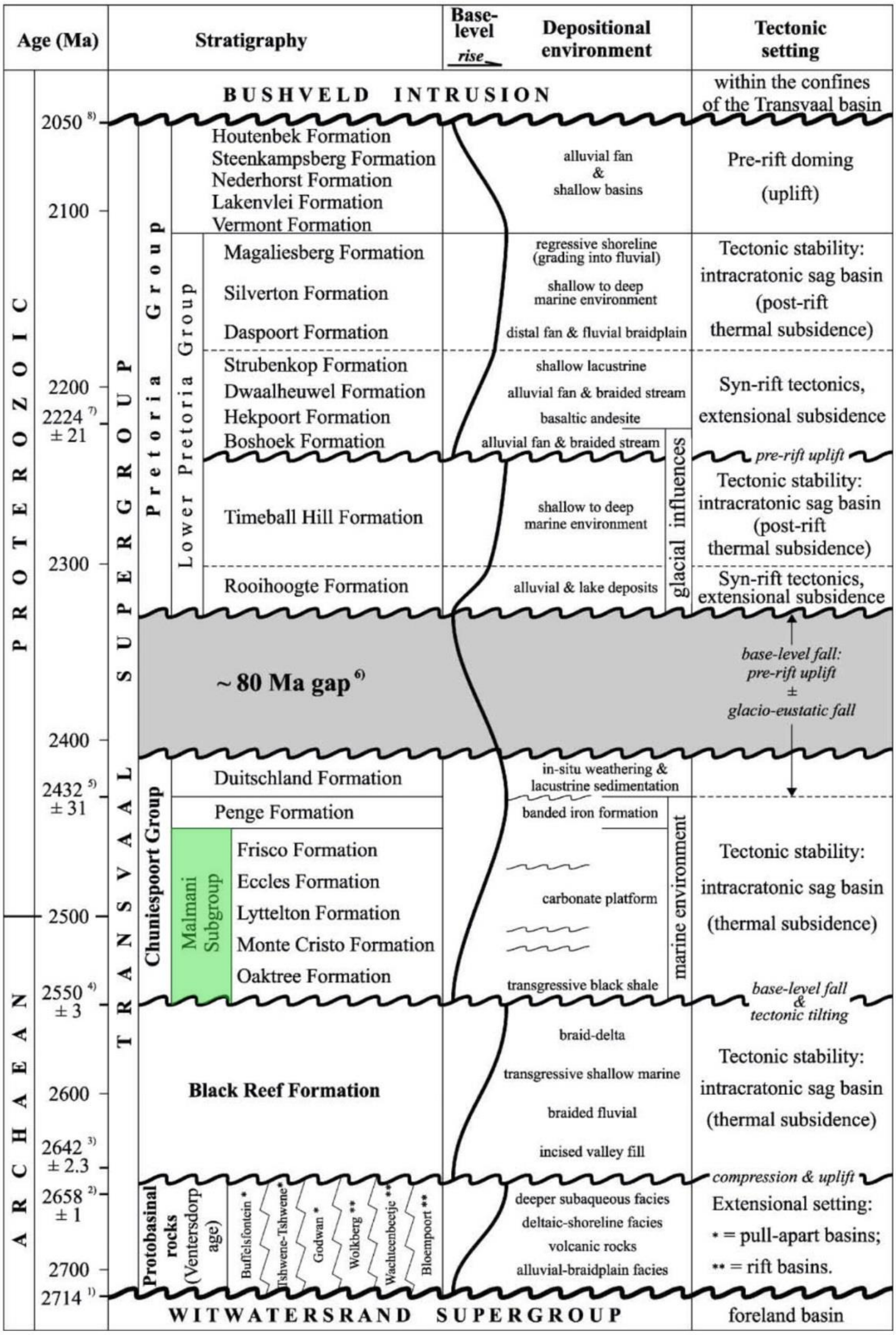



*Figure 2. 1. The lithostratigraphy, chronology tectonic setting and palaenvironments and inferred basin-level changes for the Transvaal Supergroup highlighting the stratigraphic position of the Malmani Subgroup. From: Catuneanu and Eriksson (2002).*

Structurally, the carbonates of the Chuniespoort Group and overlying banded iron formations(BIFs) of the Penge Formation have a sheet-like geometry and indicate deposition within an epeiric (shallow marine) environment during a time when most of the craton was under an epicontinental sea (Eriksson and Altermann, 1998). These conditions produced iron and manganese rich limestones. The carbonates of the Malmani Subgroup represent deposition during a highstand system tract (Catuneanu and Eriksson, 1999) although some second order regression-transgression cycles have been identified by Altermann and Nelson (1998).

The Sterkfontein Valley stratigraphically occupies the contact between the Oaktree Formation and the Monte Christo Formation, the two basal units of the Malmani Subgroup (Figure 2. 2) (Eriksson et al., 1995; Martini et al., 2003; Dirks and Berger, 2013). In this part of the basin, the dolomites have a dip of $30^{o}$ N (Eriksson et al., 1990). The two formations are distinguishable by their chert abundances; this leads to the development of certain cave characteristic morphologies (*see Cave Formation and development*). The chert-deficient Oak Tree Formation forms tall, narrow passages, as supposed to the overlying chert-interbedded Monte Christo Formation dolomites, which produce low, horizontally extensive passages in between each of their chert interbeds (Martini et al., 2003; Stratford, 2011). In addition, the Oaktree is characterized by two tuff seams (Martini et al., 2003). There are also two stratigraphic markers present in the cave (Martini et al., 2003). The first marker is a well-formed and interstratified pale greenish-grey shale (with glass shard ghosts) in the Oaktree Formation. The other marker is a chert bed (4-5 m thick) with dolostone interbeds (Martini et al., 2003).

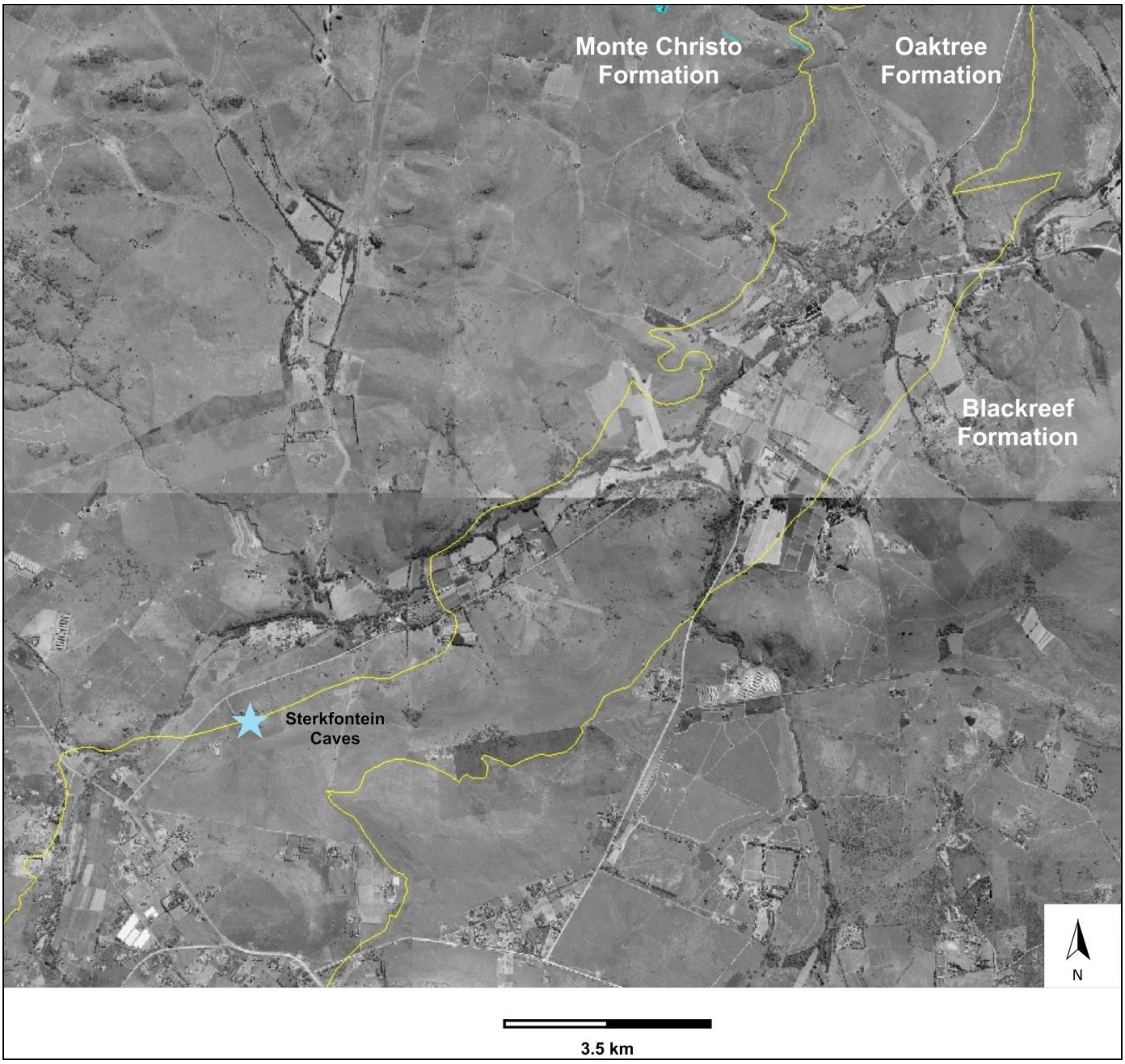



*Figure 2. 2. Map highlighting the geology around Sterkfontein. Unpublished courtesy of Paul Dirks.*

## 2.2. Geomorphology

Sterkfontein caves is situated in a hilly terrain containing valley incisions on upper levels leading to the formation of an escarpment. This escarpment divides two natural regions; the southern Highveld (1500-1600 m) and the northern Bushveld (1000-1100 m) surfaces representing peneplained erosion cycles (Partridge and Maud, 1987; Martini et al., 2003). These long-lived erosion cycles, known as the African erosion surface (King, 1962; Partridge and Maud, 1987; Burke and Gunnel, 2008), have accumulated a significantly thick weathering crust (Martini et al., 2003). The irregular topography on the Highveld region (in the steep north versus the gentle southwest) suggests an erosional reactivation controlled by the African Surface's thalweg gradient tilting on the peneplain (Martini et al., 2003). Locally, at one kilometre north of the cave, there is an eight-metre-deep bottom valley incision by a stream attributed to a much more recent erosion renewal (Robinson, 1962; Wilkinson, 1973). Cave entrances are located on the northern slope near the top of a small hill at an altitude of 1491. Vertical extents of the cave are difficult to estimate as the cave passages are below the ground water table. The maximum depth of the vadose system is 42 metres below the landscape (Figure 1. 1).

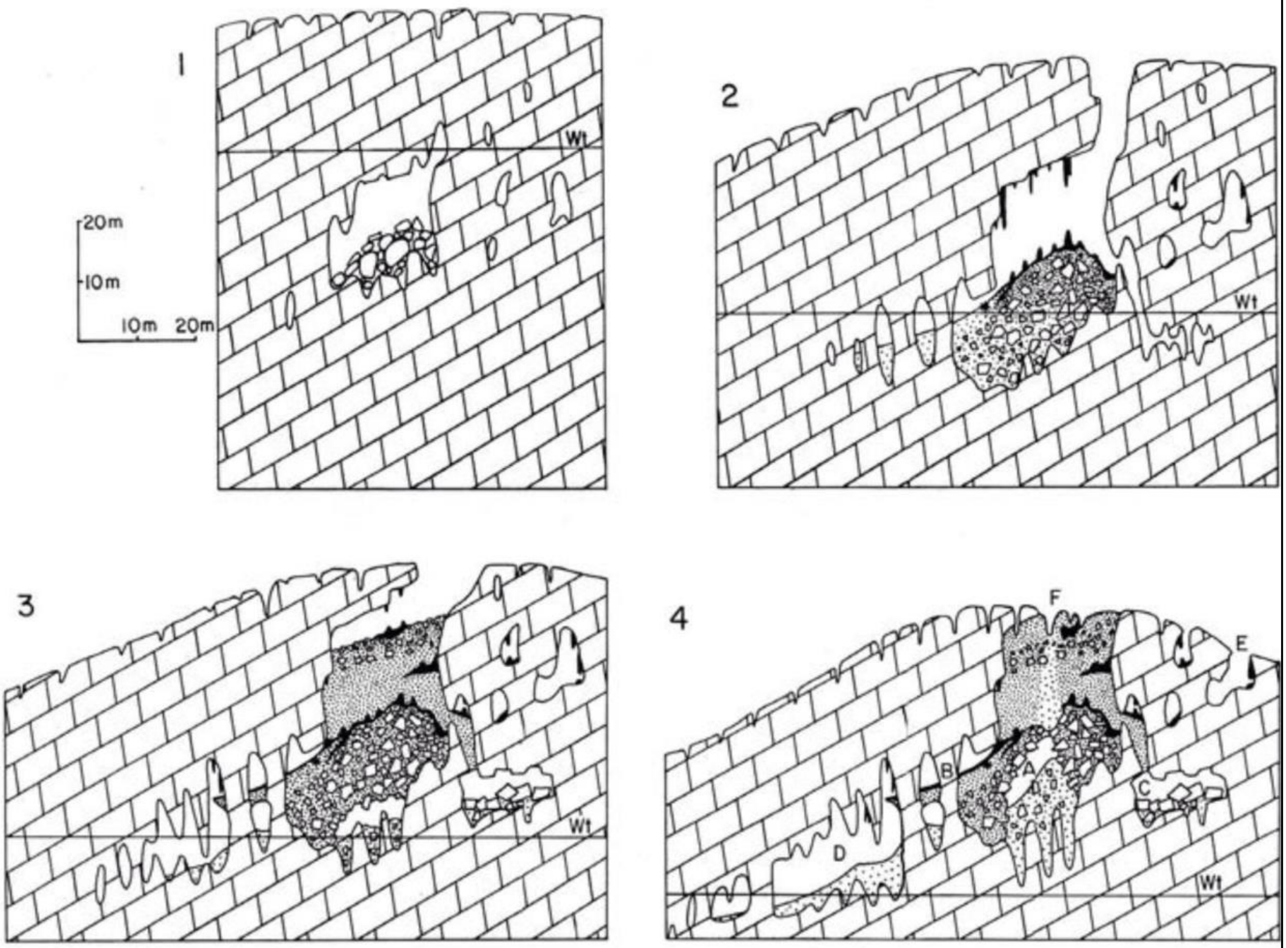
## 2.3. Cave Formation and development

The Sterkfontein dolomitic cave is complex and accounting for its opening and subsequent development is difficult and highly contentious (Stratford, 2015). This complexity is due to the geomorphological constraints and characteristics of the host rock lithology (Partridge and Watt, 1991; Martini et al., 2003). The most significant of these constraints is the system's positioning in the carbonates of the Malmani Subgroup, in a stratigraphic level that is abundant in insoluble chert beds (between the Oaktree Formation and Monte Christo

Formation). This feature is a significant contributing factor for water movement and thus directly affects the nature of water availability and potential dissolution of chambers (Martini et al., 2003). There are other contributing factors such as the presence of igneous (syenite and dolerite) dykes, and insoluble silicified faults, which also affect water movement. There is also the prevalence of east-west trending fracture zones, which dictate the morphology and the position of galleries that lie on the south (Wilkinson, 1983). As two of these lie parallel to each other less than 20 metres apart, it weakens the dolomite providing meteoric recharge conduits which lead to speleogenesis (Wilkinson, 1983). Additionally, the regional karst also differs from classic models as there is a marked absence of surface features such as polje, dolines, swallow-holes and the surficial fluvial network disappearance (Ford and Williams, 1989; Martini et al., 2003). Although there is a lack of surface karst morphologies, the caves have established a well-developed system. With this host rock morphology, the cave chamber development can is restricted to dimensions of 200x250x50 m (Martini et al., 2003). In the northern parts of the Tourist caves as well as smaller northern caves, this morphology includes small (2-5 m in diameter) bedding planes which have minor north-south trending passages (about 3- 6 m). The south occurring caves (the southern parts of the Tourist cave and Fossil Cavern) have large, narrow, elongated and vertically extensive (10 -30 m) galleries with planar and subvertical walls which are all controlled by the east-west trending fracture zones.

Originally, gallery formation was divided by elevation (Brain, 1958; Robinson, 1962; Brink and Partridge, 1965). They attributed the formation of the upper level gallery to “African” erosion surface water table level, and the lower gallery to a later post- or late- “African” erosion cycle (Brink and Partridge, 1965; Marker and Moon, 1969; Partridge, 1973). Thus, the mechanism of progressive formation of deeper galleries with a lowering water table level is used to support the theory of the deepest deposits necessarily being the youngest.

The most popular theory on Cradle cave formation is chemical dissolution of the soluble host rock by groundwater during hyperphreatic phases (Martini and Kavalieris, 1976; Martini et al., 2003; Pickering and Kramers, 2010; Dirks and Berger, 2013). The hyperphreatic process involves the local ground water's base level lowering as a key mechanism in subsequent lower lying cave network formation (vertical extension) as dissolution is most effective within the upper 10 m of the base level (Martini et al., 2003). The shallow levels are associated with allochthonous alluvial of chert, reddish clastics (Martini et al., 2003) (Figure 2. 3). This model includes water table subsidence, promoting uplift and erosion processes below the vadose level (Partridge and Watt, 1991). Mechanical erosion is also a key factor in dissolving and removing dolomite therefore a rejuvenation of fresh water is required. In the Cradle, this formation involves the formation of a passage network (whose formation is dictated by joints) resulting in the dissolution of chert-free beds of the chert-dolomite interbeds. The caves open up channels restricted to zones of intense dissolution instead of forming integrated systems (Martini et al., 2003). The karstification of lower-lying caves has been attributed to artificial aquifer dewatering and is associated with minimal sedimentation of allogenic material (Moen and Martini, 1996).




**KEY**

Wt - Water table

<u>Karstification Stages:</u>

1- Fill from ceiling breakdown along with surface soil reworking.

2 - Opening to the surface due to water level drop, which introduces detrital and animal material (conducive to speleothem formation).

3 - Further water level drop, there is reworking and redeposition of older calcified breccia.

4 - Breccia body de-roofing breccia decalcification and karstification.

<u>Features in chambers</u>:

A - Sedimentation in the Name Chamber by detrital reworking.

B - Member 2 and 3 deposition as well as mechanical reworking and resolution.

C - Chamber filling (Terror Chamber) from Member 3 detritals followed by induration and speleogenesis.

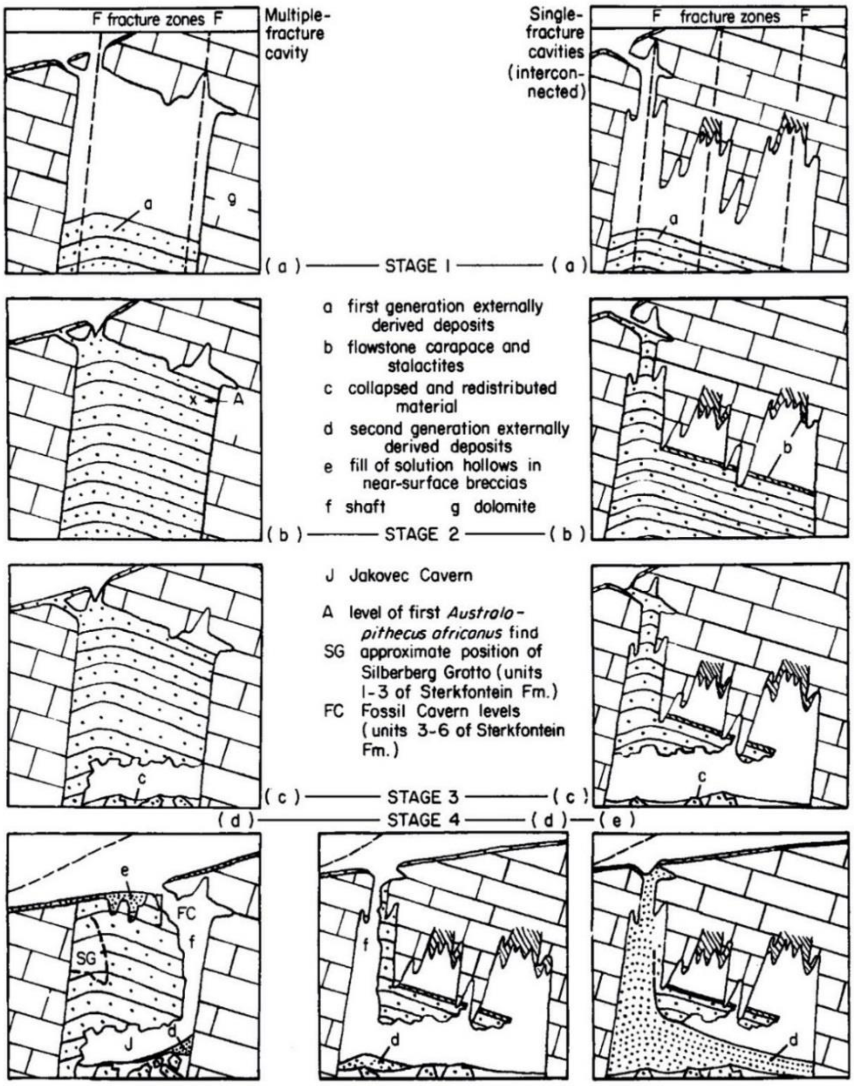
D - Sedimentation from older detritals (seem in Elephant Chamber and Milner Hall).

E - Unfilled, surface-accessed old phreatic passage.

F - Decalcified breccia subsidence forming the “Swallow Hole”.

*Figure 2. 3. Schematic drawing of the hyperphreatic model for Sterkfontein (Martini et al., 2003).*

Contrary to this model, Wilkinson's (1985) geomorphological analysis suggested that cave formation can be explained by a deep phreatic karstification system (Ford, 1971), in which the vertical extent of the cave system was fully formed prior to the development of openings to the landscape surface. If this is the case, and the full vertical extent of the cave was developed when the cave opened then some of the earliest deposits would have been deposited at the base of the system (Stratford, 2015). His evidence pointed to a structurally controlled dissolution of the dolomite throughout the entire altitudinal range. In contrast to the hyperphreatic model, this theory also does not favour water movement. Wilkinson's proposed model of sedimentation is summarized in Figure 2. 4.




**KEY**

Stage 1 - Externally derived debris deposited at the lower levels of the caves (cemented by percolating water) slowly fill up (in discrete units) the chamber facilitated by vertical accretion.

Stage 2 - Sedimentation halting in galleries but continues in supply shafts and cavities containing multiple fractures.

Stage 3 - Intense displacement of cemented infills leaving remnants. This displacement is caused by:

(a) rising water table corrosion

(b) debris mass compaction

(c) phreatic current facilitated breccia redistribution

(d) undermining and collapse from (a) - (c)

Stage 4 - Filling of underground galleries by a sufficient new generation of externally derive debris (e) via reopened shafts to the level dictated by underside of older deposit.

*Figure 2. 4. Stages of sediment accumulation and removal in Sterkfontein (Wilkinson, 1985).*

Alternatively, Martini et al. (2003) and Klimchouck (2007) considered a hypogenic karst model. This model derives its origin beneath the surface where cave formation (especially in the primary phases) was controlled by rising water flow, with caves having no link to surface karst or recharge (Palmer, 2007). This model is associated with sparse coarse-grained sediments because of rapid water flow with complete cementation (sealing) and sediment lithification (Klimchouck, 2007; 2009). As Sterkfontein has numerous network caves with a lack of surface karst morphologies, it may possibly have had hypogenic origins. Klimchouck (2007) stated that Martini et al (2003) suggestion of deep-routed source (hypogenic) which mixes with shallow flow systems that are close to the surface. This suggests that allogenic sediments are only introduced during the inclusion of shallow flow systems in the surface. This hypogenic development may have begun as early as the Miocene (18 mya) during the African surface uplift and tilting event (Klimchouck, 2007) karstification (associated with thermal subsidence - this could have provided the necessary energy needed for rising water flow).

In this suggestion Bruxelles et al. (2009) and Dubois et al. (2014) have proposed a more sophisticated explanation of the karstification that provides more detailed chemical and physical weathering mechanisms in the alteration of the soluble rock. The ghost rock model begins with chemical weathering of soluble rock, followed by a removal of this dissolved substance and a development of weathered feature (which is filled with the remaining alterite). Under favourable conditions, this stage of the undissolved weathered feature is mechanically eroded to create an open gallery (Dubois et al., 2014). During its initial stages, the chemical dissolution in ghost rock formation is achieved by flowing (or renewal) acidified water. This dissolution will occur on micritic carbonate leaving insoluble structures. This stage doesn't mechanically erode undissolved matter that would create an open void. Instead, this causes ghost rock features of the undissolved matter known as alterite (Dubois et al., 2014). During a change in the vadose environment, the state of original alterite will be preserved if the ghost rock is below the groundwater's water table surface. If the ghost rock is above the water table surface, water from the alterite removes the buoyant support and the alterite collapses. Remnants of the alterite are often found near roofs where the ghost rock has been calcified. Finally, there is the stage that involves mechanical erosion which sees the emptying of the alterite thus leading to a cavity (cave). This void looks very similar to that of the traditional karst process by removal and will later continue to develop through vadose weathering processes (e.g. Osborne, 2002).

As seen, this model mimics phreatic morphologies but are distinguishable from traditional phreatic forms by dissolution paths and final removal of dolomite. In Sterkfontein, evidence for this model is also noted by Martini et al. (2003) and includes a near-static base level, non-hierarchical high passage wall and passage development as well as ghost rock remnants in gallery roofs.

Contrasting views have been presented to account for the timing of the caves in the Cradle of Humankind. Dirks and Berger (2010) claim that the oldest exposures would be represented by the oldest deposits as caves are static sedimentary traps. This claim has placed exposure to the north of the Cradle where the oldest cave sediments may be found, after the erosion and removal of Karoo-aged cover rocks. This is placed at 2 Ma near Malapa. Recently, Dirks et al. (2016) used $^{10}$Be cosmogenic concentrations to determine erosion rates and local valley incision rates. They concluded that there was an old landscape in the Cradle of Humankind, which eroded at a very slow rate where the dolomites were exposed well into the Miocene.

Additionally, they suggested that the lack of Pliocene- and Miocene-aged fossils indicates that the caves in the Cradle of Humankind started forming more recently, in the last 4 Ma (Dirks et al., 2016). Other work suggests that the cave system has been open for more than 5 Ma and has avoided complete erosion by slow rate karst landscape evolution as well as low ground water recharge (Martini et al., 2003, Klimchouck, 2007).

### 2.4. Sterkfontein Stratigraphy

Following the discovery of fossil material in Sterkfontein, the site has received a lot of attention in terms of explaining and classifying the deposits (Clarke, 2006). Cooke (1938) first tried to explain the stratigraphy of the cave in the area where the *Australopithecus* cranium (TM1511) was found in 1936. The discovery of the first known adult Australopithecine (Broom, 1936), prompted stratigraphic assessment of the Sterkfontein by Cooke (1938). The cave was described as being filled with a mostly stony, bone-deficient breccia overlain by a finer grained, mostly fossiliferous breccia and thus concluded to be a shallow, single breccia deposit (Clarke, 2003). Later, the discovery of a fossil hyena (later identified as *Chasmaporthetes silberbergi*) from much deeper quarry workings of the cave system incited the conclusion that the deposits were Pliocene rather than Pleistocene in age (Broom and Schepers, 1946). They found no age distinction with earlier deposits described by Cooke (1938) and thus categorized the two units together. This lower-lying part of the cave system would eventually be named the Silberberg Grotto by Tobias (1979); this later led to a better understanding of the stratigraphy in Sterkfontein.

Brain (1958) investigated the stratigraphy of the exposed deposits and suggested that the Sterkfontein deposits represented one continuous infill. He stratigraphically placed the Silberberg Grotto deposits as a continuation of the Australopithecus-bearing surface-exposed breccia. However, Robinson's discovery (1957) of stone artefacts in the dumps at the western end of the site (and later excavations found in situ artefacts) led him to propose that these were two different infills (Robinson, 1962). These deposits were revised into three units; the oldest Lower Breccia (seen with the presence of *Australopithecus* and is artefact void), the younger red-brown Middle Breccia (comprising stone artefacts and Equus fossils) and youngest Upper Breccia (Robinson, 1962).

The extensive geomorphological descriptions of Sterkfontein were established by Wilkinson (1973, 1983) and Partridge (1978) who proposed a more detailed stratigraphy of the breccia deposits, with Partridge's sequence was named the Sterkfontein Formation. From breccias exposed in the type site, Extension Site (now Member 5 West) and Silberberg Grotto, Partridge (1978) identified six Members (1-6) with Member 1 as the most basal (Figure 2. 5). Members 1-3 were exposed in the Silberberg Grotto and Members 4, 5 and 6 were exposed on the landscape surface.

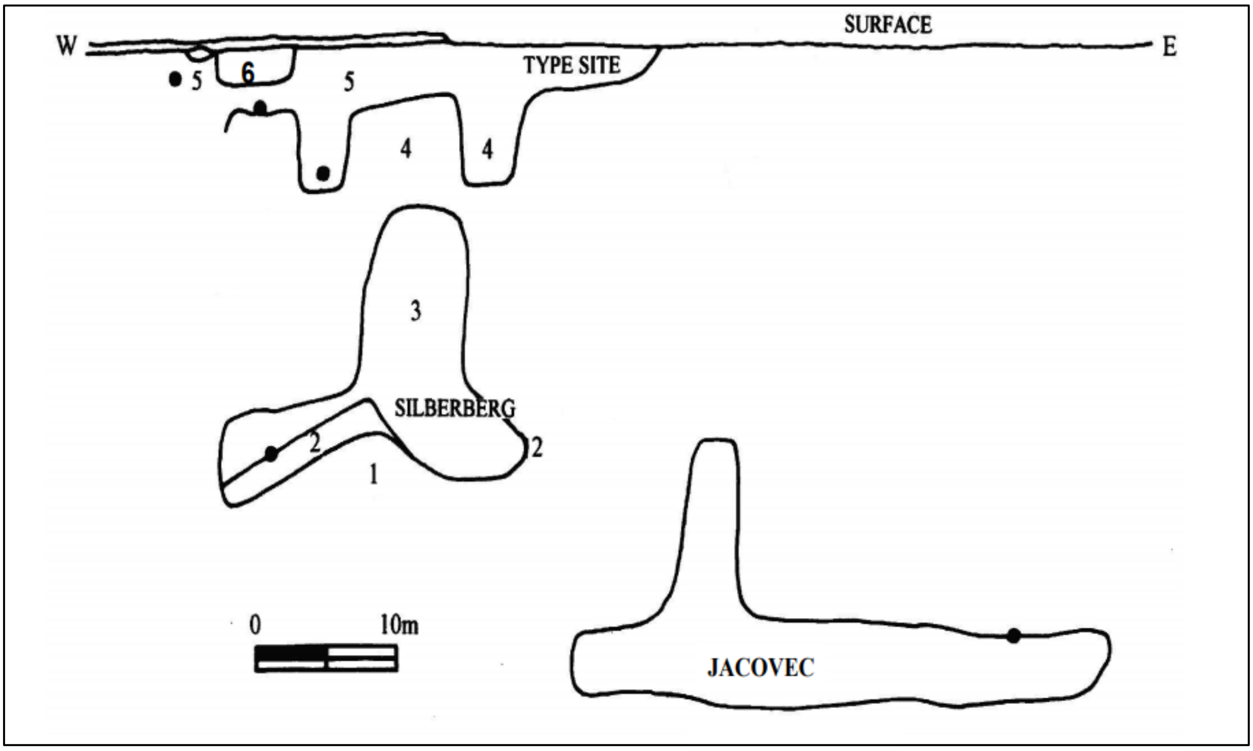



*Figure 2. 5. Stratigraphic profile of the Sterkfontein caves showing location of various Members (indicated in numbers) (Ogola, 2009, adjusted from Clarke, 2008).*

A further core drilling project by Partridge and Watt (1991) sought to refine this sequence and test and clarify the karstification and sedimentation model proposed by Wilkinson (1983). Although the Member system is still in use, its complex geology has been studied in much greater detail and revised by various researchers (Clarke, 1994, 2006; Pickering and Kramers, 2010; Stratford 2008, 2011; Reynolds and Kibii 2011; Stratford et al., 2012; Bruxelles et al., 2014). The single most contributing factor to this complexity is the extensive nature (both vertically and laterally) of the deposits, and their boundaries and thus the relationship between them (Stratford, 2011). Recent work has focused more on intricate investigations of different deposits at a more focused scale, which has helped in understanding this depositional sequence (Kuman and Clarke, 2000; Stratford et al., 2012; Bruxelles et al., 2014). In addition to the stratigraphic framework, Partridge and Watt (1991) adopted the hyperphreatic model which not only suggested the Silberberg Grotto as the oldest chamber, but excluded lower-lying more distant caves (such as the Jacovec Cavern and the Milner Hall) as younger secondary deposits.

The Sterkfontein Formation remains the most well-known stratigraphic framework for the caves and in this dissertation, I will refer to this system as the primary stratigraphic model. The Sterkfontein Formation (Figure 2. 6) is described as follows:

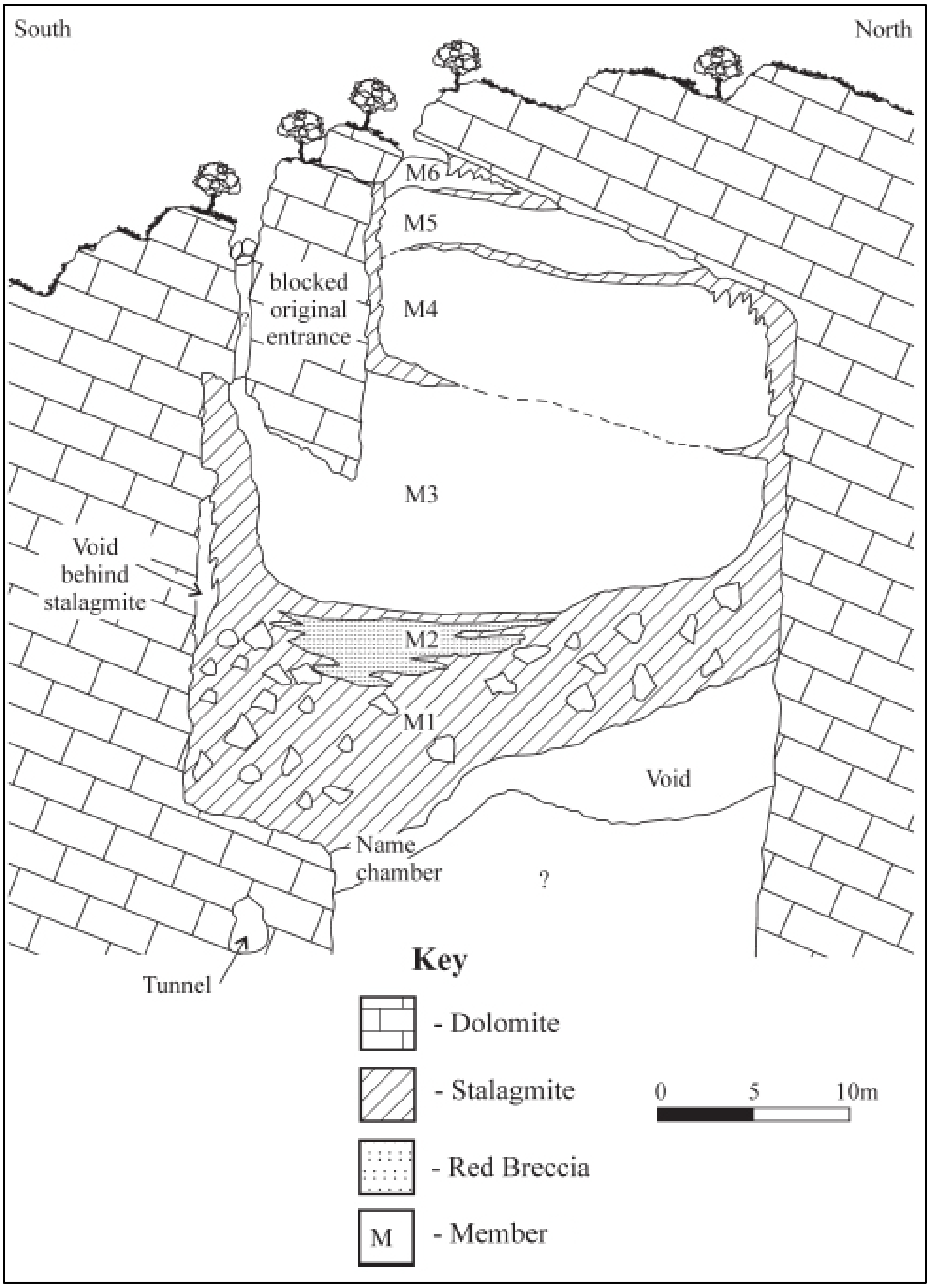



*Figure 2. 6. Diagram showing the Sterkfontein Formation (Clarke, 2006).*

*Member 1*: Exposed above the Silberberg Grotto's dolomite floor, this is a clastic-deficient dark brown (10 YR 7/3), non-fossiliferous, manganiferous, clastic sediment residual fill containing units of large chert/dolomite clasts and calcite interbeds (Partridge and Watt, 1991). A large portion of this deposit is attributed to debris accumulation from ceiling collapse and breakdown where cave access was either not present or very distant as seen through the abundance of host rock lithology (dolomite and chert).

*Member 2*: exposed in the Silberberg Grotto (Clarke 2006) and the base of the Milner Hall (Stratford et al., 2014), this is a bedded pale brown and red (7.5 YR 6/4 - 2.5 YR 5/6) clastic talus deposit (sands and silts) with rock debris clasts and on abundant fossil content (Partridge, 1978) that lies on top of Member 1 (Partridge 1978; Brain, 1981; Bruxelles et al., 2014). A stony breccia contained the oldest South African hominid fossil (StW 573) as well as other fauna including carnivores and primates (Clarke and Tobias, 1995; Clarke, 1998). This Member begins with the development of a talus cone on the roof of the Silberberg Grotto (which introduced fossil material that are cemented with the infiltration of calcium carbonate charged water. Later, the entrance of water from above led to cavity formation. Deposition is attributed to a restricted entrance of red sediment in the Silberberg Grotto with bone clasts indicating death traps (Bruxelles et al., 2014). There is however some age contestation of the age of these deposits. Berger et al. (2002) places the deposit at no older than 3 Ma considering the possible mixing of fauna as well as various interpretations of paleomagnetic signals (Herries and Shaw, 2011; Herries et al. 2013). Partridge (2005) however claims an age of 4.17-3.3 Ma (from U-Pb methods on the capping flowstones) while Walker et al. (2006) places the deposit at 2.24-2.17 Ma for the StW 573 hominid. Using U-Pb dating Pickering and Kramers

(2010) U-Pb dating obtained an age of 2.6 - 2.8 Ma. Detailed stratigraphic work by Bruxelles et al. (2014) introduced constrains to previous dating attempts, and with isochron burial dating of cosmogenic $^{26}$Al and $^{10}$Be has shown that the deposits, containing the insignificantly reworked StW 573 are 3.67 ± 0.16 Ma old (Granger et al., 2015). Kramers and Dirks (2017) contributed to the discussion by stating that StW 573 cannot be older than 2.8 Ma and accounted for the older date by suggesting a two-stage burial scenario, with a mixture of sediments being created from the collapse of the skeleton from an upper chamber. Stratford et al (2017) stated that they could find no stratigraphic evidence of a collapse occurring in Member 2 and that the cosmogenic nuclide data is consistent with a single episode of deposition which is contemporaneous with StW 573.

*Member 3*: This unit is exposed in the roof of the Silberberg Grotto, and consists of a Bed A and a Bed B (Partridge, 1978). Bed A is actually a basal (mesocrystalline) calcite flowstone, which is overlain by a reddish brown, calcified, clast-rich clastic Bed B (Partridge, 1978). The units contain bone, but haven't been sampled due to the excavation difficulties of the steep cave walls (Kibii, 2000). Pickering and Kramers (2010) do not recognise this as an individual unit, and attribute the deposit as a Member 4 distal equivalent.

*Member 4:* This unit is now exposed at surface following the erosion of the cave roof (Martini et al., 2003) and contains *Australopithecus* sp. specimens (Broom and Schepers, 1946; Pickering, 1999) and the only known fossil wood specimens in the site (Bamford, 1999). Partridge (1978) divided these into four beds:

- Bed A is a calcite-cemented dolomite/chert roof debris fall containing fauna that includes *Australopithecus africanus* in the sandy-silty matrix. This unit suggests several events of extensive, large roof collapses that led to cave opening;

- Bed B is a reddish brown, clast-rich (roof collapse) calcified loamy deposit with some bone fragments present;
- Bed C is similar in colour to its underlying Bed B but has less clast inclusions of the host rock debris. It is also sandier and has yielded lots of fauna including *Australopithecus* sp. ("Mrs Ples" [STS 5], StW 12, 13 and 17);
- Bed D is a well banded, patchy-outcropping calcite deposit with an erosional base.

It was suggested that the deposit is a major cave infilling; a sediment pile of coarse-grained dolomite roof block at the entrance that fines further into the cave then concluded by a wetter phase that introduces the flowing capstone (Bed D) (Pickering and Kramers, 2010).

*Member 5*: This unit exposed to the Extension Site to the western end of the Type Site (Robinson, 1962; Partridge, 1978). The unit is a well to moderately calcified reddish brown clastic fill, with rock debris seen at three infills (Member 5 East, StW 53, Member 5 West). It is associated with hominid remains as well as an Early Pleistocene fauna, and has been dated using several different methods (summarised in Table 2. 1). Deposition occurred in a shaft located at the Member 5 East base (Clarke, 1994).

| Deposit | Published dates for deposits | Species | Artefacts and industries |
|---|---|---|---|
| Member 5: StW 53 Infill | - **2.6-2.0 Ma**, Fauna (Kuman and Clarke 2000)<br>- **1.8-1.4 Ma** dating seriation (Herries et al., 2009)<br>- **1.8-1.5 Ma** ESR, isotopes and palaeomagnetism<br>(Herries and Shaw 2011) | *Homo habilis* /or late *Australopithecus* sp. | None |
| Member 5: East Infill | - **2.0-1.7 Ma**; Biochronology and archaeology (Kuman and Clarke 2000)<br>- **1.4-1.1 Ma** dating seriation (Herries et al., 2009)<br>- **1.4-1.2 Ma** ESR, isotopes and palaeomagnetism (Herries and Shaw 2011)<br>- **2.18±0.21 Ma** cosmogenic nuclide ($^{26}Al$ and $^{10}Be$) dating (Granger et al., 2015). | *Paranthropus robustus* | Oldowan Industry |
| Member 5: West Infill | - **1.7-1.4 Ma**, Biochronology and archaeology (Kuman and Clarke 2000)<br>- **1.3-0.8 Ma** dating seriation (Herries et al., 2009)<br>- **1.3-1.1 Ma** (Herries and Shaw 2011) | *Homo ergaster* | Early Acheulean |

*Table 2. 1. Summary of research from Member 5 deposits (after Reynolds and Kibii, 2011).*

*Member 6*: Located at the western part of Member 5 and above Member 5 West, this unit contains a basal calcite flowstone overlain by a dark reddish brown clastic deposit. The unit is the thinnest in the formation probably because it has been heavily eroded. It is thought to be Middle to Late Pleistocene in age, and formed on top of the Member 5 capping flowstone (Kuman and Clarke, 2000).

## 2.5. Lower Cave deposits

With the exception of the Silberberg Grotto the underground deposits have been excluded from the Sterkfontein Formation stratigraphic framework. This has led the stratigraphic framework to be criticised by researchers such as Wilkinson (1983) who proposed that deposits deeper than Member 1, like those in the Jacovec Cavern, would need to be represented with this classification. Partridge and Watt (1991) responded by suggesting that this chamber did not form part of the Sterkfontein Formation sequence. Since the deposits in the passages and chambers below the Silberberg Grotto were not represented in the borehole sequences, Partridge and Watt (1991) argued that they were not part of the Sterkfontein formation, were younger and were redeposited from overlying chambers. After a reanalysis of the boreholes and facies establishment, Pickering and Kramers (2010) suggested that these boreholes only terminated at the Silberberg Grotto rather than sampling the basal allogenic infills. Geomorphological investigation of the Jacovec Cavern has however suggested that these deposits may represent the oldest sediments in the Sterkfontein Caves (Wilkinson, 1983; Clarke, 2006; Stratford, 2011).

### 2.6. The Jacovec Cavern

#### 2.6. 1. Jacovec Cavern Deposits

Most geological work done focused on what is defined in this dissertation as the Thulasizwe Chamber. The term “Thulasizwe Chamber” refers to the eastern chamber of the Jacovec Cavern (Figure 1.1). This distinction was made as earlier works had not differentiated between the chambers in the Jacovec Cavern. The first comprehensive lithological descriptions (Table 2. 2) of the fill of the Jacovec Cavern were produced by Kibii (2000) when he conducted taphonomic studies on the faunal assemblage. Kibii (2000) identified two major breccia types; an orange and brown. Due to R.J. Clarke’s investigations, Kibii (2000) placed the Orange Breccia as the first (older) deposit as it was preserved in the roof and is thus a remnant. This breccia is a highly fossiliferous and hominid-bearing sediment containing silt loam deposits with orange sediments (Kibii, 2000). After this, the Brown Breccia entered until the entrance closed and it was subsequently covered by a flowstone. It is a mosaic of autogenic and allogenic deposits. Finally, these breccias collapsed and mixed on the floor of the cavern. This collapsed section was used for the taphonomic investigation (Kibii, 2000).

| Sample | Rock type | Description |
|---|---|---|
| **A** | Clear grey to white 5.0 mm long crystals of calcite ($CaCO_3$) | *Crystallized in situ either from groundwater saturated with Ca and $CO_2$, or precipitation from limestone.* |
| **B** | Greyish white brown calcrete ($CaCO_3$) | *Formed as part of regolith (weathered rock) or soil horizon by the concentration of $CaCO_3$ and removal of other elements.* |
| **C** | Reddish brown, brecciated regolith consisting of angular clasts (fragments) of 5.0-10 mm thick, finely bedded (0.5-1.0 mm) limestone, and small (0.5 mm) discrete crystals of clear grey calcite. | *Slump deposits formed from collapsed limestone and other superficial material cemented together and weathered to form regolith, with calcite being formed by circulating groundwater. Angularity of clasts indicates that they have not been transported far from the origin.* |

| | | |
|---|---|---|
| **D** | Dark reddish brown to brown regolith with angular, 10-20 mm thick, isolated clasts of fine-grained bedded, white grey limestone,<br>as well as discrete 0.2-0.5 mm calcite crystals. | *The weathering of a breccia forms this form of brecciated regolith with some precipitation from groundwater.* |
| **E** | Dark reddish brown with thin lenses (3.0-4.0 mm thick) of greyish white calcrete throughout. | *This is regolith that is further weathered with calcrete resulting from the soil forming process.* |
| **F** | Very dark brown regolith with small 0.5 mm dark brown rounded clasts (concretions) and angular clasts of greyish white, finely bedded, limestone (8.0-10 mm). | *This is formed from the weathering of a limestone breccia, with concentrations possibly forming by the concentration of iron (Fe) or derived from another soil horizon.* |
| **G** | Dark brown regolith with numerous clear grey, 2-10 mm thick, calcite veins throughout. | *These form from weathered rock that was infiltrated by circulating groundwater, with precipitation out of* $CaCO_3$ *in joints and fractures within the host rock.* |
| **H** | Dark reddish brown to red regolith with fine (2.0-3.0 mm) rounded haematite clasts throughout, with angular (10-15 mm) clasts of greyish white, finely bedded limestone, and rare fine (0.5-1.0 mm) clear grey calcite crystals. | *This is formed from weathered limestone breccia where removal of other elements results in the concentration of Fe into nodules, and circulating groundwater precipitated out calcite.* |
| **I** | Has two components, the first consisting of reddish brown regolith similar to Rock H, and a brown limestone regolith similar<br>to Rock C. | *This was probably formed elsewhere and cemented together in another slump deposit.* |

*Table 2. 2. Sediment and rock types from the Jacovec Cavern breccia (Kibii, 2000).*

With an increased interest in dating the faunal assemblage of the Jacovec Cavern, Partridge et al. (2003) described the *in situ* deposits of the cave. He identified three deposits in Jacovec of distinct generations of filling. The stratigraphic interactions are prominent on the eastern wall of the chamber (Figure 2. 7). Partridge et al. (2003) also noted that the walls of the chamber were mostly covered by a stony breccia (Brown Breccia) with pockets of an orange stony breccia (Orange Breccia). The Orange Breccia is also placed as the oldest deposit in the chamber, and that they were naturally undercut following the deposition of the younger underlying brown fossiliferous sediments (Partridge et al., 2003). In addition, there was a west-sloping dark brown debris cone which fills the eastern end of the chamber. This debris cone deposit was interpreted as the youngest and entered from an entrance on the eastern proximity of the chamber. This claim was supported by the presence of the fragments from the two breccias (Partridge et al., 2003)

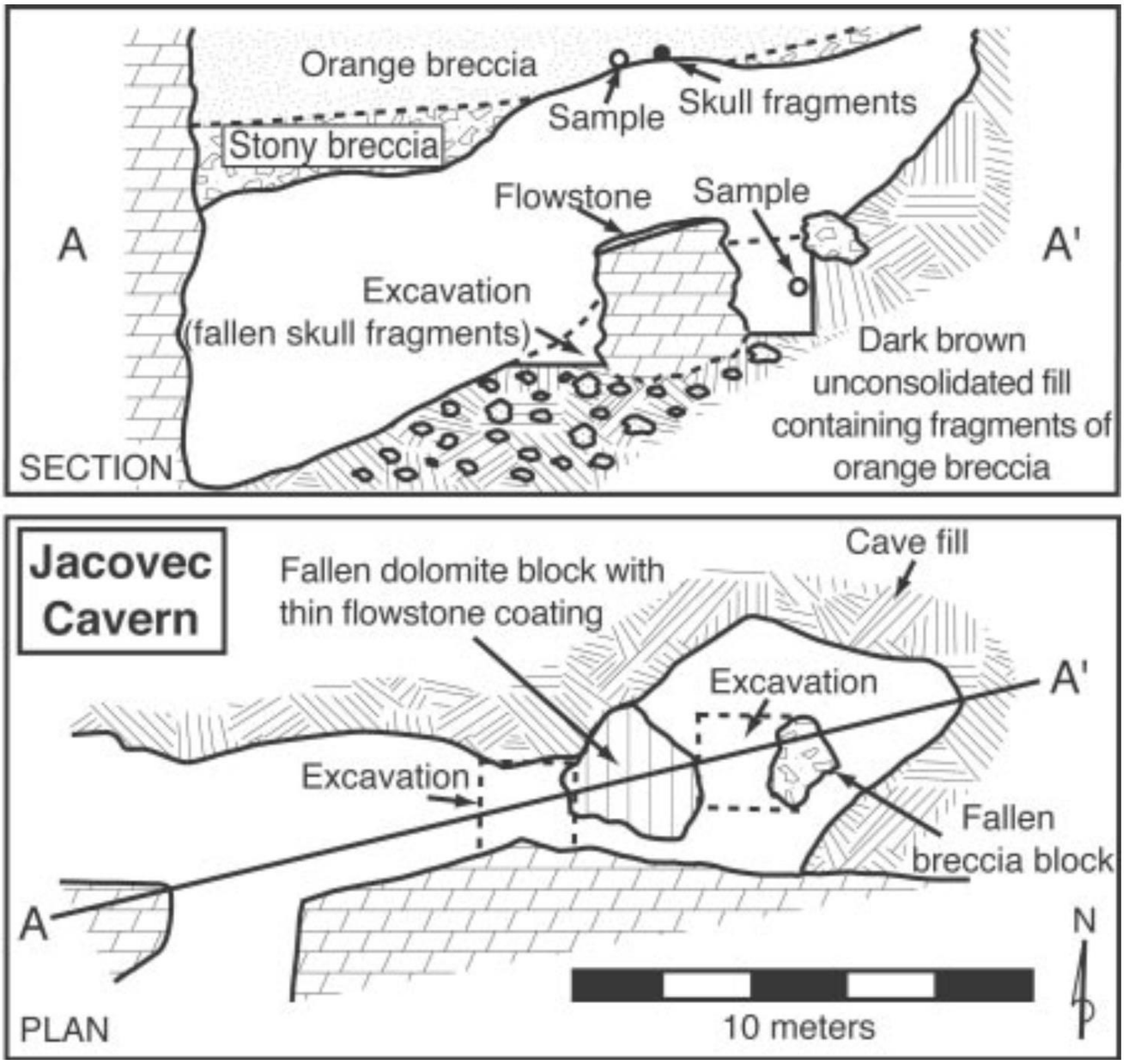



*Figure 2. 7. Schematic diagram and cross section of the eastern section of the Thulasizwe Chamber in the Jacovec Cavern (Partridge et al., 2003).*

### 2.6.2. Palaeontology

All the fossil material retrieved from the Jacovec Cavern is from the Orange Breccia (Reynolds and Kibii, 2011; Partridge et al., 2003). Jacovec has yielded a large faunal assemblage that includes skeletal elements (teeth, cranial and postcranial) assignable to the genus *Australopithecus,* which represent three adult and three juvenile individuals (Partridge et al., 2003). StW 578 is one of these specimens, a well preserved partial adult cranium (Partridge et al., 2003). There is also a femur (StW 99) that resembles *Paranthropus* and a well-preserved clavicle (StW 606) with carnivore gnaw marks (Partridge et al., 2003). This clavicle has a unique morphology similar to those of chimpanzees relative to humans and other *Australopithecus* (Partridge et al., 2003). Other primates present in the assemblage include *Parapapio jonesi, Parapapio broomi, Papio izodi,* some colobine and cercopithecoids (Kibii, 2000, 2004, 2007; Partridge et al., 2003). There are also five families from the order Carnivora, which include representatives of the Herpestidae (*Cynictis penicillata*), Viverridae (*Genetta genetta* and an indeterminate *Herpeste*) Canidae (*Vulpes chama, Canis mesomelas* and an indeterminate canid species*),* Felidae (*Felis caracal, Homotherium latidens, Panthera pardus, Panthera leo* and an indeterminate felid species) and the Hyaenidae (*Chasmaporthetes silberbergi, Chasmaporthetes nitidula, Chasmaporthetes* sp*.* and an indeterminate hyaenidae species) (Reynolds et al., 2007). There are also three families of Bovidae present, namely the Bovinae, Alcelaphinae and Hippotraginae. Other fauna retrieved included *Potamochoerus porcus* (a bush pig), *Pedetes capensis* (a springhare), *Lepus capensis* (a Cape hare), a tortoise and hyraxes (Kibii 2000, 2004).

### 2.6.3. Stratigraphic positioning

There have been attempts to relate the deposits of the Jacovec Cavern to the main Sterkfontein Formation deposits (Kibii, 2000; Partridge et al., 2003; Clarke, 20006; Reynolds and Kibii, 2011). Clarke (2006) argued that there may be a connection between the breccias of the Jacovec Cavern and those of the Silberberg Grotto as they are close to each other in the cave network. The discovery of an *Australopithecus* clavicle with unique "ape-like morphology" in the Jacovec Cavern suggests that it is older than Member 4, which contains more "human-like" clavicles (Partridge et al., 2003; Clarke, 2013). The Jacovec deposits could be contemporaneous to Member 2 deposits as it they both contain *Australopithecus sp. fossils*. In addition, the occurrence of other extinct fauna such as *Parapapio jonesi, Parapapio broomi* and *Papio izodi* suggests that the Jacovec deposits is amongst the oldest deposits in the Sterkfontein cave system (Kibii 2000, 2004, 2007; Partridge et al., 2003; Clarke, 2006). Most hominid fossils and macrofauna were recovered from the collapsed sediments investigated by Kibii (2000) and have potentially been mixed with younger sediments leading to difficulties in establishing a biostratigraphic context for the hominid material (Reynolds and Kibii, 2011). The absolute dating from cosmogenic nuclides ($^{26}$Al and $^{10}$Be) assisted in clarifying the chronostratigraphic context of the deposits (c. 4.02 ± 0.27[0.41] Ma for the Orange Breccia and c. 3.76 ± 0.26[0.41] Ma for the Brown Breccia) and supported the interpretation of a reverse stratigraphy (Partridge et al., 2003).

## 2.7. Project aim and objectives

This research aims to analyse the Jacovec Cavern stratigraphy by adopting a multifaceted sedimentological analysis in order to develop a model on the contributing accumulation processes. It also seeks to source a provenance for the clastic deposits and explain the depositional regimes (and thus environments) which these sediments were subjected to. This will ultimately provide a high resolution context for the associated fossils found in the Jacovec Cavern.

More specifically, the aims include:

1. ***Stratigraphic investigation*** - To clarify the relative stratigraphic position of the fossil deposits within the context of the Jacovec Cavern and to establish a link between the cavern, its deposits and the rest of the Sterkfontein Formation stratigraphic sequence as established by Partridge (1978).

2. ***Sedimentary facies analysis*** - To establish a high resolution reconstruction of the depositional environment as well as investigate the dynamics that led to the transport, accumulation and modification of the sediments and its faunal assemblage.

## 3. Materials and Methodology

Due to complex nature of the depositional and faunal accumulation history in the Sterkfontein caves (Stratford, 2013), any work undertaken in the region requires involved, multifaceted sedimentological approaches. This will assist in clarifying depositional, stratigraphic and their associated faunal assemblages in the site. This research set out to achieve just that; sedimentological analyses that are both qualitative and quantitative, as well as spanning varying scales to thoroughly examine the sedimentary units present in the Jacovec Cavern. This was achieved by regular fieldwork conducted during 2015 and 2016 to document the lithological features of the exposed deposits in the Jacovec Cavern so that they may be later analysed. These analyses are described below.

### 3.1. Sedimentary Facies analysis

In a geological context, 'facies' refers to observable features that make a rock unit distinct from other rock units (Miall, 2000). 'Lithofacies' are bodies of rock containing similar chemical and physical properties (Reading, 1986). These facies exist in a finite number in sedimentary units and are produced by a finite number of physical parameters regardless of the location and time period on Earth (Selley, 1985; Miall, 1996). In particular reference to karst systems, storm flow (runoff producing mechanism) and particle size are the determinants of clastic sediments and the flux of these sediments through the aquifer (White, 2007). For an accurate interpretation of depositional environments, the set of lithofacies within a sedimentary sequence need to be defined (Harms et al., 1982). Sedimentary facies analysis is not only a tool that describes and characterises sedimentary rocks (Nichols, 2009), it is vital in the formational interpretation of any ancient sedimentary unit. This method requires observation, identification and interpretation of the biotic and abiotic features (physical and chemical) of sedimentary deposits. These observations then assist in the reconstruction of sedimentary processes and environments. It also helps in identifying provenance of these deposits (Nichols, 2009).

The investigation adopted a streamlined facies characterization scheme. This classification scheme ensures that there is consistency in not only the descriptions, but also the facies classification which were derived from established facies units. Firstly, the described units were characterised by the lithological facies scheme of Miall (1996, 1999). Although Miall (1996, 1999) is a fluvial scheme, the facies code system is a good framework for any sedimentological environment and therefore was used in this work for descriptive and ordering purposes only. Following (but not limited to) to the work of Kibii (2000) and Partridge et al. (2003), these facies units were then grouped into sedimentary units as facies associations. A facies association is a group of specific facies that are associated with a specific depositional setting. The cave facies association scheme adopted varies depending on whether the deposit is siliciclastic or karst carbonate, each of which have their own facies association scheme. For siliciclastic deposits the scheme of Bosch and White (2004) and Bosch (2015) was adopted while the scheme of Latham (1999) and Flügel (2004) used for the karst carbonate facies.

### 3.2. Lithological descriptions of *in situ* exposure

Before any sedimentary facies analysis may be applied to the deposits they have to be well documented and described. To ensure consistency in the description, the following was recorded in each sedimentary unit: bed shape and extent, colour, grain size and variation (both laterally and vertically), sedimentary structures present (e.g. laminated, convoluted, massive), bed-top and -bottom features, visible post depositional features (bioturbation, soft sediment deformation). The Munsell Rock Colour Chart was used to determine the sediment colour. This was done from collected samples outside the cave in sunlight. For consistency in grain size assessment a SciOptic grain size chart was used. These descriptions were compiled into representative sedimentary logs (drawn on Adobe Illustrator CC Software) whose vertical extent was noted for lithological correlation across space. Additionally, these lithological descriptions were also made into sketch diagrams using Adobe Illustrator CC Software.

The sedimentary features of the exposure demonstrate evidence of transport energy regimes as well as sedimentary unit relationships. The representative sedimentary logs of the cavern exposure as well as the exposure were photographed (for illustrative purposes) and digitised then annotated with details with Adobe Illustrator.

## 3.3. Mineralogy and geochemistry

### 3.3.1. Sample Collection

A total of 25 samples were collected in the Jacovec Cavern from all the sedimentary units exposed (Figure 4.2). These were used for petrographic and geochemical analysis for mineralogical investigation of the sedimentary units. Sample collection achieved to obtain the most representative parts of the entire exposure; diagnostic samples for each unit, along their contacts and other interesting features (such and slumping and visible facies changes). For petrography, the collection of the sample depended on the physical nature of the area being sampled. The hard, well consolidated sediments were sampled by chiselling with a rock hammer with upward direction noted, with the sample obtained then wrapped with cling film for protection. The soft, friable sediments were sampled by placing aluminium gutter piping on it, hammering it in to position and then removing it before wrapping it with cling wrap and noting the upward direction.

Geochemical samples were removed from freshly exposed surfaces (achieved by scraping the area with a trowel) and placed in plastic bags. Moisture in the samples is removed by spreading them in a tray and air drying them over three days.

**3.3.2. Petrographic light microscopy**

Samples were cut and polished at the School of Geosciences, University of the Witwatersrand to obtain ~30-µm-thick thin sections. Preparation of thin sections differed according to the nature of the sediment. In hard sediments, the sample was cut using a diamond blade. This was done to obtain a slab that contains a flat surface. Soft samples required more care and attention to preserve the features present in the sediment. These samples were firstly dried. They were then imbedded in epoxy resin before being cut. The sample is then polished by using different grades of grit (coarse to fine) to obtain a smooth surface. Following this, the sample is then dried and the embedding epoxy removed of any air bubbles. The rock on the slide is then ground by polishing with grit until it is 30µm thick. This is measured by looking at interference colours (mostly feldspars and quartz) in cross polarized light on a petrographic microscope. Once the desired thickness is achieved, the sample is covered with a thin layer of epoxy.

The analysis of these thin sections was conducted both at the University of the Witwatersrand and the University of Bordeaux III. A systematic approach was adopted when analysing the thin sections. Firstly the mineralogy was identified using the guide of Deer et al. (1992) at the University of the Witwatersrand. An Olympus polarising microscope was used for the analysis. Photos of the thin section were analysed with Olympus Stream software. At the University of Bordeaux III an Olympus polarising microscope was used for the petrographic analysis.

The thin sections were analysed under both cross polarised light(XPL) and plane polarised light (PPL) to determine micromorphological features (Jongerius and Rutherford, 1979; Goldberg, 1979; Adams et al., 1984; Bullock et al., 1985; Courty et.al., 1989; Adams and McKenzie, 1998; Railsback, 1999; Karkanas et al., 2000; Stoops, 2003; Flügel, 2010; Karkanas and Goldberg, 2013).

### 3.3.3. X-Ray Fluorescence analysis

X-Ray flouresence analysis (XRF) is one of the most widely used analytical methods used to determine major element of rock samples (Rollinson, 1993). This aids in understanding sedimentary composition as well identifying trends in the sedimentary horizon. For the purposes of this dissertation, the XRF data aimed to confirm mineralogy observed under the microscope thus only major element analysis was conducted.

Samples were pulverised and analysed at the School of Geography, Archaeology and Environmental Sciences, University of the Witwatersrand for XRF Spectroscopy. Eight samples (~10 µm), which were collected adjacent to the location of thin section samples, were analysed. The analysis was run for major (1g per sample). The following major elements were tested for and are presented in weight percentage (%):

- $SiO_2$
- $Al_2O_3$
- $Fe_2O_3$
- FeO

- MnO
- MgO
- CaO
- $Na_2O$
- $K_2O$
- $TiO_2$
- $P_2O_5$
- $Cr_2O_3$
- NiO

# 4. Results

This chapter shall describe the lithological investigations of the Jacovec Cavern as explained in the methods section. The description will begin with a sedimentary facies analysis. This description will be ordered into lithofacies and shall include micromorphological and petrographic descriptions. These lithofacies will be assigned into sedimentary facies associations. Thereafter, geochemical data (XRF) of the facies associations shall be presented. Finally, process geology will be explained for each of the cave facies associations.

## 4.1. Sedimentary facies analysis

The most continuous (laterally and vertically) sedimentary exposure of the Thulasizwe Chamber occurs on the eastern side of the chamber (Figure 4.1). It is here that most of the sedimentological work was conducted. The lower sedimentary units were defined from vertical exposures filling the eastern end of the chamber. The upper sedimentary units (i.e. the Brown and Orange breccias) are better exposed in the north-western and western walls of the chamber. A cumulative sedimentological log of approximately 12 m was described in various parts of the chamber to obtain a representative description of each sedimentary unit. Lateral sedimentary descriptions were significant in this investigation (Figure 4.2).


*Figure 4.1. The eastern section of the Thulasizwe chamber showing the most continuous sedimentary exposure in the Jacovec Cavern.*

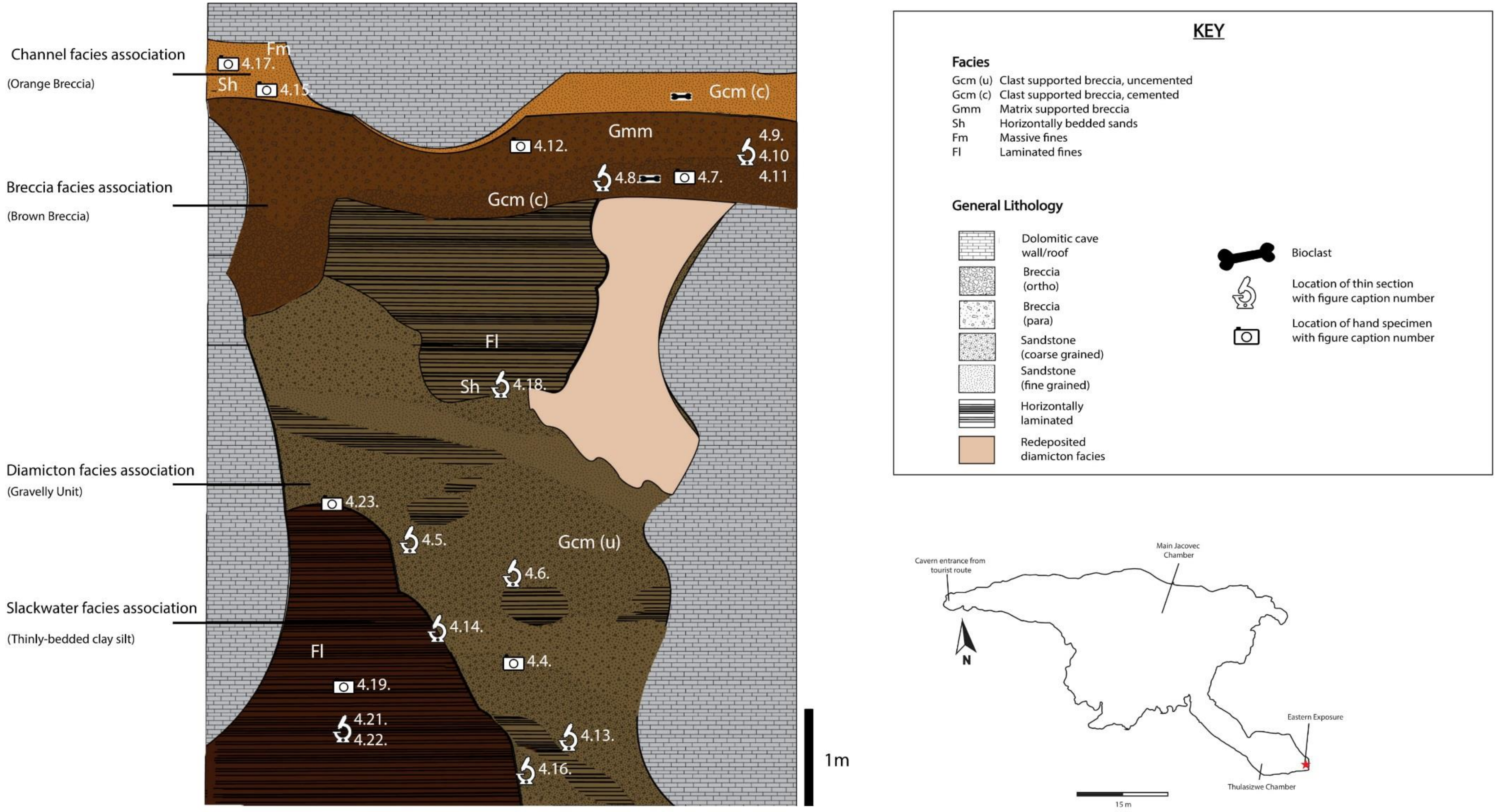



*Figure 4.2. Sedimentary log of the Thulasizwe Chamber showing lithofacies, lithofacies associations and sampling of thin sections.*

Representative exposure in the Main Jacovec Cavern is very limited and thus only two representative sections were described. The first section (Figure 4.3a), Section A-B (extending 160 x 70 cm) sits adjacent (NNE) to the modern entrance while the second (Figure 4.3b), section C-D (extending 140 x 180 cm) is on the further east of this section.

The lithologies from the entire Jacovec Cavern were described, after which characterization was done by descriptions of facies (from Miall, 1985, 1996, 1999; Reading, 1986, 2012). In the case of the Main Jacovec chamber, only lithofacies were assigned as there was very limited continuous exposure.

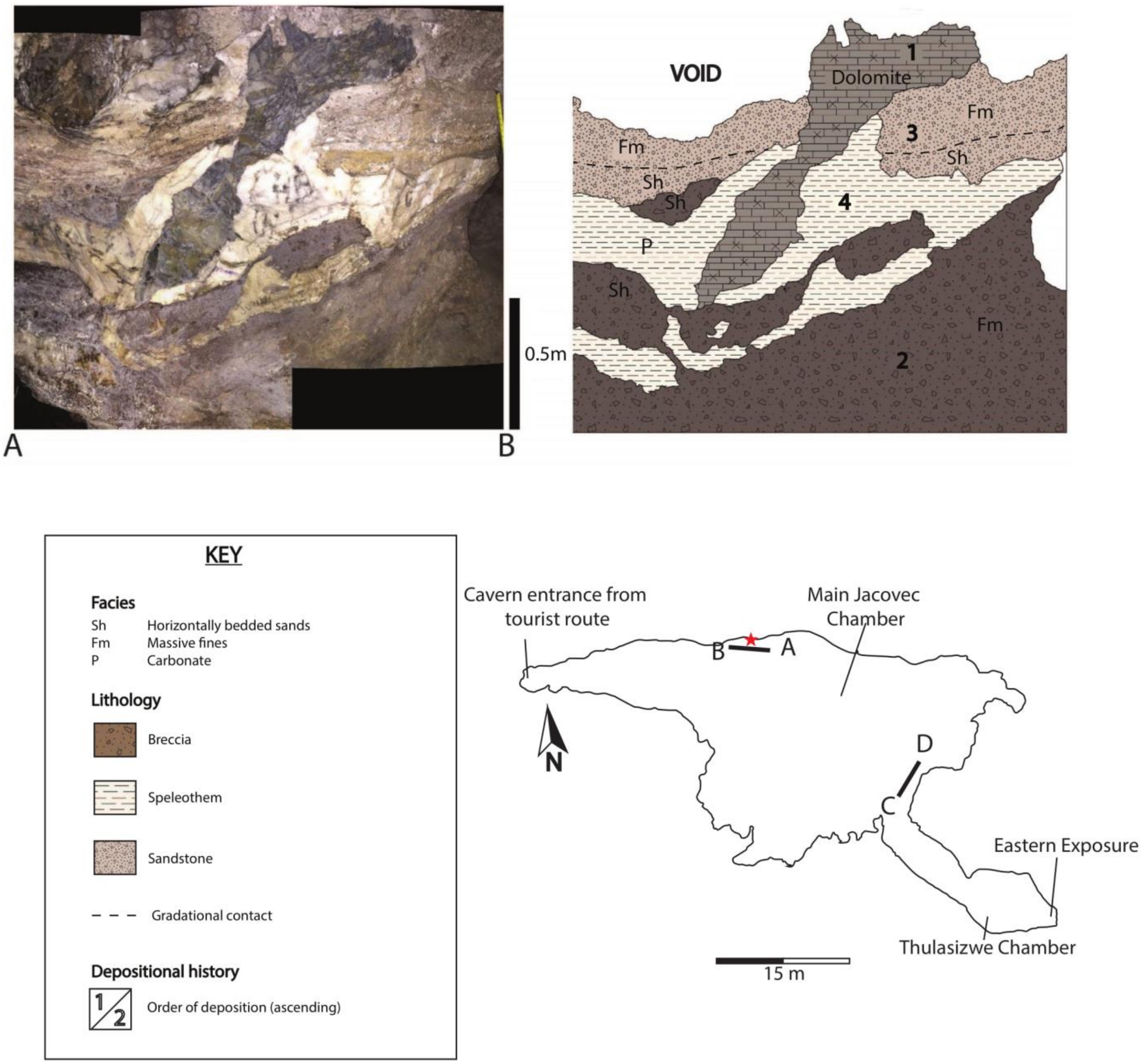



*Figure 4.3a. Section A-B in the Main Jacovec Chamber.*

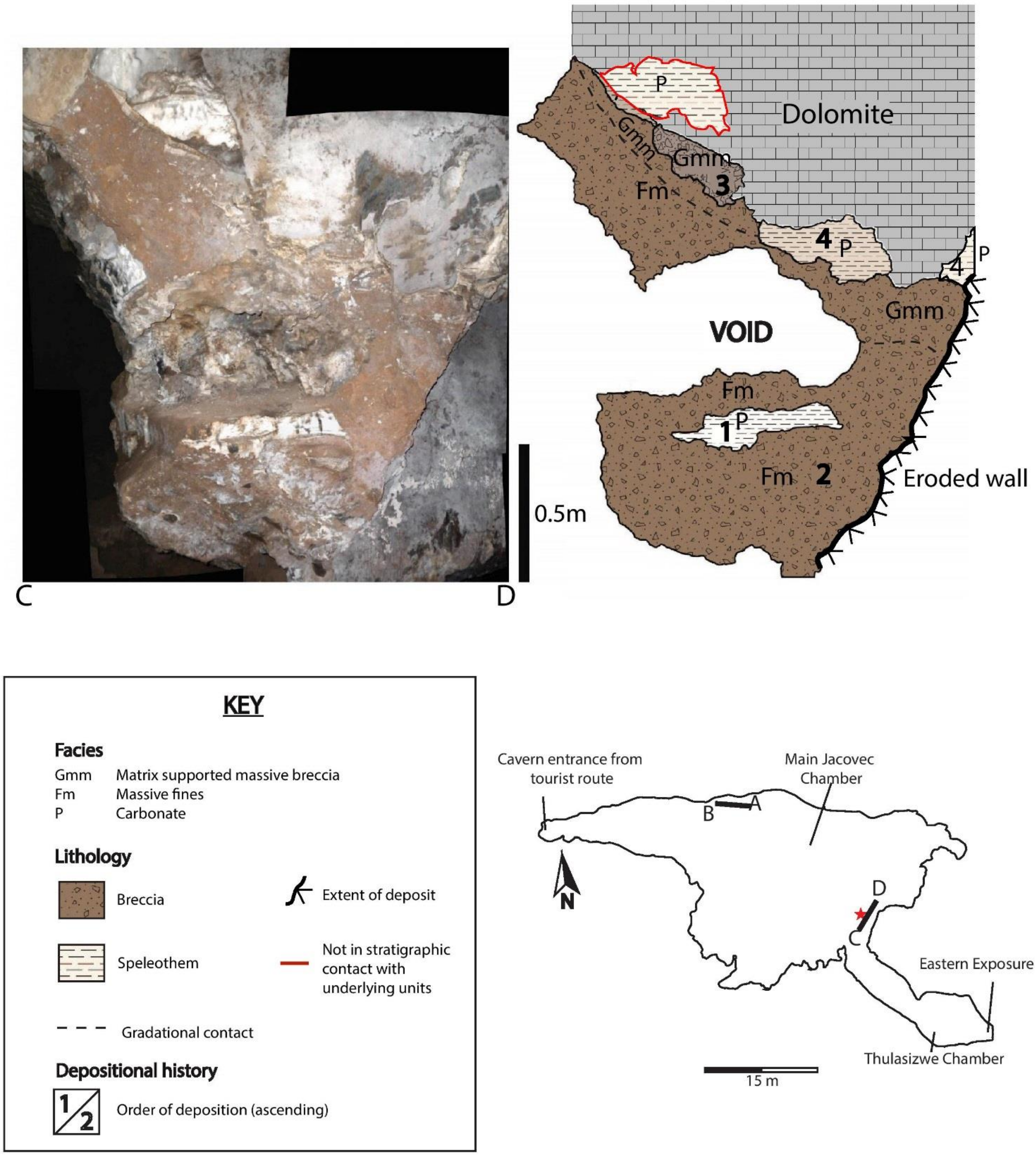



*Figure 4.3b. Section C-D in the Main Jacovec Chamber.*

.

#### *4.1.1. Facies*

The Jacovec Cavern contains a variety of lithologies which follow different lithological schemes depending on their nature (siliciclastic vs carbonate). Therefore, these have been separated for facies descriptions. Facies are described then facies codes assigned following from the convention by Miall (1996, 1999).

*Clast supported massive breccia, uncemented - Gcm (u)*

This facies is the thickest in the Thulasizwe Chamber exposure (~18 cm) and is documented in the eastern exposure (Figure 4.4). Clast lithology and shape vary in different parts of sedimentary sequences. A diagnostic feature of the facies is an absence of sedimentary structures and bioclasts, very poor sorting, and a large clast (angular) range (2 - 38 cm). The clasts have no preferred orientation. The matrix is uncemented, homogenous and usually dark greyish brown in colour (2.5YR 4/2).

Microscopically, the facies is poorly sorted and thus an immature sediment (Figure 4.5). It is also isotropic. The clast mineralogy is predominantly quartz and chert of highly variable sizes. The clasts are mostly subrounded and spherical with most of the quartz grains (especially polycrystalline grains and cherts) and Fe rimmed. (Figure 4.34). The matrix is very ferric, containing many angular cherts. There is ferrobacteria as well as alteration of quartz by calcite (Figure 4.6).

*Figure 4.4. Facies Gcm (u) facies in the Thulasizwe Chamber.*

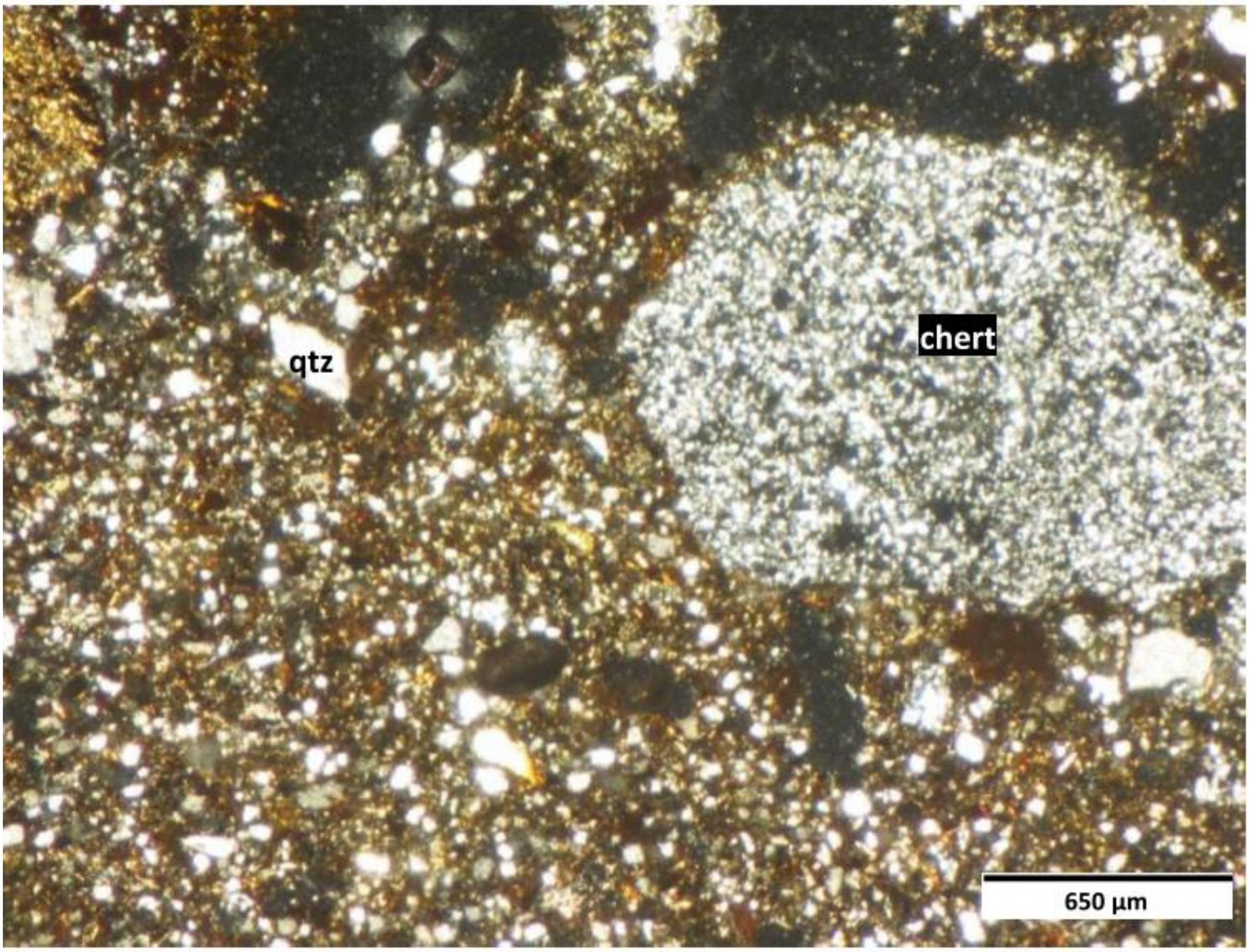



*Figure 4.5. Photomicrograph (XPL- cross polarized light) of Facies Gcm (u) showing poorly sorted immature sediments with high chert and quartz abundance. Sample MM3.*

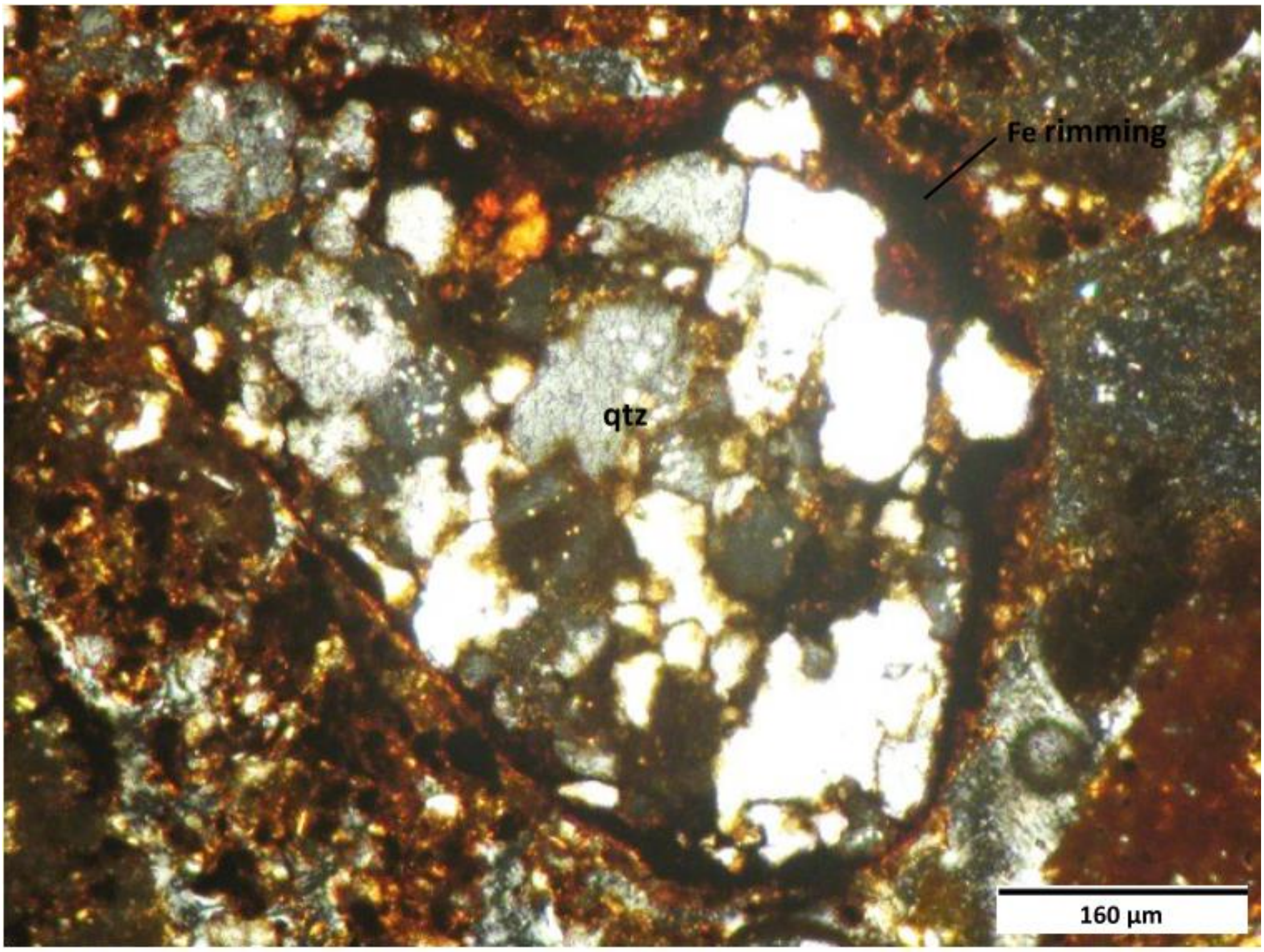



*Figure 4.6. Photomicrograph (XPL) of facies Gmm (u) showing Fe rimming of a polycrystalline quartz (centre) and ferrobacteria (bottom left).*

*Clast supported massive breccia, partially cemented - Gcm (c)*

This facies is restricted to the upper parts of the Thulasizwe Chamber with variable thicknesses (thinnest is 10 cm in the Orange Breccia). The clasts are poorly sorted (between 2- 15 cm in length) and polymictic, consisting of chert, quartz and volcanic tuff and more diagnostically, bioclastic material. As in the case of facies Gcm (u), these units have no sedimentary structures. The matrix is homogenous, cemented can either be yellowish red (5YR 5/6) or dark greyish brown (2.5YR 4/2) in colour (Figure 4.7).

In thin section, the facies is poorly sorted thus an immature sediment. The clast mineralogy consists mostly of calcite (microsparite), quartz, chert, ferrigenous crust, bone fragments and rock fragments (Figure 4.8). The clasts are poorly sorted with a large grain size range (µm). The bones are usually elongate and represent shaft elements (Figure 4.9). These skeletal elements have been altered as seen through crystal growth of calcite and silica in their void parts (Figure 4.10). The grain edges are angular and rimmed by opaque (ferric) minerals. This is applicable to other void spaces (Figure 4.11). The matrix is very dark and largely opaque. There seems to be some evidence of porous spaces, but cementation is seen with interstitial calcite

Organic content present include ferrobacteria (visible at 90x). These organisms are rounded and blotchy. In certain areas, they congregate and form a large isotropic section. Calcite grains are usually angular in shape although the edges are altered by opaque minerals (most probably Fe).

*Figure 4.7. Facies Gcm (u) facies showing large clasts in the greyish brown unit, Thulasizwe Chamber.*

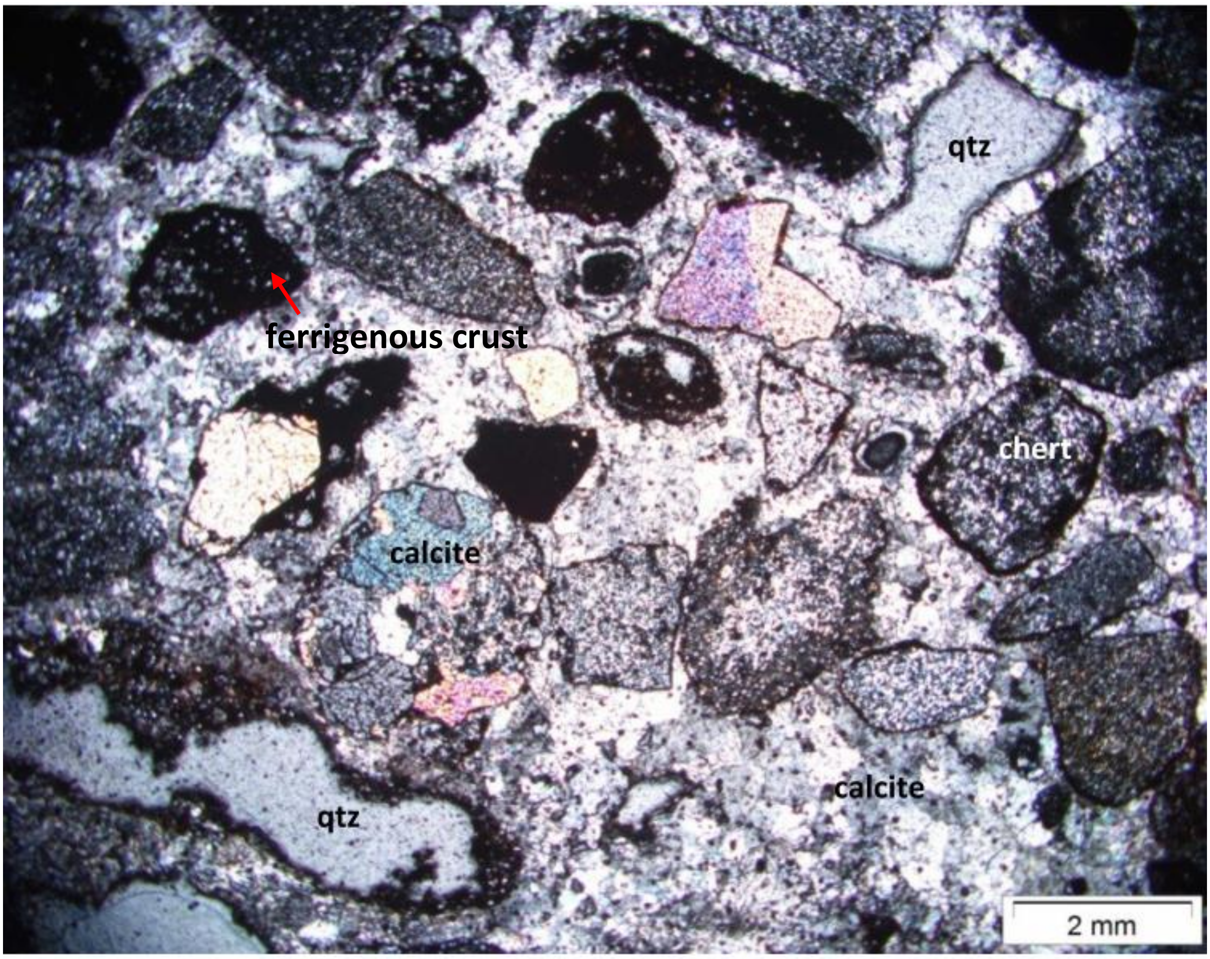



*Figure 4.8. Photomicrograph (XPL) of facies Gcm (c) showing cementation with subrounded grains and Fe rimming (bottom left grain of quartz).*

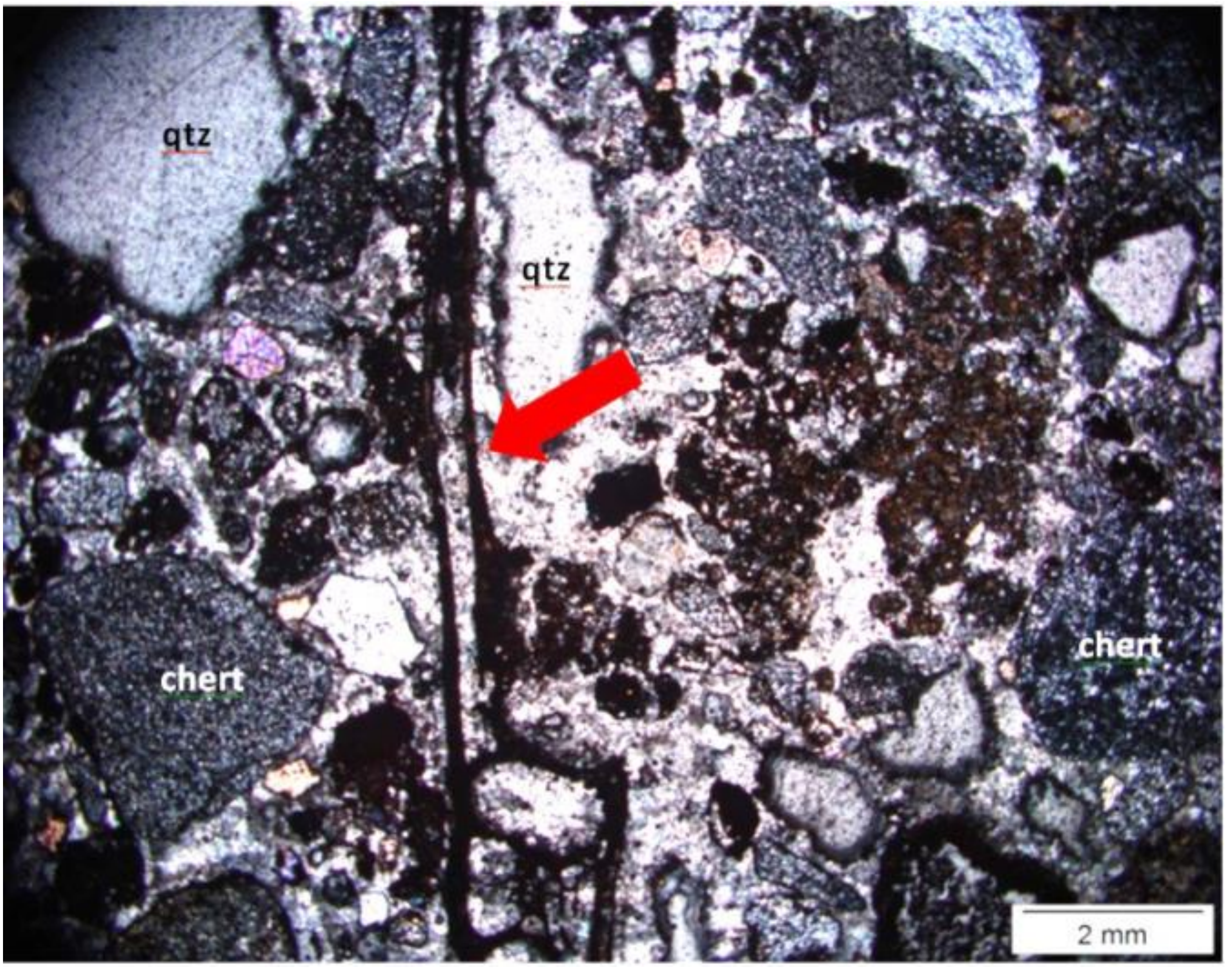
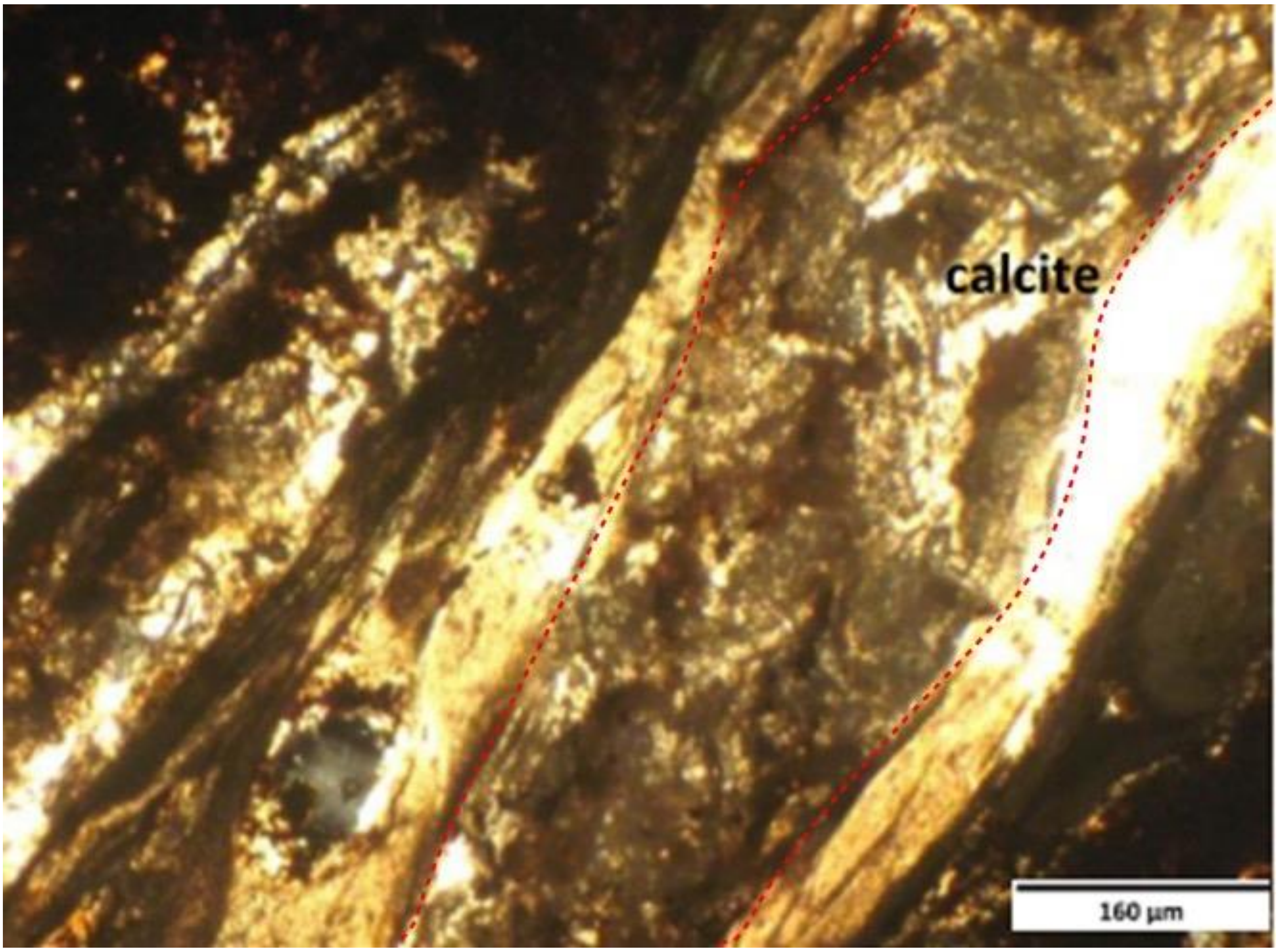



*Figure 4.9. Photomicrograph (XPL) of facies Gcm (c) showing fossil bone shaft (indicated with arrow) with calcite filling in the yellowish red unit.*


calcite
160 µm

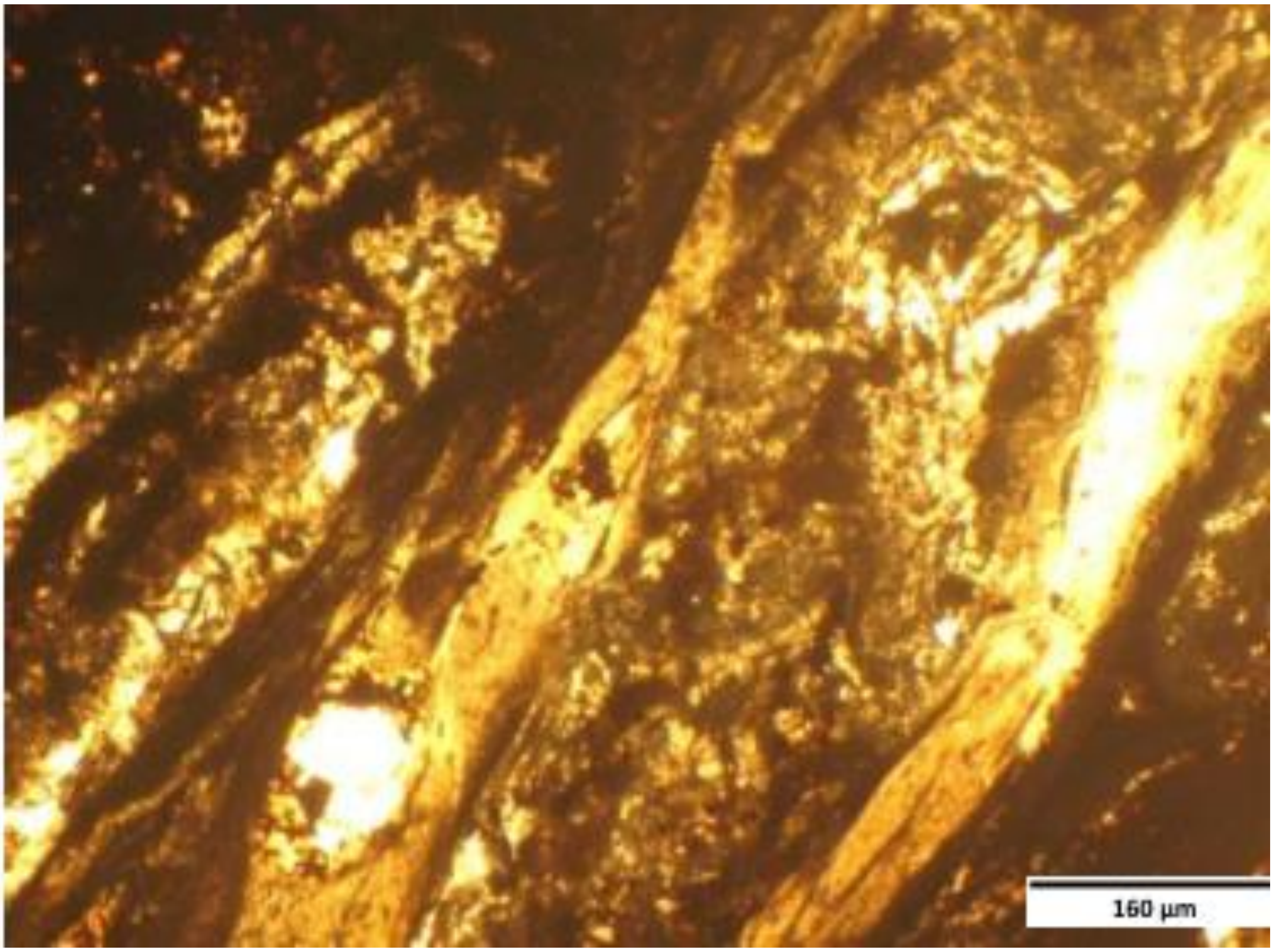



*Figure 4.10. Photomicrograph (XPL and PPL- plane polarized light) of facies Gcm (c) showing calcitic growth in skeletal elements (elongate structures).*

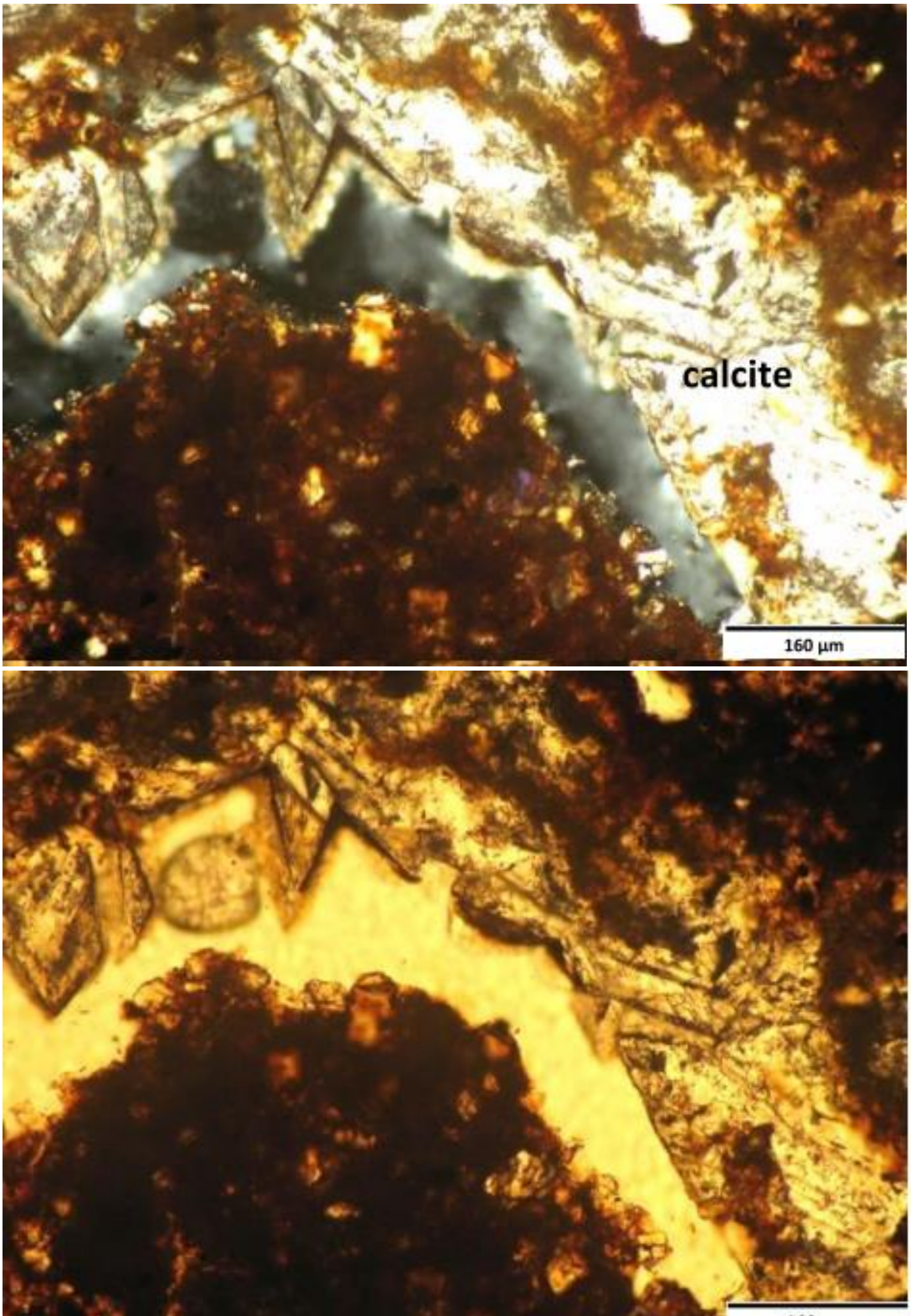



*Figure 4.11. Photomicrograph (XPL and PPL) of facies Gcm (c) showing calcitic growth in void spaces.*

*Matrix supported massive breccia - Gmm*

This facies is common and appears as pockets (largest ~45 cm) in both the Main Jacovec and Thulasizwe chambers. There are no sedimentary structures present. Much like the massive gravels, it is very chaotic and poorly sorted. The facies present slightly more rounded, more spherical clasts which have a narrower clast range (0.5 cm to 8 cm). The matrix makes up the larger proportion of the sediment with the very large clasts being scarce (Figure 4.12). Colours include is dark brown (5YR 3/2) and greyish brown (2.5YR 4/2).

In thin section, it is very ferric hence the highly isotropic appearance. The clasts of the unit are mostly quartz, ferruginous crust, cherts, as well as a few micas and rock fragments. These clasts are spherical, well sorted (at 0.5 to 0.2 cm) but subangular to subrounded. The matrix is mostly composed of quartz, ferruginous crust, chert, some rock fragments as well as mud clasts (Figure 4.13). It is a very well sorted matrix with close packing of grains thus very little interstitial cement material is present. There is presence of ferric alteration of the quartz grains. (Figure 4.14)

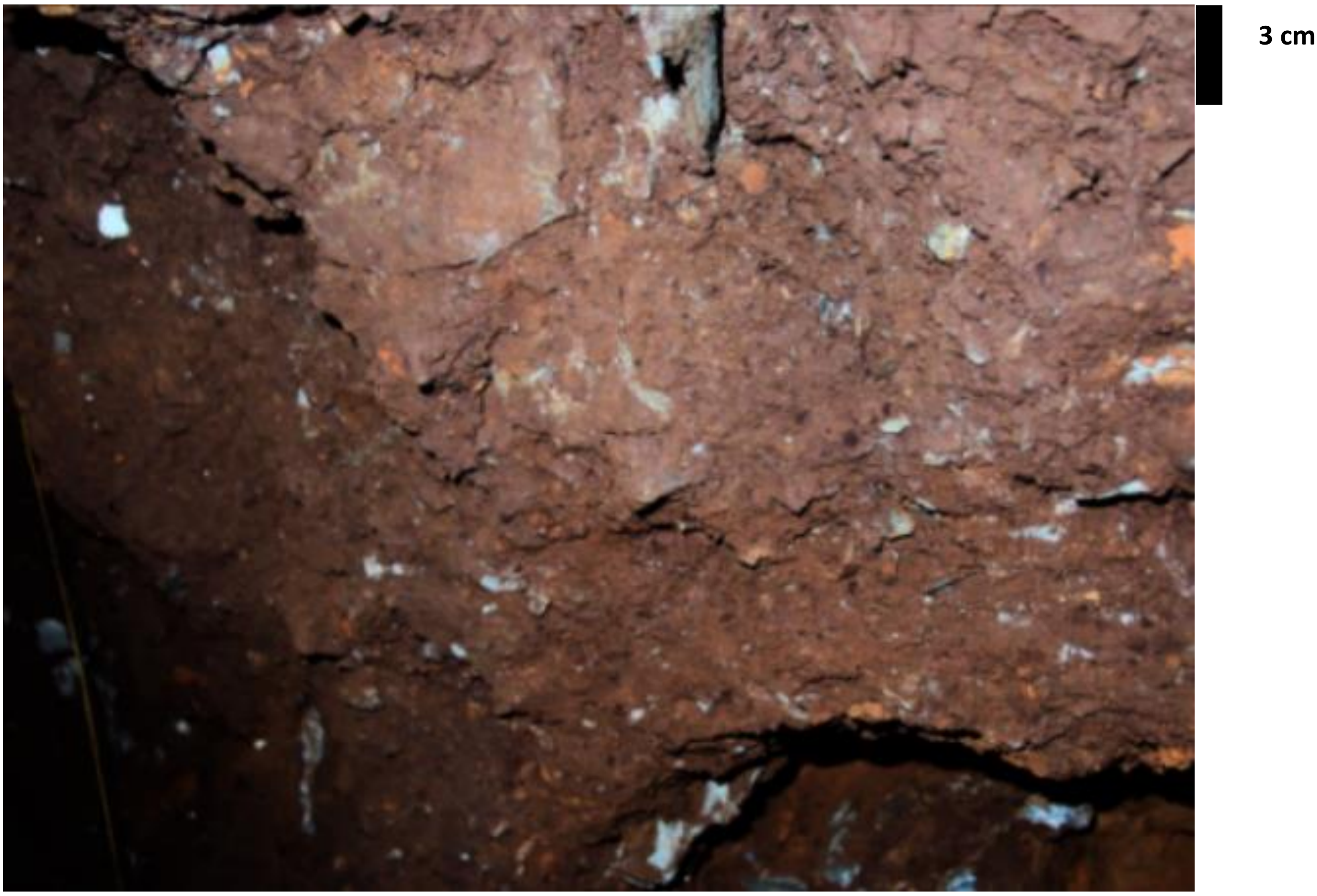



*Figure 4.12. Facies Gmm facies in the Thulasizwe Chamber.*

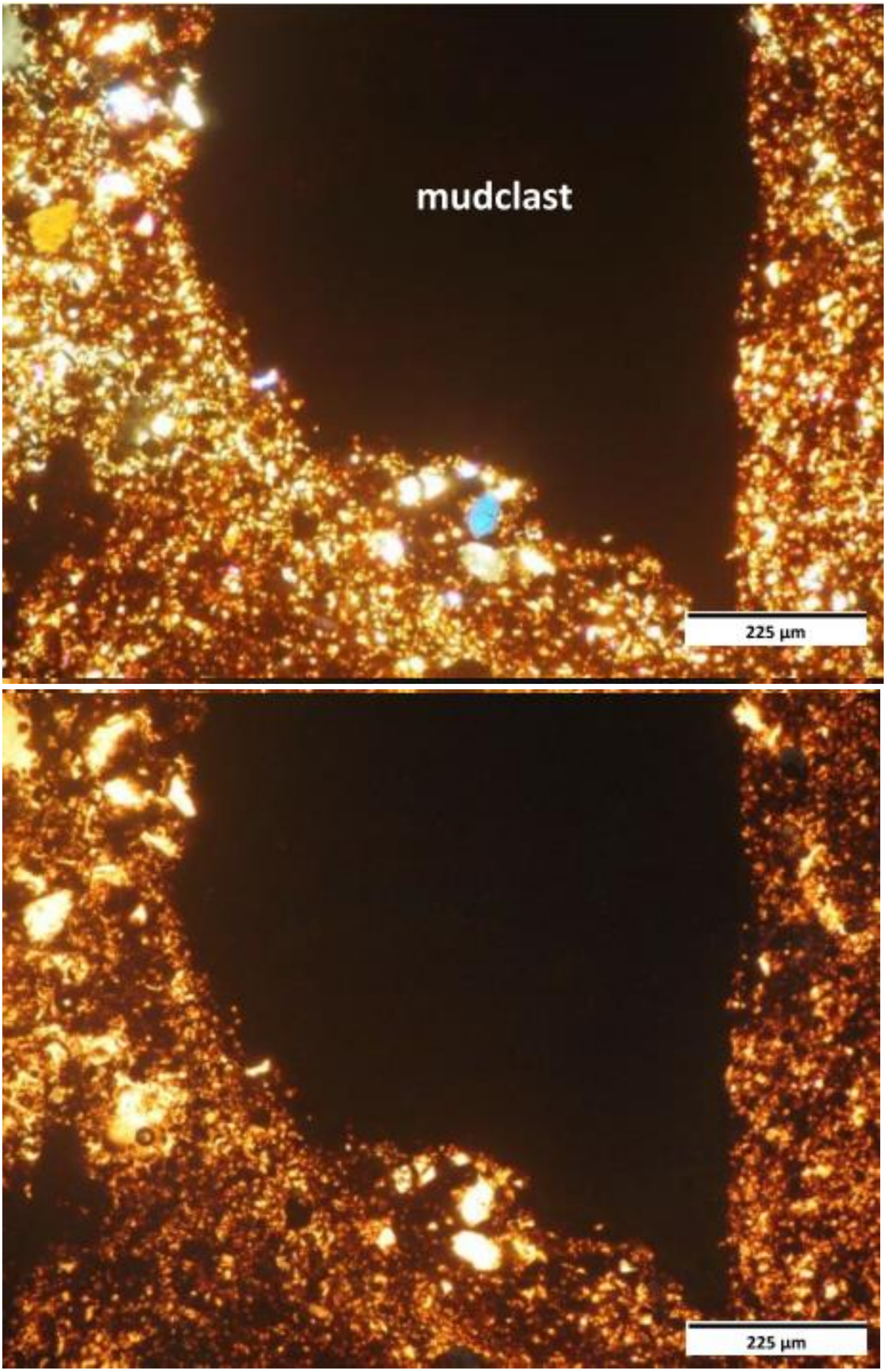



*Figure 4.13. Photomicrograph (XPL and PPL) of facies Gmm showing mud clast in matrix of silt unit.*

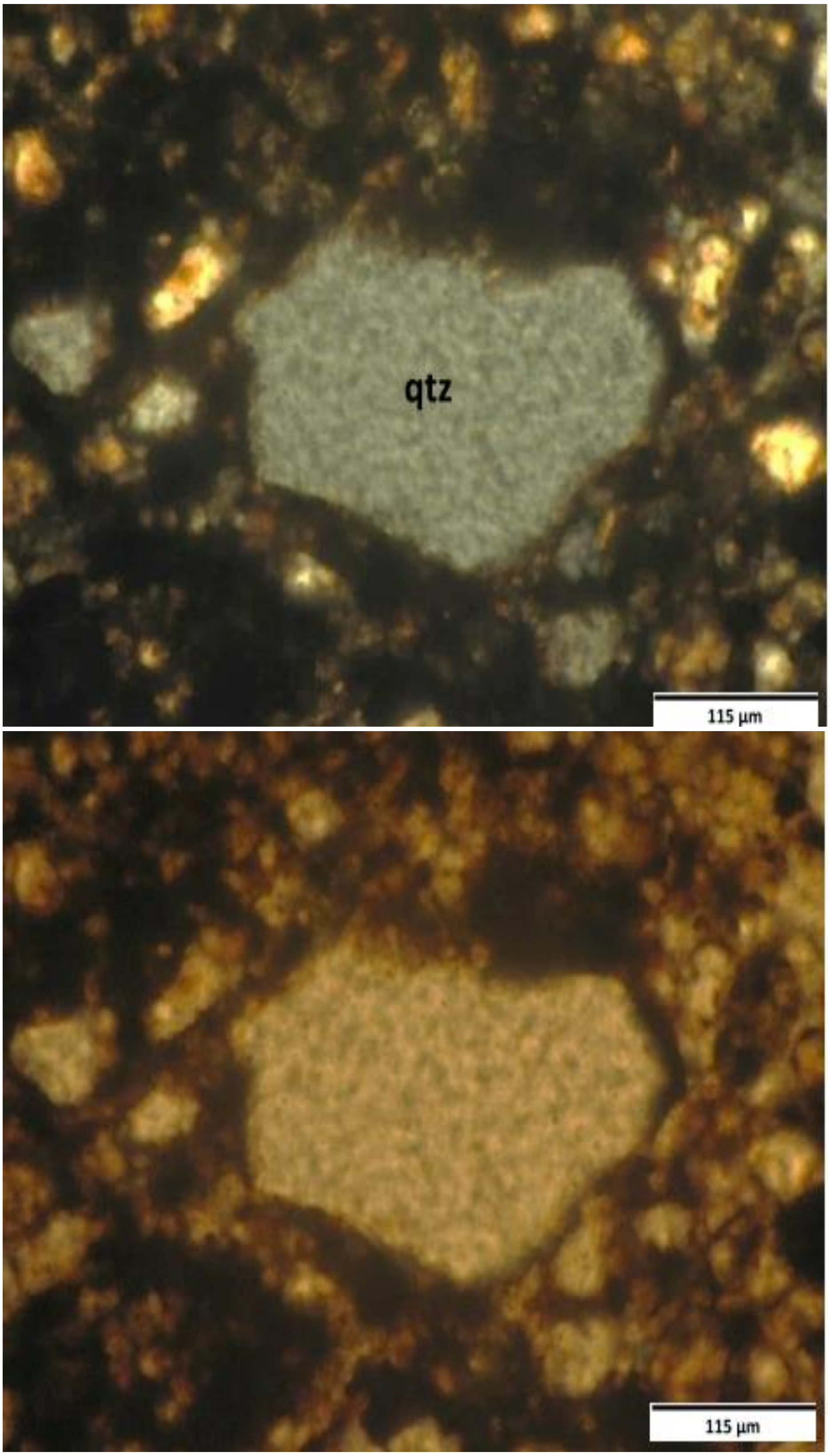



*Figure 4.14. Photomicrograph (XPL and PPL) of facies Gmm showing ferric rimming around angular quartz grain.*

*Massive Clay/silt and sand - Fm*

This facies is restricted to the uppermost section of the Thulasizwe Chamber and prominent in the Main Jacovec Chamber. Thicknesses average at around 7 cm, but some beds may be as thick as 15-20 cm. It is characterized by having sand and silt particles and no internal sedimentary structures. There is variation in colour; yellowish red (5YR 5/6), dark yellowish brown (10YR 4/4), very pale brown (10YR 7/3) and pale red (2.5YR 6/2). There is variation in silt-sand ratios. There are also occasional larger, angular clasts (about 2 to 15 cm in size) some of which can be bioclasts (Figure 4.15).

In thin section, this facies is mostly moderately sorted. The grain size ranges between silty sands and sandy silts. It is homogenous and highly isotropic making mineralogy difficult to decipher. From the decipherable grains, it is quartz and chert rich. The sediment does however contain some large clasts, but they are infrequent (Figure 4.16). The grains are spherical and subrounded.

*Figure 4.15. Facies Fm in the Thulasizwe Chamber.*

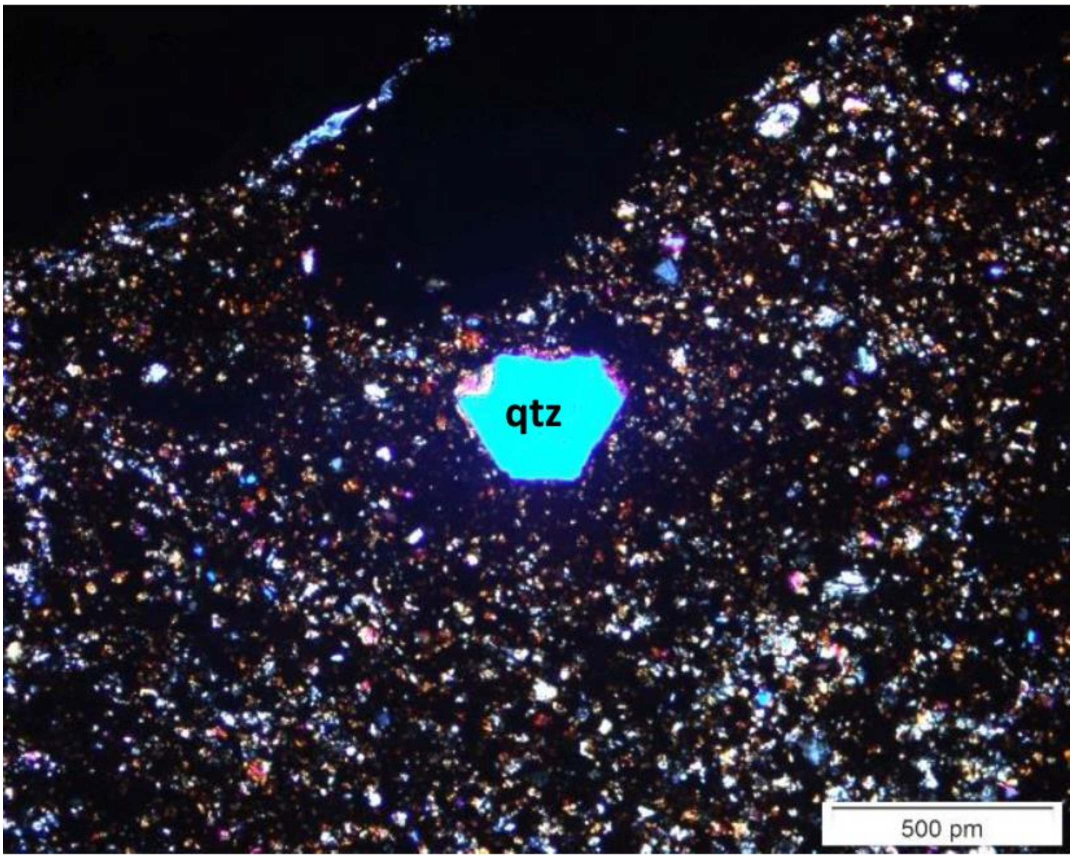



*Figure 4.16. Photomicrograph (XPL) of Facies Fm large infrequent clasts in a massive sediment.*

*Horizontally bedded sands - Sh*

This facies occurs in the top parts of the Thulasizwe Chamber exposure and in the upper parts in section A-B of the Main Jacovec Chamber (Figure 4.17). The overall thickness in the Thulasizwe Chamber is 10 cm while thicknesses in the Main Jacovec Chamber are about 10-15 cm. The facies is seen in Thulasizwe Chamber in a yellowish brown (10YR 6/8) colour and dark yellowish brown (10YR 4/4) or very pale brown (10YR 7/3) in the Main Jacovec Chamber. The grain size has a limited range (average grain size is between coarse to medium sand) making it very difficult in hand specimens to distinguish a clast-matrix boundary. Individual beds 0.5-1 cm thick although thicker beds can get up to 2 cm.

Microscopically, individual beds are homogenous. They have internal bedding but lithologically similar between beds (Figure 4.18). There is moderate sorting with a silt dominance. The unit is quartz-rich and less ferric than most of the other facies.

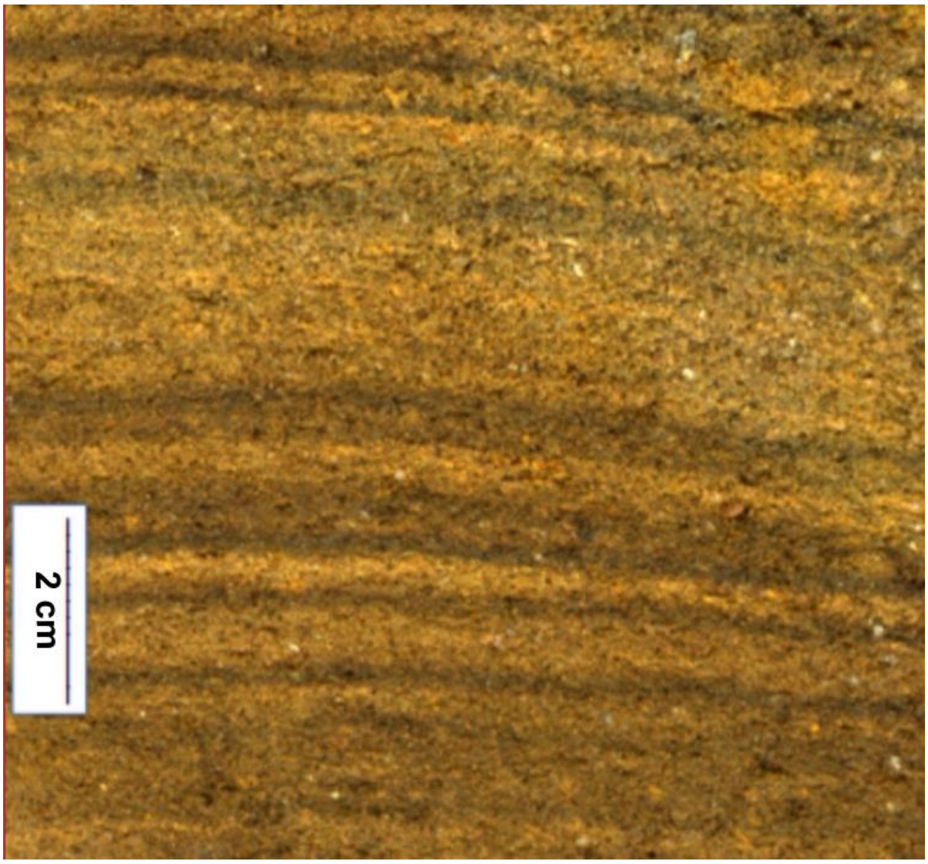



*Figure 4.17. Facies Sh in the Thulasizwe Chamber.*

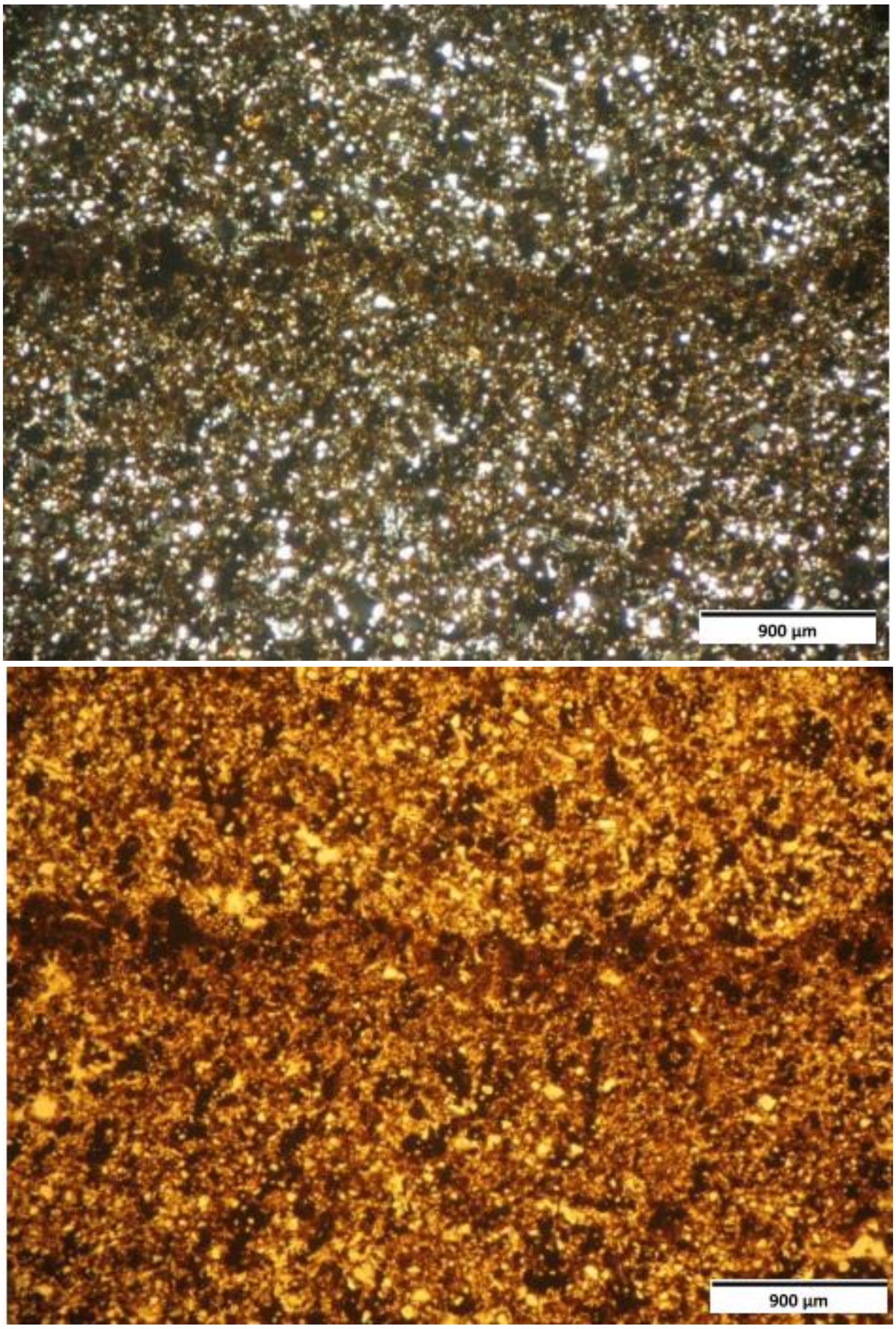



*Figure 4.18. Photomicrograph Facies Sh in Main Jacovec Chamber.*

### *Horizontally laminated fines - Fl*

This facies is found in various parts of the Thulasizwe Chamber exposure with variable thicknesses. It is characterized by silt and clay interlaminate. There are colour differences at various parts of the chamber. The clays are a dark brown (7.5YR 3/3) or black (5YR 2.5/1) and homogenous while the fine sands and silts (less sorted) are reddish yellow (7.5 YR 6/5). Laminae thicknesses vary, but silt laminae are generally thinner (average at 1.5-2 mm) than the clay laminae (average 4 mm) (Figure 4.19). The sand/silt units demonstrate some degree of sorting (moderately to poorly sorted).

Under thin section, this facies is characterized by having oscillatory units of silt/sandy and mud laminae (Figure 4.20). There is an abrupt contact between the laminae. The mud laminae are homogenous, highly isotropic and matrix supported with a wide thickness range (0.5 cm to 3 cm). It is mainly composed of quartz (monocrystalline) and ferric components (in the form of spherulite) while other notable minerals are chert, micas), and trace amounts of rock fragments. There is a range in silty/sandy laminae thicknesses that with an average thickness of 2 cm through various parts of the section. The composition of the sandy/silty laminae is mostly quartz and ferric components of clast grains are moderately to poorly sorted subrounded grains. It is interesting to note that the mica grains are usually long, extensive and tabular in shape and are present throughout the entire unit (Figure 4.21). There is also alteration of quartz by calcite (sparite) as observed in the small bright, high interference colour specules on the quartz grains. The facies contains ferrobacteria (usually agglomerated) as seen through the highly isotropic nature of the facies (Figure 4.22). The grain subrounding, can be attributed to Fe- rimming. Sphericity of grains varies but generally becomes more spherical with decreasing size.

*Figure 4.19 Facies Fl with turbation (microfaulting).*

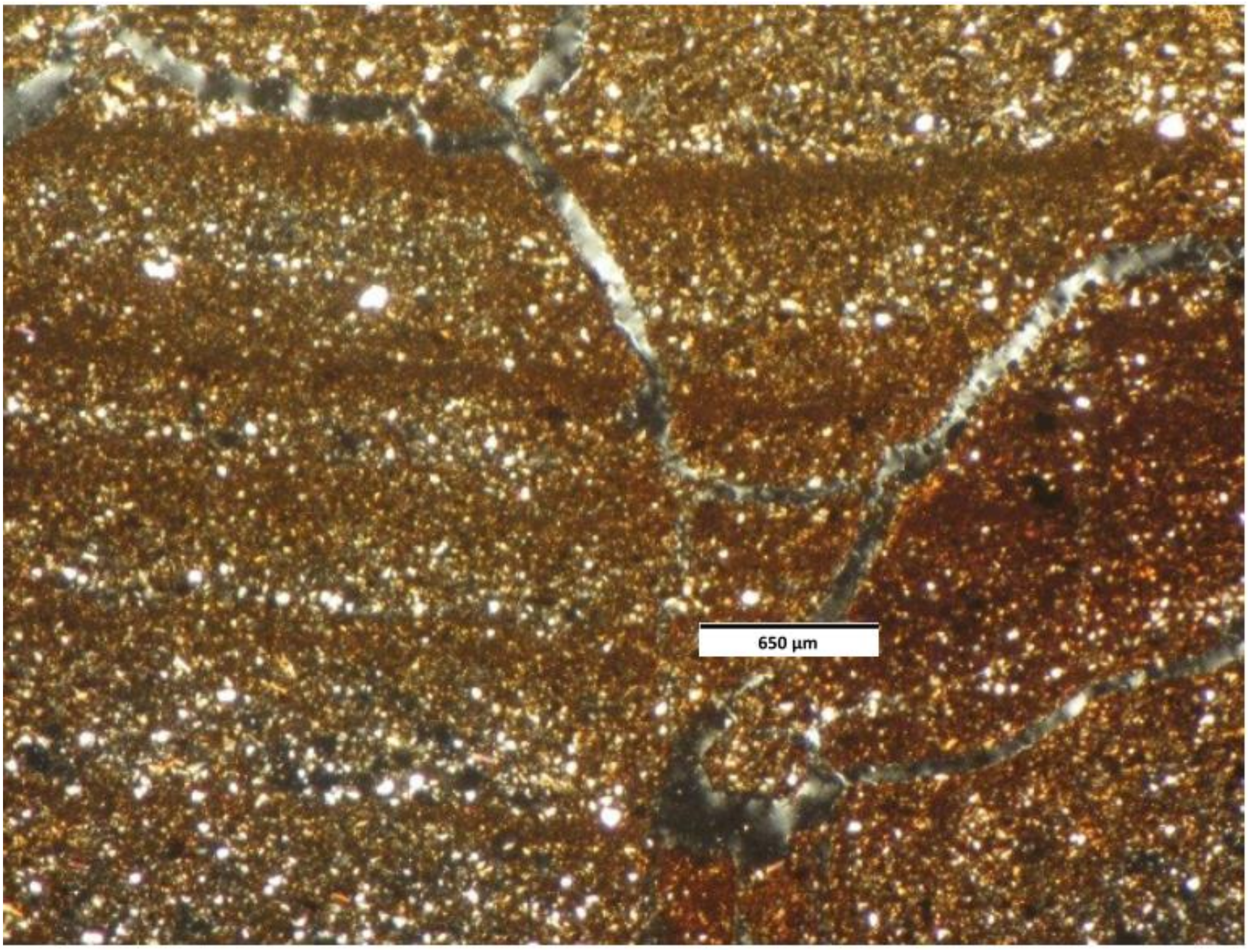



*Figure 4.20. Photomicrograph (XPL) of facies Fl showings sandy/silty-mud interlaminae.*

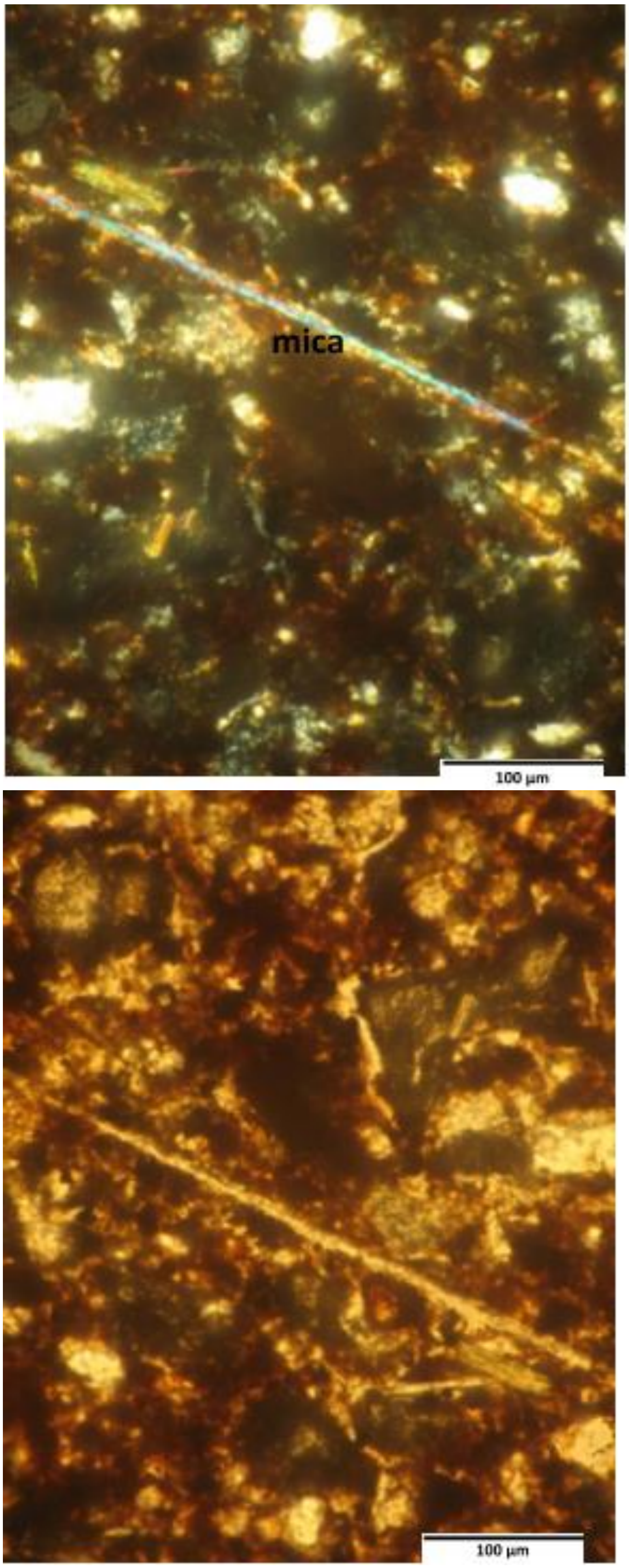



*Figure 4.21. Photomicrograph (XPL and PPL) of facies Fl showing tabular micas depicting depositional orientation.*

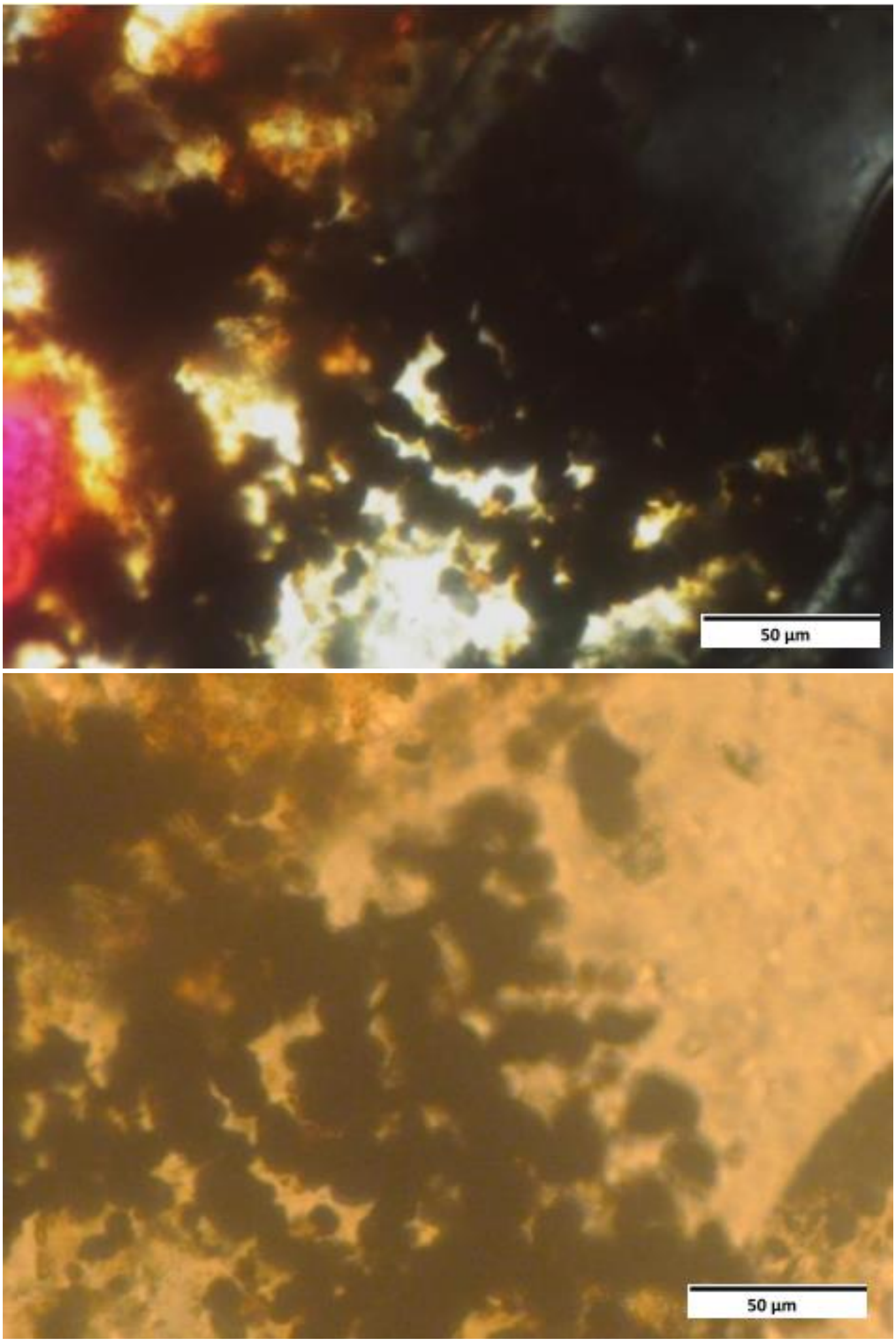



*Figure 4.22. Photomicrograph (XPL and PPL) of facies Fl showing agglomerated ferrobacteria.*

*Flowstone facies - P*

Flowstones are found in the Main Jacovec Chamber. Section A-B has a laterally extensive flowstone which is approximately 35 cm in maximum thickness. These are calcium carbonate sheets that occur on the wall as well as on top of and between sediments infiltrating void spaces from above. In the exposure, it lies conformably around and above the breccia and it is perturbated by host rock (dolomite) (Figure 4.3). In addition, there are fragmented flowstones present as clast inclusions in both Jacovec Chamber sections.

#### ***4.1.2. Cave facies associations***

Caves can be seen as larger sedimentary traps in which various debris and sediments can accumulate (Flügel, 2004). The clastic karst scheme of Bosch and White (2004), as adapted by White (2007) shall be followed. This scheme is based on the notion that the clastic particles deposited into the karst system are part of the sediment record (White, 2007; Flügel, 2004). In addition to the assignment of facies association, terminology of previous work in the Thulasizwe Chamber, by Partridge et al. (2003) and Kibii (2000), shall be mentioned (Figure 4.1). This Bosch and White (2004) classification is arranged according to particle size and degree of sorting.

*Slackwater facies*

The common slackwater facies is represented in the Jacovec sequence. It is found in the upper parts of the Gravelly Unit as well as the basal thinly-bedded clay-silt. The thinly-bedded clay-silt is the deepest of the exposed units in Thulasizwe Chamber. The unit is 2.3 m thick and reaches a maximum length of 2.5 m. There are some very fine sand laminae present in the unit (<1 cm thick). It is characterised by clay and silty interlaminates (Fl) which average 1 cm in thickness. Post depositional deformation structures are apparent in the unit as either slumping or microfaulting (Figure 4.19).

These apply to the sequences of laminated, fine-grained clays and silts (Fl) transported into the system in suspension. The sediments are introduced by muddy waters in the cavity openings. Rising waters (from either water table or blockage pools) fill all available spaces and become ponded for extended periods of time, at which the suspension load begins to settle out and form a sediment layer (Bosch and White, 2004). These form as the top unit of a clastic deposit and are associated with blind side passages, pockets and other cave niches where flowing streams are unlikely to occur (White, 2007). Considering fall velocity varying with the square of particles (as per Stokes law), the clay and silt can be transported for several kilometres with a falling distance of less than the conduit's diameter (Bosch, 2015). This facies can be deposited from a suspended load which is carried in the normal flow direction or from suspended load in water back-flooded possibly from surface streams (Bosch, 2015).

*Diamicton facies*

These are seen in the Gravelly Unit of the sequence. This unit has an erosional contact with the underlying thinly-bedded clay-silts

This is seen with the irregular contact, as well as by basal thinly-bedded clay-silt inclusions in the lower part of the section. It is also very poorly consolidated and porous. It is the thickest unit in the sequence with a maximum height of 5.2 m and width of 3.5 m. The unit is generally very chaotic (massive sediment with no imbrication or orientation of clasts) with some areas showing grading (both reverse and normal). Although chaotic, it is noticeable that some parts of the unit are clast supported (Gcm[u]) but most of the unit is matrix supported (Gmm). The unit occurs very remotely with an average thickness of 1.3 m. This bed has very thin laminae (~0.5 cm). There is also turbation in the form of microfacturing (Figure 4.19) in the laminae.

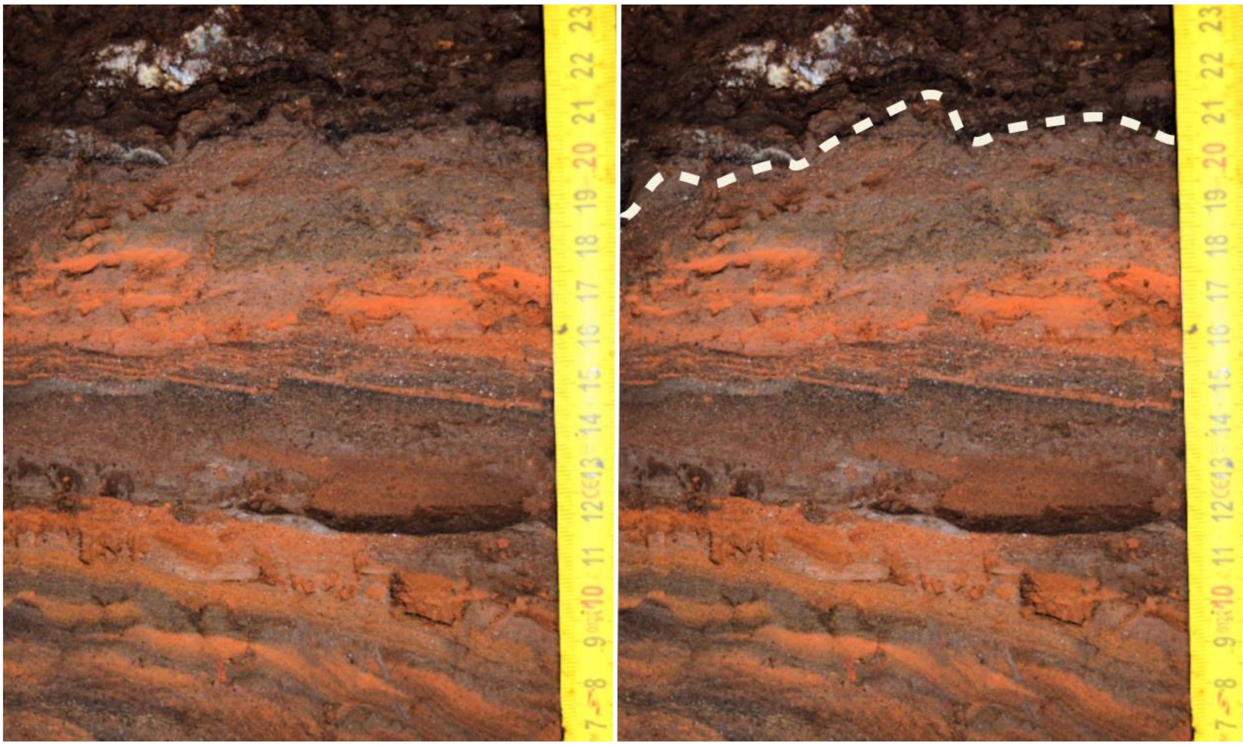


*Figure 4.23. Erosional contact between basal thinly-bedded clay-silt and Gravelly Unit.*

They are chaotic deposits with a widely varying grain size, from clays to boulders in a deposit that contains no sorting or bedding (White, 2007; Bosch, 2015). Clasts are usually angular in a fine grained, sub-mature (subangular-rounded) matrix (Bosch and White, 2004). They require a lot of energy for transport and therefore deposits are associated with high gradient dipping drainage basins and passages.

These are interpreted as debris flows, where the whole sediment is caught and moves as a suspended load. Specific processes for the debris flows include debris avalanches, mudflows and colluvial slumping that lead to a decrease in depositional energy (Gillieson, 1985). They are also associated with old deposits suggesting conditions of higher energy flooding events (Bosch and White, 2004).

*Channel facies*

This is represented by the Orange Breccia unit of the sequence (Figure 4.2). This is the facies associations that erosionally overlays the Brown Breccia (Figure 4.2). It occurs widely around the chamber and has a maximum thickness of 1.7 m. The exposure varies in the Thulasizwe Chamber but can be correlated across strike around the chamber. The dominant grain size is sands (very fine to coarse; Fm, Sh) as well as abundant occurrences of silts (Fm). Some less frequently occurring gravel units are also present (Gcm [c]). The bedded sand horizons are composed of more mature, moderately sorted, low-spherical, subrounded grains. Some of the massive sandstones are as mature as the bedded horizons, but usually tend to be more angular, poorly sorted and contain more bioclasts. The conglomerate units are usually submature; moderately sorted, clast supported, imbricated, polymictic and fossiliferous. The laterally extensive beds can demonstrate upward fining and upward coarsening sequences as the lithologies change between facies.

The cave channel deposits as suggested by Bosch and White (2004) are those sediments with a degree of sorting by transport along a conduit (Bosch, 2015). They consist of distinct beds of silts, sands and gravels (Bosch and White, 2004; Bosch, 2015). There is constrained bed sorting within the units, but they change rapidly along section (Bosch, 2015).

*Breccia facies association*

Usually common in karst sequences, carbonate breccias are mostly angular and rounded rock fragments cemented (or uncemented) to a finer grained matrix (Flügel, 2004).

This is represented by the Brown Breccia deposit in the Thulasizwe Chamber sequence and both sections in the Main Jacovec Cavern (Figure 4.3).

In the Thulasizwe Chamber, this facies association (Figure 4.2) lies conformably (abruptly) above the Gravelly Unit and is well preserved in the eastern exposure. It has a maximum thickness of 2 m, but averages around 1 m in most of the section. The dominant clasts in the unit are chert, quartz, bioclasts (vertebrate) and volcanic tuff. The unit consists of a very consistent lithology throughout the section but is composed of a lower orthobrecciated horizon (Gcm [u]) which grades to an upper parabrecciated horizon (Gmm). The orthobreccia section is a clast supported immature sediment polymictic, poorly sorted, with highly angular low sphericity clasts. The occurrence of the upper parabreccia appears gradational with a better degree of sorting and a higher frequency of bioclasts. The bioclastic material is fragmentary, with most elements unidentifiable and angular bone fractures. The facies association is partly, locally and randomly cemented (by calcite as confirmed by petrography).

This is a polymictic, poorly sorted matrix sediment. There is increasing matrix support upsection (grading). It is the deposit of assorted angular/subangular rock clast fragments in a finer grained matrix with very poor fitting (Latham, 1999; Flügel, 2004). The clastic material present is from the cave earth (the insoluble host rock material) as well as bone and teeth fragments (Latham, 1999).

This deposit represents a boulder choke, a largely uncemented rock debris. This choke arises by a mechanical readjustment of the stress field in an enlarging cave. This is done by stoping, the spalling off of roof and wall rock (Ford and Williams, 1989; Latham, 1999).

*Flowstone facies - P*

Found in the Main Jacovec Chamber, flowstones are speleothems that have been horizontally laminated (Moriarty et al., 2000). Sedimentary deposition in a cave is associated with specific events. Upon this temporal cease in deposition, it has been demonstrated that it is indicated by the development of flowstones (Moriarty et al., 2000).

**41.3. Geochemistry (X-Ray) of facies associations**

The geochemical analysis aimed at complementing quantitative sedimentological work of facies associations in the Thulasizwe Chamber. In the major element signal, silica ($SO_2$) is the most abundant compound in all facies associations in the Thulasizwe chamber (Figure 4.24). This is consistent with the prevailing mineralogy identified in thin section i.e. quartz and chert. CaO is typically less common, with the exception of the Orange Breccia and represents the calcic cementation/alteration and high prevalence of calcite identified in the facies. Other common compounds include FeO, MnO, MgO and $K_2O$. The abundance of these ferro/manganese oxide (mineralogically as well as post depositionally with ferrobacteria) throughout the chamber accounts for the observation of the highly isotropic petrographic sections as well the prevailing dark brown colour observed in the exposure.

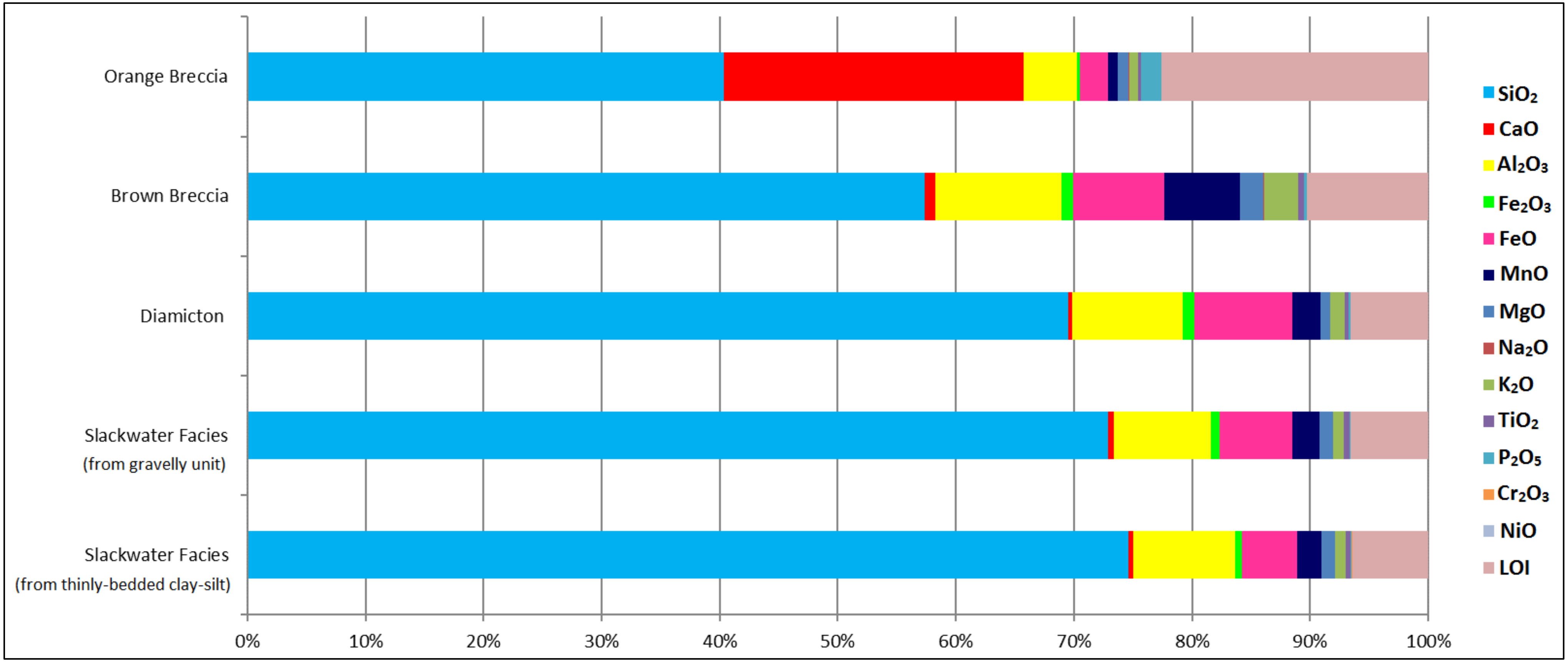



*Figure 4.24. Graph showing major element chemical proportions of each facies unit.*

### 4.1.4. Summary

The described lithofacies, whose codes are derived from Miall (1996, 1999) have been assigned to lithofacies associations within previously established sedimentary unit of the Thulasizwe Chamber. Therefore, these lithofacies associated can be classified into depositional framework, similar to that of Bosch (2015). This framework is summarised in Table 4.1.

| **Facies Code** | **Facies** | **Sedimentary Structures** | **Interpretation** |
|---|---|---|---|
| Gcm (c),<br>Gmm | Breccia - clast supported,<br>Breccia -matrix supported | Grading (more matrix or more clast supported) | Boulder choke karst deposit |
| Gcm (c),<br>Fm,<br>Sh, | Massive gravels,<br>Med to coarse sands/silts; massive and bedded | Conglomeritic beds, massive and horizontally bedded, upward fining and coarsening sequences | Channel karst deposit |
| Gmm,<br>Gcm (u) | Matrix-supported massive clay to boulder | Unbedded, poorly sorted, polymictic, chaotic | Diamicton karst deposit (debris flow) |
| Fl | Very fine silts to clays | Horizontal interlamination | Slackwater karst deposit |
| P | Calcium carbonate precipitation | Horizontal lamination | Speleothem |

*Table 4.1. Classification of the sedimentary facies in the Jacovec cavern. Adapted from Bosch (2015), using Miall (1996) facies codes convention.*

# 5. Discussion

The sediments of the Jacovec Cavern are particularly interesting as they represent the most extensive siliciclastic deposits in the Sterkfontein Cave System. This makes them very distinct from other deposits in the cave system and thus formed under different conditions which are explored in this chapter.

### *5.1. Cave input, provenance and accumulation dynamics*

The Jacovec Chamber has a long history of sedimentation as seen through deposits in respective chambers as well as lithologically diverse deposits. This project aimed to clarify the punctuation of these deposits to contextualise the Jacovec Cavern stratigraphy in the larger Sterkfontein Cave System.

The mineralogy provided good insight into the sources and constraints of the sediments. For the lower deposits (Basal thinly-bedded clay-silt and Gravelly Unit), the sedimentary sequence in the Thulasizwe Chamber consistently contains host rock minerals; quartz (monocrystalline, polycrystalline and chert) micas, dolomite and ghost rock remnants (sparite). This host rock material is obtained from the path of the conduit as the deposit is being transported to the chamber. The immaturity of clasts (non-spherical, angular) suggests sources are nearby; within the cave and any network conduits. In the upper units (Brown Breccia and Orange Breccia), there is significant proportion of allogenic clast and matrix material being deposited, such as ferruginous crust and fossils whose sourcing is harder. Although this material can be attributed to the surface, the location (and thus distance from the cave) is difficult to decipher and can owe their provenance to a variety of sources. Fossil bone material is from the surface as this is where fauna would have entered the cave through pits (Kibii, 2004, 2007). The presence of feldspars and micas can be attributed to the volcanic ash interbedded in the host rock and surface shale outcrops (Schellmann, 1994; Stratford, 2001). Other sources include outcrops from siliceous dykes and breccias exposed on the surface. The entire sedimentary section is also rich in aluminum, manganese and iron which can be attributed to the cave dolomite alteration. This has been previously suggested by Bruxelles et al. (2014)

The breccias of the Main Jacovec Chamber also have a similar lithology to the Thulasizwe Chamber, resembling host rock lithologies (quartz, dolomites, cherts, reworked clays) and those derived from outside the cave system (fossil bone, ferruginous crust). In the sediments of the Thulasizwe Chamber, it is difficult to establish a general sediment flow direction or trend as there is lack of sedimentary structures and turbation in the facies presented. However, the presence of tuff seam mineralogy in the sequences constrains the source direction. Understanding that the beds of the host rock (and interbedded tuff) dip $30^{o}$ NW and an outcrop of the tuff is observed at the end of the tourist route (which can be extrapolated along dip) and the relative position of the cave in relation to the tuff (Figure 5.1), one can constrain the path to which sediments would take in order to reach the Jacovec Cavern while carrying these lithologies. This places the flow and entrance to the south, in a more elevated ground surface than seen today.

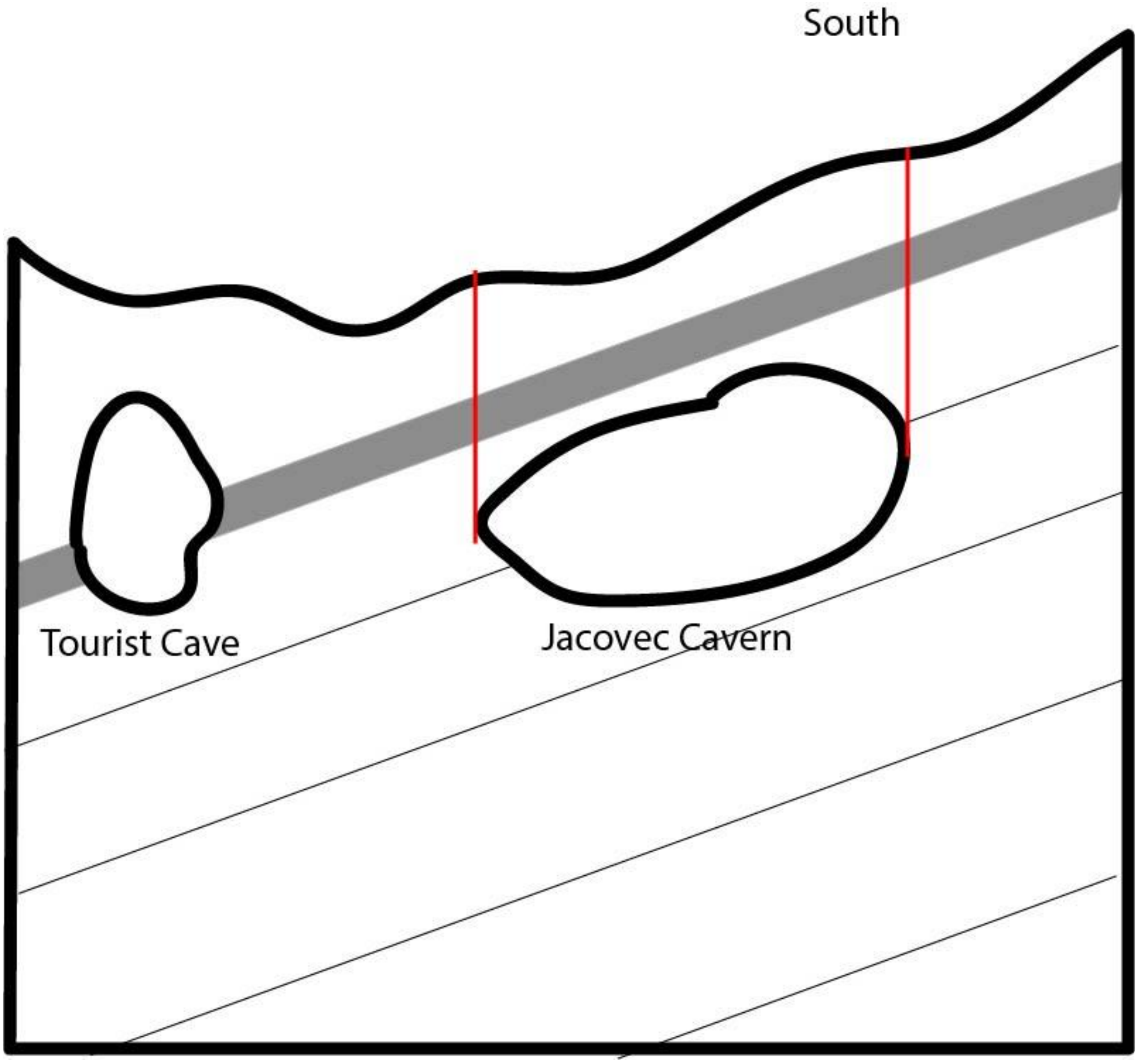


*Figure 5.1. Schematic showing tuff extrapolation in relation to Jacovec Cavern for sourcing direction (not drawn to scale)*

### *5.2. Deposit alteration*

Alteration is evident in the chamber and happened during and after the deposition. This alteration could have been caused by biotic and/or abiotic factors. As revealed by the petrography, ferrobacteria was a contributing biotic factor. This active process is very prominent in rock and mineral weathering and thus promotes dissolution and diagenesis of minerals (Ehrich, 1998). In this case, the microbial weathering action is probably caused by mineral constituents (especially manganese and iron, Figure 4.40) that are being reduced or oxidized (Ehrich, 1998). Microbial action could also have contributed to the weathering of silicas and carbonates, as they are also susceptible (Ehrich, 1998). This microbial abundance suggests pedogenic activity occurred in the cave, at a time when the cavern had access to the surface. The commonly occurring ferrigenous crust that appears as clasts in the sediments (mostly in the Thulasizwe Chamber and the Main Jacovec Chamber) could have derived from eroded paleosols (Figure 4.8). Another interesting feature is the presence of amorphous silica-carbonate precipitations found in both chambers of the Jacovec Cavern (Figure 4.9). This can arise from an acid-water submerged medium. This could have occurred at any stage of cave development (post depositionally) granted the required chemistry and longevity of the medium is present. Therefore, it would be difficult to understand the punctuation of this epigenesis. One possible cause of this epigenetic process could have been from the ghost rock alterite as suggested by Quinif (2011).

### *5.3. The stratigraphy of the Jacovec Cavern*

The Thulasizwe Chamber and the Main Jacovec Chamber (Figure 1.2) have no sedimentological connection despite the geological structure of the cave restraining them to the same cavern. The proposed lack of sediment interaction is based on the abrupt vertical deposit termination observed in Section C-D (Figure 5.2). This termination suggests that the passage leading from the Main Jacovec Chamber to the Thulasizwe Chamber was blocked at some point, stopping deposition from occurring further east of the Main Jacovec Chamber, where the Thulasizwe Chamber is located. Because the deposits in these two chambers represent two distinct sequences, it is justified to consider them as two different chambers within the Jacovec Cavern. In order to determine a cave's origin the overall pattern of the cave and passages must be understood (Palmer, 2007). In the Thulasizwe Chamber, there seems to be no current evidence of an entrance. The Main Jacovec Cavern has very limited deposits but Section C-D is located and open to the portion of the tourist route that lies north of the Fossil Chamber.

The stratigraphic sequence of the Thulasizwe Chamber was reported by Kibii (2000) and Partridge et al. (2003)'s chronostratigraphic research. Kibii (2000) investigation revealed nine different rock types from the collapsed section. Partridge et al.'s (2003) investigation revealed three stratigraphic units, a basal sediment, overlain by a Brown Breccia and finally a matrix-rich Orange Breccia where the Brown Breccia undercuts the older Orange Breccia. This investigation has demonstrated that there are in fact four sedimentary packages and that this includes a deeper clay-silt/sand/gravel laminated unit. The facies analysis also revealed that the basal sediment suggested by Partridge et al. (2003) is a diamicton facies sediment (capped by a slackwater facies) from debris flows moving particles as a suspended load. The cosmogenic nucleotide dates show a reverse stratigraphy in the upper two deposits where the underlying Brown Breccia is younger than the overlain Orange Breccia. However, the observation of Brown Breccia inclusions at the erosive base of the Orange Breccia suggests that the Brown Breccia preceded the Orange Breccia deposition. The observation of a reverse stratigraphy from the work of Partridge et al. (2003) can be attributed to the large overlap of cosmogenic date. In addition, the proximity of Partridge et al.'s (2003) stratigraphic controls lie very close to the redeposited sediments. These redeposited sediments have disproportionally more Brown Breccia material than Orange Breccia thus giving the impression of Orange Breccia as inclusions (Figure 5.3). Kibii (2000)'s collapsed rock type classification is limited as there is no stratigraphic context for the units and their interaction with each other. Additionally, it does not link the lithologies observed to a sedimentological framework that could be used to determine the depositional history of the cavern.

*Figure 5.2. Termination of sediment on wall (left).*

*Figure 5.3. Orange Breccia 'inclusions' in Brown Breccia from a redeposited sediment on the west exposure of the Thulasizwe Chamber.*

### *5.4. Stratigraphic positioning of the Jacovec Cavern in the Sterkfontein Formation*

Within the entire Jacovec Chamber, the presence of a constricting wall between the Thulasizwe Chamber and the Main Jacovec Chamber makes it difficult to correlate and relate stratigraphically. More work in dating methods need to be applied to stratigraphically link these deposits. In this case, the Thulasizwe Chamber may have had its own entrance, but would still be lithologically constrained by the same parameters as outlined above (Figure 5.1). If it had its own entrance, it would be located more to the south east. The stratigraphic placing of the Jacovec Cavern within the context of the Sterkfontein Formation has been a topic of debate. Partridge et al. (1991) suggests that the BH4 terminates as it intersects the dolomite (Figure 1.1). This borehole sits directly above the Main Jacovec Chamber (near the section A-B). After following the vertical extent (filling it with water) it led to a delayed drip into the Main Jacovec Chamber. This delayed drip is from cavities or joints within the dolomite which eventually lead to the Jacovec Chamber. This implies that Partridge et al. (1991)'s borehole does not describe the bottom of the sequence but rather the roof of the chamber. This means of investigation independently confirms the claim originally made by Pickering and Kramer (2010) who added the base of the boreholes does not intersect the current cave floor, but is rather a remnant pillar of dolomite. This means it cannot be used to calibrate the sequence, as there are lower lying sediments, namely those of the Jacovec Cavern.

### *5.5. Ghost rock presence and karstification models*

The ghost rock remnants have important implications on the refinement of specific mechanisms that occur within the karstification of the caves. These ghost rock remnants in the Basal thinly-bedded clay-silt and Gravelly Unit of the Thulasizwe Chamber (e.g. Figure 4.11) are a redeposition of the remnants of the karstification process that formed the cavern (Dubois et al., 2010). The presence of these features in the sediments begins with a long-lived phreatic stage, where soluble elements (dolomite) dissolve but undissolved (insoluble) components maintained in place. Upon a change in ground water, mechanical erosion occurs which removes the remnant of this process, forming the cave. At this point, some of the ghost rock remnants are preserved to which they will be included with deposits filling in the cave (Dubois et al., 2014); this is observed in the sediments. The process of forming ghost rock (and other lithological features) can assist in understanding and testing the models for karstification. In addition to ghost rock remnants, Jacovec Cavern sediments show no reworking of sediments from overlying galleries. This reworking would have been observed in extraformational (to the Jacovec) clasts, where some clasts would be in the form of reworked lithogically diverse breccias. The absence of this feature implies that the cavern would have to have been fully formed and subsequently opened to allow autogenic and allogenic sediment deposition (filling from the bottom up). When reconciling this with the proposed formation models, the deep phreatic model of Wilkinson (1985) is more likely to have led to karstification rather than the hierarchal hyperphreatic model and the chemically aggressive hypogenic model by and Klimchouck (2007). A depositional history similar to Wilkinson (1985) model on the formation and filling of the cavern is concluded for this work, but this investigation has provided more detail. This is presented below:

**5.6. The depositional evolution at the Jacovec Cavern**

As mentioned, it is not possible to link the depositional events between the Thulasizwe Chamber and the Main Jacovec Chamber and thus, the depositional histories shall be discussed separately.

1. The cavern was formed through a long-lived phreatic stage (which could rejuvenate the water thus continue removing dolomite); this is seen through the presence of ghost rock remnants. After the cavern was formed, waning floodwater (slackwater facies) introduced thinly-bedded clay-silt sediments into the Thulasizwe Chamber (Figure 4.9).

2. After this autochthonous sediment flowed as a suspended load debris flow, possibly facilitated by a flooding event derived a topographically elevated area. This was probably rapid and short-lived, as is the case of diamicton facies (Gillieson, 1985). Towards the final stages of this flood event, the upperlying suspended load led to the deposition of laminated sediment (slackwater facies) marking a halt in sedimentation (Bosch and White, 2004).

3. A boulder choke (uncemented rock debris) is then deposited (Brown Breccia). Subsequently, the sediments were cemented. This cementation may have occurred during a long-lived water submergence of the sediments in localized pooling. This pooling can be accounted for by the wall between the chambers (Figure 5.2).

4. The cavern was reopened, introducing freshwater which partially decalcified the boulder choke, hence uncemented facies (Gcm [u] and Gmm) of the Brown Breccia, see *Brown Breccia*) and then introduced a channel deposit, which incorporated some underlying Brown Breccia deposits. After some time, this deposit was also calcified (Gcm [c]) and then decalcified (Gcm [u]) (as seen in Figure 4.2). and has shown that this is a Diamicton facies association thus a boulder choke. This decalcification happens by the dissolution of water flow into the cavern. Following the collapse of the restricting wall, the entire deposit was then washed out leaving the section that can be observed today. The reopening and washing out and redeposition of the main sequence sediments (Figure 5.2) can be found on the southern to western walls of the cavern.

The two deposits of the Main Jacovec Chamber may be different phases of the same sequence but there is no exposure linking them. The sections have been labelled according to their order of deposit (Figure 4.3). In Section A-B, dolomite (1) seems to be stable host rock material (either attached to the wall or as a collapse). This is seen in the manner at which adjacent sediments wrap around it. The breccia deposit (2) is the oldest deposit. This is apparent through its positioning at the bottom of the sequence as well as it being a lithological inclusion in the other upper-lying deposits. It is then succeeded by the channel deposit (3) as evident by the erosional contact into lithofacies. There was an erosional event that led to the removal of some parts of the sequence. This left a void which was then filled by the precipitation of $CaCO_3$ (4) into a speleothem. In the section C-D, the flowstone (1) is the oldest deposit. It is then overlain by breccia (2) deposits which include the underlying flowstone clasts. A channel facies (3) deposit follows. After this, there is a flowstone (4) precipitation as seen by the remnant near the cave roof.

## 5.7. Conclusions

In conclusion, the Jacovec cavern represents one of the most complex and interesting depositional sequences and histories in the Sterkfontein cave system. This mostly low-lying, two-chambered, exposure-rich, semi-cemented siliciclastic, fossil bearing cavern provides a unique opportunity to thoroughly investigate the depositional context of a karst system that has produced remains which have contributed to our understanding of human origins. Although met with limitations, this investigation has greatly assisted in clarifying previous work on the cavern as well as introducing new inferences and interpretations that reach beyond the cavern itself. This is seen with a revision of the depositional history and relationships between and within caverns, the relative chronostratigraphic positioning of the cavern within the entire cave network, as well as the karstification mechanisms responsible for not only the chamber but the entire cave system. This has interesting implications when considering the karst deposits of the Cradle of Humankind. Although rather complex, a range of sedimentological investigations are important in providing context and history to the many faunal and hominid remains that are found in these sites.

## References

ALTERMANN, W. AND NELSON, D.R. 1998. Sedimentation rates, basin analysis and regional correlation of three Neoarchean and Paleoproterozoic sub-basins o the Kaapvaal craton, as inferred from precise U-Pb zircon ages from volcaniclastic sediments. *Sedimentary Geology* 120: 225-256.

ADAMS, A.E. AND MACKENZIE, W.S. 1998. A Colour Atlas of Carbonate Sediments and Rocks under the Microscope. W.S. Manson Publishing, London.

ADAMS, A.E., MACKENZIE, W.S. AND GUILFORD. 1984. Atlas of Sedimentary Rocks under the microscope. Longman, Harlow.

ALTERMANN, W. AND WOTHERSPOON, J. McD. 1995. The carbonates of the Transvaal and Griqualand West Sequences of the Kaapvaal craton, with special reference to the Lime Acres limestone deposit. *Mineralium Deposita* 30 (2): 124-134.

BAMFORD, M. 1999. Pliocene fossil woods from an early hominid cave deposit, Sterkfontein, South Africa. *South African Journal of Science* 95: 231-237.

BERGER, L.R., DE RUITER, D.J., CHURCHILL, S.E., SCHMID, P., CARLSON, K.J., DIRKS, P.H.G.M. AND KIBII, J.M. 2010. *Australopithecus sediba*: A New Species of *Homo*-Like Australopith from South Africa. *Science* 32: 195-204.

BERGER, L.R., LACRUZ, R. AND DE RUITER, D.J. 2002. Brief communication: revised age estimates of *Australopithecus*-bearing deposits at Sterkfontein, South Africa. *American Journal of Physical Anthropology* 119: 192-197.

BOSCH, R.F. 2015. *Lithofacies and transport of clastic sediments in Karstic acquifers. M.Sc. thesis, The Pennsylvania State University, Pennsylvania*.

BOSCH, R.F. AND WHITE, W.B. 2004. Lithofacies and transport of clastic sediments in karstic aquifers. In SASOWSKY, I.D. AND MYLROIE, J. (Eds.), *Studies of Cave Sediments,* 1-22. Kluwer Academic, New York.

BRAIN, C.K. 1958. The Transvaal ape-man-bearing cave deposits. *Transvaal Museum Memoir* 11: 1-131.

BRAIN, C.K. 1981. The Hunters or the Hunted? An Introduction to African Cave Taphonomy. University of Chicago, Chicago.

BRINK, A.B.A. AND PARTRIDGE, T.C. 1965. Transvaal karst: some considerations of development and morphology. *South African Geographical Journal* 47: 11-34.

BROOM, R. 1936. A new fossil anthropoid skull from South Africa. *Nature* 138: 486-488.

BROOM, R. 1947. Discovery of a New Skull of the South African Ape-Man, *Plesianthropus*. *Nature* 159: 672-672.

BROOM, R. AND ROBINSON, J.T. 1947. Jaw of the Male Sterkfontein Ape-men". *Nature* 160: 153.

BROOM, R., ROBINSON, J.T. AND SCHEPERS, G.W.H. 1950. Sterkfontein ape-man *Plesianthropus*. *Transvaal Museum Memoir* 4: 1-83.

BULLOCK, P. FEDOROFF, N. JONGERIUS, A. STOOPS., G.J., TURSINA. T.N. AND BABEL, U. 1985. Handbook for Soil and thin section description. *Wayne Research Publication* 152 pp

BRUXELLES, L., CLARKE, R. J., MAIRE, R., ORTEGA, R., AND STRATFORD D. 2014. Stratigraphic analysis of the Sterkfontein StW 573 *Australopithecus* skeleton and implications for its age. *Journal of Human Evolution* 70: 36-48.

BRUXELLES, L., QUINIF, Y. AND WIÉNIN, M. 2009. How can ghost rocks help in karst development? *15th International Congress of Speleology* 814-818.

BURKE, K. AND GUNNELL, Y. 2008. The African erosion surface: a continental-scale synthesis of geomorphology, tectonics, and environmental change over the past 180 million years. *Geological Society of America Memoirs*. 201: 1-66.

BUTTON, A. 1973. *A regional study of the stratigraphy and developments of the Transvaal Basin in the eastern and northern Transvaal. Ph.D. thesis, University of the Witwatersrand, Johannesburg*.

CATUNEANU, O. AND ERIKSSON, P.G., 1999. The sequence stratigraphic concept and the Precambrian rock record: an example from the 2.7-2.1 Ga Transvaal Supergroup, Kaapvaal craton. *Precambrian Research* 97: 215-251.

CATUNEANU, O., ERIKSSON, P.G., 2002. Sequence stratigraphy of the Precambrian Rooihoogte-Timeball Hill rift succession, Transvaal Basin, South Africa. *Sedimentary Geology* 147: 71-88.

CLARKE, R.J. 1988. A new *Australopithecus* cranium from Sterkfontein and its bearing on the ancestry of Paranthropus. In GRINE, F. (Eds.), *Evolutionary History of the 'Robust' Australopithecines*, 287-292. Aldine de Gruyter, New York.

CLARKE, R.J. 1994. On some new interpretations of Sterkfontein stratigraphy. *South African Journal of Science*. 90: 211-214.

CLARKE, R.J. 1998. The first ever discovery of a well-preserved skull and associated skeleton of *Australopithecus*. *South African Journal of Science* 94: 460-463.

CLARKE, R.J. 2006. A deeper understanding of the stratigraphy of the Sterkfontein fossil hominid site. *Transactions of the Royal Society of South Africa* 61: 111-120.

CLARKE, R.J. 2013. *Australopithecus* from Sterkfontein Caves, South Africa. In REED, K.E., FLEAGLE, J.G. AND LEAKEY, R.E. (Eds), *The Paleobiology of Australopithecus,* 105-123. Springer, Dordrecht.

CLARKE, R.J. AND TOBIAS, P.V. 1995. Sterkfontein Member 2 foot-bones of the oldest South African Hominid. *Science* 269: 521-524.

CLENDENIN, C.W. 1989. *Tectonic influence on the evolution of the early Proterozoic Transvaal Sea, southern Africa. PhD thesis, University of the Witwatersrand, Johannesburg.*

COOKE, H.B.S. 1938. The Sterkfontein bone breccia: a geological note. *South African Journal of Science* 35: 204-208.

COURTY, M.A., GOLDBERG, P. AND MACPHAIL, R.I. 1989. Soil and micromorphology in archaeology. Cambridge University Press, New York.

DEER, W.A., HOWIE, R. A., AND ZUSSMAN, J. 1992. An introduction to the rock-forming minerals. Longman Scientific and Technical, England.

DICKINSON, W.R. 1985. Interpreting provenance relations from detrital modes of sandstones. In Zuffa, G.G. (Ed), *Provenance of Arenites,* 333-361. Reidel Publications, Dordrecht

DIRKS, P.H.G.M., AND BERGER, L.R. 2013. Hominin-bearing caves and landscape dynamics in the Cradle of Humankind, South Africa. *Journal of African Earth Sciences*. 78: 109-131.

DIRKS, P.H.G.M. PLACZEK, C.J., FINK, D., DOSETTO, A. AND ROBERTS, E. 2016. Using $10^{Be}$ cosmogenic isotopes to estimate erosion rates and landscape changes during the Plio-Pleistocene in the Cradle of Humankind, South Africa. *Journal of Human Evolution* 96: 19-34.

DRAPER D. 1896. Report of meeting, Geological Society of South Africa, 8th April 1895. *Transactions of the Geological Society South Africa* 1: 1.

DUBOIS, C., QUINIF, Y., BAELE, J., BARRIQUAND, L., BINI, A., BRUXELLES, L., DANDURAND, G., HAVRON, C., KAUFMANN, O., LANS, B., MAIRE, R., MARTIN, J., RODET, J., ROWBERRY, M.D., TOGNINI, P. AND VERGARI., A. 2014. The process of ghost-rock karstification and its role in the formation of cave systems. *Elsevier* 131: 116-146.

EHRLICH, H.L. 1998. Geomicrobiology: its significance for geology. *Earth Science Review* 45: 45-60.

ERIKSSON, P.G. AND ALTERMANN W. 1998. An overview of the geology of the Transvaal Supergroup dolomites (South Africa). *Environmental Geology* 36: 179-188.

ERIKSSON, P.G., ALTERMANN, W., CATUNEANU, O., VAN DER MERWE, R. AND BUMBY, A.J. 2001. Major influences on the evolution of the 2.67-2.1 Ga Transvaal basin, Kaapvaal craton. *Sedimentary Geology* 141-142: 205-231.

ERIKSSON, P.G., RECZKO, B.F.F. 1995. The sedimentary and tectonic setting of the Transvaal Supergroup floor rocks to the Bushveld Complex. *Journal of African Earth Sciences* 21: 487-504.

ERIKSSON, P.G., TWIST, D., SNYMAN, C.P., BURGER, L. 1990. The geochemistry of the Silverton Shale Formation, Transvaal Sequence. *South African Journal of Geology* 93: 454-462.

FIELD, A.S. 1999. *Analytical and comparative Study of the Earlier Stone Age Archaeology of the Sterkfontein Valley. M.Sc. thesis, University of the Witwatersrand, Johannesburg.*

FLÜGEL, E.A. 2004. Microfacies of Carbonate Rocks. Analysis, Interpretation and Application.: Springer-Verlag, New York 976 pp.

FLÜGEL, E.A. 2010. Microfacies of Carbonate Rocks. *Springer*.

FORD, D.C. 1971. Geologic structure and a new explanation of limestone cavern genesis. *Cave Research Group Trans* 13 (2): 81-94.

FORD, D.C., AND WILLIAMS, P.W. 1989. Karst geomorphology and hydrology. Unwin-Hyman, London.

GILLIESON, D. 1985: Geomorphic development of limestone caves in the Highlands of Papua New Guinea. *Zeitschrift für Geomorphologie* 29: 51-70.

GOLDBERG, P. 1979. Micromorphology of Pech-de-l'Aze II sediments. *Journal of Archaeological Science* 6: 17- 47.

GRANGER., D.E. GIBBON, R.J., KUMAN, K. CLARKE, R.J., BRUXELLES, L. AND CAFFEE, M.W. 2015 . New cosmogenic burial ages for Sterkfontein Member 2 *Australopithecus* and Member 5 Oldowan. *Nature* 522: 85-88.

HARMS, J.C., SOUTHARD J.B. AND WALKER, R.G. 1982. Structures and sequences in clastic rocks. *Society of Economic Paleontologists and Mineralogists* 9: 4-19.

HERRIES, A.I.R., CURNOE, D. AND ADAMS, J.W. 2009. A multidisciplinary seriation of early *Homo* and *Paranthropus* bearing palaeocaves in southern Africa. *Quaternary International.* 202(1-2): 14-28.

HERRIES, A.I.R. AND SHAW, J. 2011. Palaeomagnetic analysis of the Sterkfontein palaeocave deposits: implications for the age of the hominin fossils and stone tool industries. *Journal of Human Evolution* 60: 523-539.

HERRIES, A.I.R. PICKERING, R., ADAMS., J., CURNOE, D., WARR, G., LATHAM, A. AND SHAW, J. 2013. A multi-disciplinary perspective on the age of *Australopithecus* in Southern Africa. In REED, K.E., FLEAGLE, J.G. AND LEAKEY R.E. (Eds.), *The Paleobiology of Australopithecus* 21-40. Springer, Dordrecht.

JONGERIUS, A. AND RUTHERFORD, G.K. 1979. Glossary of Soil Micromorphology. Centre for Agricultural Publishing and Documentation, Wageningen.

KARKANAS, P. AND GOLDBERG, P. 2013. Micromorphology of cave sediments. In SHRODER, J.F. (Eds.), Treatise on Geomorphology, Karst Geomorphology, San Diego: *Academic Press* 6: 286-297.

KARKANAS, P., BAR-YOSEF, O., GOLDBERG, P. AND WEINER, S. 2000. Diagenesis in prehistoric caves: The use of minerals that form in situ to assess the completeness of the archaeological record. *Journal of Archaeological Science* 27: 915-929.

KIBII, J. 2000. *The macrofauna from Jakovec Cavern, Sterkfontein. M.Sc. Dissertation, University of the Witwatersand, Johannesburg.*

KIBII, J.M. 2004. *Comparative Taxonomic, Taphonomic and Palaeoenvironmental Analysis of 4-2.3 Million Year Old Australopithecine Cave Infills at Sterkfontein. PhD Dissertation. University of Witwatersrand Johannesburg.*

KIBII, J.M. 2007. Taxonomy and taphonomy of non-hominid primates from the Jacovec Cavern, Sterkfontein. *The South African Archaeological Bulletin* 62: 90-97.

KING, L.C. 1962. The Morphology of the Earth: A Study and Synthesis of World Scenery. London, Oliver and Boyd 699 pp.

KLIMCHOUK, A. 2009. Morphogenesis of hypogenic caves. *Elsevier* 106: 100-117.

KLIMCHOUK, A.B., 2007. Hypogene speleogenesis - Hydrogeological and morphogenetic perspective: Carlsbad, New Mexico. *National Cave and Karst Research Institute, Special Paper* 1: 106.

KUMAN, K. 1996. The Oldowan Industry from Sterkfontein: raw materials and core forms. In PWITI, G. AND SOMPER, R. (Eds.), *Aspects of African Archaeology: papers from the 10th Congress of the Pan African Association for Prehistory and Related Studie*s, 139-146. University of Zimbabwe Publications, Harare.

KUMAN, K. AND CLARKE, R.J. 2000. Stratigraphy, artefact industries and hominid associations for Sterkfontein Member 5. *Journal of Human Evolution* 38: 827-847.

KUMAN, K. AND FIELD, A.S. 2009. The Oldowan Industry from Sterkfontein Caves, South Africa. In SCHICK K. AND TOTH, N. (Eds.), *The Cutting Edge: Approaches to the Earliest Stone Age*, 151-170. Stone Age Institute Press, Indiana.

LATHAM, A.G. 1999. Cave breccias and archaeological sites. *Capra* 1

MARKER, M.E. AND MOON, B.P. 1969. Cave Levels and Erosion Surfaces in the Transvaal, South Africa. *South African Geographical Journal* 51(1): 106-113.

MARTINI J. and KAVALIERIS I. 1976. The karst of the Transvaal (South Africa). *International Journal of Speleology* 8: 229-251.

MARTINI, J., WILINGER, P.E., MOEN, H.F.G. AND KEYSER, A. 2003. Contribution to the Speleology of Sterkfontein cave, Gauteng province, South Africa. *International Journal of Speleology* 32: 43-49.

MIALL, A.D. 2000. Principles of Sedimentary Basin Analysis. Springer-Verlag, New York.

MIALL, A.D. 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology. Berlin, Springer-Verlag.

MIALL, A.D. 1999. In defense of facies classifications and models. *Journal of Sedimentary Research* 69: 2-5.

MIALL. A.D. 1985, Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews* 22: 261-308.

MOEN, H.F.G. AND MARTINI, J.E.J. 1996. The exploration of Swartgat Sinkhole. South African *Speleological Association Bulletin* 36: 45-49.

MORGAN, R.M. AND BULL, P.A. 2007. The philosophy, nature and practice of forensic sediment analysis. *Progress in Physical Geography* 31(1): 43-58.

MORIARTY, K.C., MCCULLOCH, M.T., WELLS, R.T., MCDOWELL, M.C. 2000. Mid-Pleistocene cave fills, megafauna remains and climate change at Naracoorte, South Australia: towards a predictive model using U-Th dating speleothems. *Palaeogeography, Palaeoclimatology, Palaeoecology* 159: 113-143

NICHOLS, G. 2009. Sedimentology and Stratigraphy. Wiley-Blackwell, Oxford. 419 pp.

OSBORNE, R. 2002. Cave Breakdown by Vadose Weathering. *International Journal of Speleology* 31: 37-53.

PALMER, A. 2007. Cave geology. Cave Books, National Speleological Society, Trenton, New Jersey.

PARTRIDGE, T.C. 1973. Geomorphological dating of cave opening at Makapansgat, Sterkfontein, Swartkrans and Taung. *Nature*. 246: 75-79.

PARTRIDGE, T.C. 1978. Re-appraisal of lithostratigraphy of Sterkfontein hominid site. *Nature* 275: 282-287.

PARTRIDGE, T.C. 2005. Dating of the Sterkfontein hominids: progress and possibilities. Transactions of the Royal Society of South Africa 60: 107-109.

PARTRIDGE, T.C. AND MAUD, R.R. 1987. Geomorphic evolution of southern Africa since the Mesozoic. *South African Journal of Geology* 90: 179-208.

PARTRIDGE, T.C. AND WATT, I.B. 1991.The stratigraphy of the Sterkfontein hominid deposit and its relationship to the underground cave system. *Palaeontologia Africana* 28:35-40.

PARTRIDGE, T.C., GRANGER, D.E., CAFFEE, M.W. AND CLARKE, R.J. 2003. Lower Pliocene hominid remains from Sterkfontein. *Science* 300: 607-612.

PICKERING, R. AND KRAMERS, J.D. 2010. Re-appraisal of the stratigraphy and determination of new U-Pb dates for the Sterkfontein hominin site, South Africa. *Journal of Human Evolution*. 59: 70-86.

PICKERING, T.R. 1999. *Taphonomic interpretations of the Sterkfontein early hominid site (Gauteng, South Africa) reconsidered in light of recent evidence. Ph.D. thesis, University of Wisconsin, Madison*.

PICKERING, T.R., WHITE, T.D. AND TOTH, N. 2000. Cutmarks on a Plio-Pleistocene hominid from Sterkfontein, South Africa. *American Journal of Physical Anthropology* 111: 579-584.

QUINIF, Y., 2011. Ghost rock structures and the nature of Azé Caves. *Quaternaire (Special Issue)* 4: 7-14.

RAILSBACK, L.B., 1999, Patterns in the compositions, properties, and geochemistry of carbonate minerals. *Carbonates and Evaporites* 14: 1-20.

READING, H.G. 1986. Sedimentary environments and facies. Blackwell, Oxford.

READING, H.G. 2012. Sedimentary Environments: Processes, Facies and Stratigraphy, third edition. Blackwell Publishing Limited, New Jersey.

REYNOLDS S. AND KIBII J. 2011. Sterkfontein at 75: Review of palaeoenvironments, fauna and archaeology from the hominin site of Sterkfontein (Gauteng Province, South Africa). *Palaeontologia Africana* 46: 59-88.

ROBINSON, J.T. 1962. Sterkfontein stratigraphy and the significance of the Extension Site. *South African Archaeological Bulletin* 17: 87-107.

ROLLINSON, H.R. 1993. Using Geochemical Data: Evaluation, Presentation, Interpretation. Longman Scientific and Technical, London.

SCHELLMANN, W. 1994. Geochemical differentiation in laterite and bauxite formation. *Catena* 21: 131-143.

SELLEY, R.C. 1985. Ancient Sedimentary Environments: And their sub-surface diagnosis. Springer US, Boston.

SPRINGER, G.S. AND KITE, J.S., 1997, River-derived slackwater sediments in caves along Cheat River, West Virginia. *Geomorphology* 18: 91-100.

STOOPS, G. 2003. Guidelines for the Analysis and Description of Soil and Regolith Thin Sections. Soil Science Society of America, Madison.

STRATFORD, D. 2011. *The underground central deposits of the Sterkfontein Caves, South Africa. Ph.D. Dissertation. University of Witwatersrand, Johannesburg.*

STRATFORD, D. 2015. The Sterkfontein Caves: Geomorphology and Hominin-Bearing Deposits. In GRAB, S. AND KNIGHT, J. (Eds.), *Landscapes and Landforms of South Africa, World Geomorphological Landscapes* 147-153. Springer International Publishing, Switzerland.

STRATFORD, D.J. 2008. *A Study of Newly Discovered Lithics from Earlier Stone Age deposits at Sterkfontein, Gauteng Province, South Africa. M.Sc. Dissertation, University of Witwatersrand, Johannesburg.*

STRATFORD, D.J., BRUXELLES, L., CLARKE, R.J. AND KUMAN, K. 2012. New stratigraphic interpretations of the fossil and artefact-bearing deposits of the Name Chamber, Sterkfontein. *South African Archaeological Bulletin* 67: 159-167.

TOBIAS, P.V. 1979. The Silberberg Grotto, Sterkfontein, Transvaal, and its importance in palaeo-anthropological research. *South African Journal of Science* 75: 161-164.

TURNER, A. 1987. New fossil carnivore remains from the Sterkfontein hominid site (Mammalia: Carnivora). Annuals of the Transvaal Museum 34: 319-347.

TURNER, A., 1997. Further remains of Carnivora (Mammalia) from the Sterkfontein hominid site. *Palaeontogica africana* 34: 115-126.

VRBA, E.S. 1975. Some evidence of chronology and palaeoecology of Sterkfontein, Swartkrans and Kromdraai from the fossil *Bovidae*. *Nature* 254: 301-304.

VRBA, E.S. 1976. The fossil *bovidae* of Sterkfontein, Swartkrans and Kromdraai*. Transvaal Museum Pretoria Memoirs* 21.

VRBA, E.S. 1980. The significance of bovid remains as indicators of environment and predation patterns, In BEHRENSMEYER, A.K. AND HILL, A.P. (Eds.), *Fossil in the Making* 247-271. University of Chicago Press, Chicago.

WALKER, J., CLIFF, R.A. AND LATHAM, A.G. 2006. U-Pb Isotopic age of the StW 573 hominid from Sterkfontein, South Africa. *Science* 314: 1592-1594.

WENTWORTH, C.K. 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology* 30: 377-392.

White, W.B., 2007. Cave sediments and paleoclimate. *Journal of Cave and Karst Studies* 69 (1): 76-93.

WILKINSON M.J. 1973. *Sterkfontein Cave System: evolution of a karst form. M.A. thesis, University of the Witwatersrand, Johannesburg.*

WILKINSON, M.J. 1983. Geomorphic perspectives on the Sterkfontein australopithecine breccias. *Journal of Archaeological Science* 10: 515-529.

WILKINSON, M.J. 1985. Lower-lying and possibly older fossiliferous deposits at Sterkfontein. In TOBIAS, P. V. (Eds.), *Hominid Evolution: Past, Present and Future,* 165-170. Alan R. Liss, New York.