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Regional geological formation and speleogenesis of the 'Fossil Hominid Sites of South Africa' UNESCO World Heritage Site☆

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1. Introduction

The dynamic karst landscapes of South Africa reflect a long, diverse geological and anthropogenic history and as such, they have been the focus of research for over 100 years (Draper, 1896, 1898; Dart, 1925; Broom, 1938; De Wit et al., 1992; Herries et al., 2009, 2013; Berger et al., 2010; Delph and Porter, 2015; Kuhn et al., 2016; Leece et al., 2016). Research was first undertaken here following Charles Darwin's expeditions in the 1830's (Master, 2012), and again in the early twentieth century after a surge in hominin fossil discoveries (Dart, 1925; Broom, 1938). The underlying Kaapvaal craton contains some of the world's oldest and most intensively studied Archean rocks and forms the stable basement on which subsequent landforms were developed. Specifically, to the north-eastern provinces of South Africa, landscapes were shaped by numerous, multifaceted geomorphological processes (i.e. uplift, karstification, erosion; Marker and Moon, 1969) that modified surface and sub-surface materials; as well as modification through anthropogenic impact (Durand et al., 2010). The latter is specifically relevant to scientific research in many regions of southern Africa, as many fossil and archaeological bearing sites were discovered during active mining (e.g. at Langebaanweg for phosphate; along the Vaal River for diamonds; and, at Kabwe in Zambia for lead and zinc; Woodward, 1921; Herries, 2011; Roberts et al., 2011). Perhaps most significant, was the discovery of the first early hominin fossils in the late 19th and early 20th century in north-eastern South Africa, found during the mining of speleothem within caves, which was then used locally for extracting gold.

The destruction of *in-situ* material within karst sites has impacted the level of contextual information collected from fossil-bearing sites. To better assess palaeoanthropological and archaeological material, further efforts are required to locate new and *in-situ* palaeokarst material, which has been minimally impacted by mining activities. In addition, within the different exposures of karst in South Africa, the geological history has had a clear influence on the creation and preservation of caves and palaeokarst. Consequently, some karst exposures (e.g. in Gauteng) have many caves and have yielded many hominin fossils, and others only a few (e.g. the Taung Child within the Ghaap Plateau; Dart, 1925). To assess the level and significance of geological bias on karst development, a better understanding of the local environment and karst formation needs to be established. Most mapping projects within north, north-eastern South Africa (i.e. SACS, 1980; Andreoli, 1988a; Eriksson and Reczko, 1995; Obbes, 2000; Alexandre et al., 2006; Grab and Knight, 2015; Ingram and van Tonder, 2011) have been carried out at scales required for regional tectonic analysis,

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which has led to a gap in research at scales relevant to karst formation and associated geological controls. For these reasons, a comprehensive understanding of the geological history is the first stage in understanding the relationship in geology and fossil-hominin discoveries; expanding the discovery and context of palaeoanthropological and archaeological material.

This new synthesis assimilates available geological data to construct a chronostratigraphic framework of these north- northeast provinces (Gauteng, Limpopo, North West and Northern Cape), highlighting major stratigraphic successions that have shaped the landscapes of the region. An important emphasis is placed on lithologies in association with the 'Fossil Hominid Sites of South Africa' UNESCO World Heritage Site. The Gauteng portion of this is known locally as the Cradle of Humankind (CoH). The highest density of hominin fossils (*Australopithecus, Paranthropus* and early *Homo*) have been identified in palaeocave deposits such as Sterkfontein, Swartkrans, Kromdraai B (within the Blaaubankspruit Valley (alt. Blaaubankspruit or Blauubank Stream Valley) and Drimolen Main Quarry, formed within the Malmani dolomite in the Gauteng Province (Fig. 1; 2; Broom, 1938; Grine, 1982, 2005; Brain, 1993; Keyser et al., 2000; Herries et al., 2009, 2013).

There are two satellite sites to the UNESCO World Heritage Site outside Gauteng. Approximately ~250 km to the north-east, the Makapansgat Valley in the Limpopo Province contains a series of palaeokarst deposits. The Makapansgat Limeworks (MLW) is the oldest deposit and contains late Pliocene fossils, including around 40 fossils of *Australopithecus africanus* dated between 3.03 and 2.61 Ma (Fig. 1) (Herries et al., 2013). The Cave of Hearths has also yielded rare Acheulian deposits within a cave context, as well as < 780 ka hominin fossils attributed to *Homo rhodesiensis* (Latham and Herries, 2004; Herries and Latham, 2009). Other non-hominin sites such as the ~1.07 – 0.78 Ma Buffalo Cave also occur at Makapansgat (Herries et al., 2006b).

The other satellite site is located 350 km to the southwest of the Gauteng sites in the Northwest Province. The Buxton-Norlim Limeworks contains fossil sites covering the Pliocene to Holocene and yielded the type specimen of *Australopithecus africanus*, known as 'The Taung Child', as well as younger modern human fossils from Equus Cave and Black Earth Cave (Fig. 1) (Dart, 1925; Peabody, 1954; Kuhn et al., 2016). The Taung Child has been dated to between 3.03 and 2.61 Ma (Herries et al., 2013), and along with the Makapansgat Limeworks hominins it represents some of, if not the oldest, hominin fossil in South Africa. The Stw 573 fossil, referred to as 'little foot', from Sterkfontein Member 2, has been argued to be older at ~3.67 Ma based on cosmogenic nuclide burial dating (Granger et al., 2015; Stratford et al., 2017). However, a recent reinterpretation of this nuclide burial dating model concluded an age of < 2.8 Ma, which fits with the previous radiometric and faunal age estimates (< 2.8–2.2 Ma; Berger et al., 2002; Pickering and Kramers, 2010; Herries and Shaw, 2011; Kramers and Dirks, 2017a, 2017b). Again, these fossils sites are associated with the Malmani dolomite, although the Taung sites are formed within tufa on the edge of its exposures, and thus in a secondary calcium carbonate deposit. While it had always been considered that the Taung Child skull came from caves formed through this tufa (Dart, 1925), recent work suggests that the skull was deposited during formation of tufa (Hopley et al., 2013). These studies indicate that the Taung Child was recovered from 3.03–2.61 Ma deposits (PCS) that are stratified within the Tufa, while other fossils are found in 2.6–2.0 Ma red sandstone (YRSS) that fill caves formed both through the tufa and the PCS deposits (Herries et al., 2013; Hopley et al., 2013).

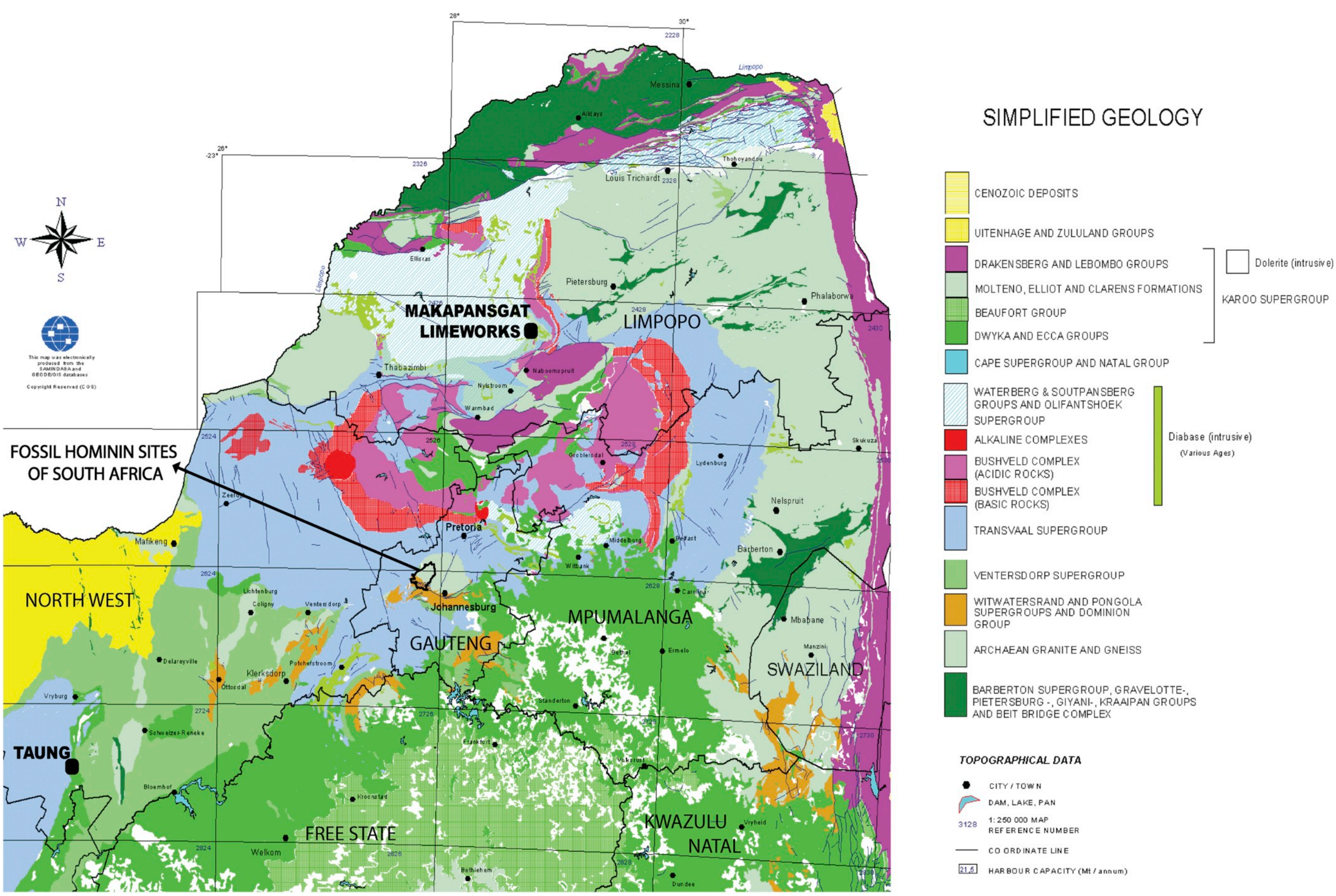

Fig. 1. Regional geological map of the north-east provinces of Southern Africa, highlighting the location of the 'Fossil Hominid Sites of South Africa' UNESCO World Heritage Site (refer to Fig. 2 for more detail). Image adapted from Vorster (2003).

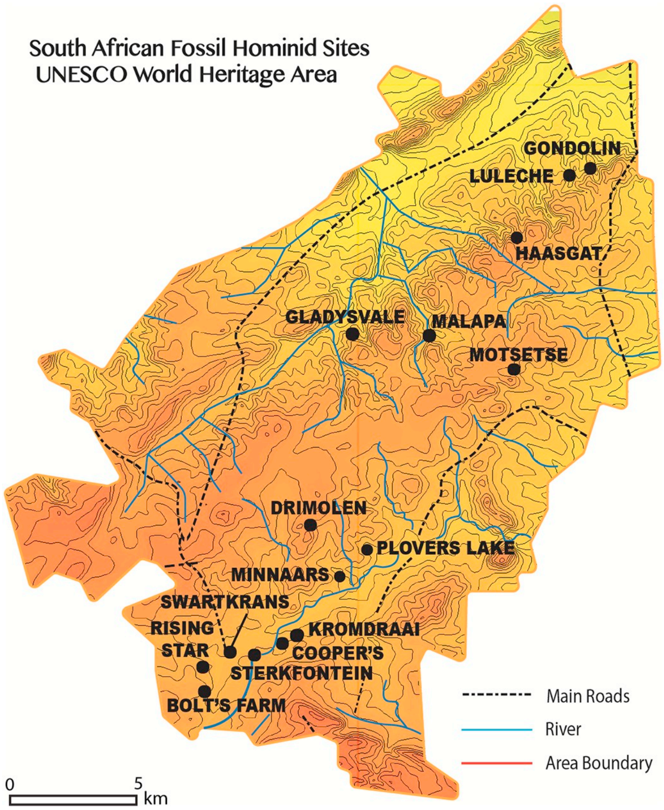

Fig. 2. Gauteng exposures of the Fossil Hominid Sites of South Africa (Cradle of Humankind) World Hertiage Area. Note: Area depicted here is represented on Fig. 1 (i.e. South African geology map).

The nearby site of Wonderwerk Cave is also positioned within the Malmani dolomite and as there has been no hominin fossils identified here, this site is not defined within the CoH. Nevertheless, this site has potentially yielded some of the oldest stone tools (> 1.78 Ma) outside of Gauteng (Chazan et al., 2012). However, there are dates that dispute this, indicating deposits within Wonderwerk Cave are younger than ~1.1 Ma (Herries, 2011; Pickering, 2015; Stammers et al., 2018). Few pre-Pleistocene fossil sites are found in South Africa other than the aforementioned terminal Pliocene sites (Taung and MLW); with no hominin fossil sites older than ~1.1 Ma existing outside the Malmani dolomite (Herries and Shaw, 2011; Brink et al., 2012). Within Gauteng Province itself, there are only a few confirmed Pliocene fossil sites older than 2.61 Ma, including deposits at Sterkfontein, the Drimolen Makondo and Hoogland Cave (Pickering and Kramers, 2010; Adams et al., 2010; Herries et al., 2018). This may be indicate that older caves have been removed from the landscape via erosion, hence preservation of karst dated outside these periods is rare (Herries et al., 2018), or that the caves are not old enough to have interned fossils prior to this period (Dirks and Berger, 2013). Again, this points to a distinct geological bias to the human fossil record in South Africa, highlighting the need for a better understanding of the geological history of the region and the processes driving hominin fossil preservation.

2. Structural and Geochemical Controls on Karst Formation

The distribution of karst in southern Africa results from a complex interaction between the bedrock geology, structural history and local environmental variables. Surface drainage is controlled by the ability of bedrock to rapidly absorb and discharge water, which ultimately depends on the development of an effectively draining system of joints and underground cavities, and depth to the saturation zone (Marker, 1980). Regional mapping projects have mapped the extents, and in some cases, local complexity of the Malmani Subgroup (Obbes, 2000). However, recent ground truthing has shown inaccuracies in mapping studies, on a scale important for understanding karst formation (Herries et al., in press). This emphasises the need for site specific or local geological maps that encompass palaeokarst sites, which are rarely constructed and utilised for modern palaeoanthropological research.

It is also important to emphasise here that karst landscapes comprise diverse and multi-generational karst systems, which lacks recognition in more recent studies that argue for single- type karst formation models (Dirks and Berger, 2013). Although similarities can be drawn, local variables have influenced karst development for at least millions of years, with a number of major phases of karst formation. While the earliest phases of karstification of the Malmani dolomites may have occurred ~2.2 Ga (Eriksson and Reczko, 1995), karst on the currently exposed landscape are the product of multiple phases of more recent (Pliocene-Pleistocene) karstification.

Herries et al. (2001; 2006) first used the term 'palaeocave' to define relict sediment filled and eroded caves systems from active, or open cave systems within the region and others (Osborne, 2004) have referred to the sites as palaeokarst, as they consist of deroofed cave systems. While active cave systems occasionally intersect the palaeocaves, they are not part of the same phase of karstification and are completely relict, infilled with sediment and significantly eroded. At most sites, such as Drimolen or Gondolin, a clear distinction can be made between sediment filled and eroded palaeokarst that contains late Pliocene to early Pleistocene fossils, and more recently formed cave passages with Middle Pleistocene to Holocene sediments (Herries and Shaw, 2011; Herries et al., 2018). This concept is less clear at sites such as Sterkfontein, where palaeokarst has collapsed into more recent cave passages (Stratford, 2015; 2017). Another potential exception to this is the Rising Star Cave system, which contains deposits that date back nearly a million years (Dirks et al., 2017), but have no evidence for the current cave system having intersected former palaeocaves (Dirks et al., 2015). This level of perceived complexity, and variability in karstification of the Malmani dolomite, highlight the importance of understanding tectonic, geological and temporal variables contributing to the karst development.

Structures including joints, bedding, foliation and other micro- or macro-features within the rocks exert significant controls on weathering processes and slope stability (Marker, 1980). Although geological structures and tectonics complement erosional activity, their effects are typically seen at the landform scale. Such tectonic events manipulate karst size and shape, as tectonic uplift rejuvenates erosion and lowers the water table (Klimchouk and Ford, 2000). Many South African cave sites have been argued to be "hyperphreatic" in origin, whereby deeper parts of the caves develop in the phreatic zone (i.e. water fill portion), but close to the interface with the vadose (air filled) zone (i.e. the piezometric surface) (Partridge, 2000). As the dolomites in the CoH are fractured, water connects through many fractures and pore spaces, whereby greater distances and rates of water movement consequently increase rates of erosion (Martini et al., 2003). This results in greater vertical water movement, influencing passage and chamber development in karst. This is mostly applicable to settings where solutions of geochemically distinct equilibria intermix, termed a mixed corrosion effect (Dreybrodt, 1981). For example, large caverns occur at the junction of two passages or cross joints, which promotes collapse and enlargement, or where two waters of different geochemistry meet. Other caves form at the contact between two lithologies, which is the case for many sites in South Africa, where carbonates are interbedded with insoluble chert layers (Marker, 1980). Early karstification stages at sites, including Sterkfontein, have also been argued to be partially hypogenic in origin, which form from the solution enlarge permeability structures by water ascending to a cave-forming zone; where deeper groundwater interacts with shallow groundwater systems (Martini et al., 2003; Klimchouk, 2009). Lastly and perhaps most relevant to karst in the CoH is geological age, which is an important variable on karst formation that is rarely considered. In most cases, young karst is relatively simple compared to older karst that has time to develop more complexity in a protracted period of changing climatic and environmental conditions (Fig. 3). Although there is a lack of convincing evidence for the development of karst within the CoH prior to ~3.2 Ma, dates for the Malmani dolomite host rock extend to ~ 2.6 Ga. Therefore, while karst in the CoH is still indisputably ancient, the question of whether older karst is still preserved remains.

The percolation of water through fractures or other structural deformities in the rock can also result in the formation of large alterite pockets (i.e. ghost rocks), where removal of residual material is prevented by very slow drainage (Bruxelles et al., 2009). Although the overall process is still poorly understood, these features can form pseudo-endokarst. The development of ghost rocks (as well as similarly formed makondo features) emphasises the importance to think unconventionally when modelling karst genesis. It can also provide new interpretations concerning karstic morphologies and the functioning of underground streams.

3. Karstification studies in the CoH

The local geology of a cave site has a significant influence on cave structure and speleogenesis. However, smaller scale mapping is rarely conducted alongside fossil-hominin discoveries to understand local karstification. Local geology is relevant to palaeoanthropological research in the CoH, as the occurrence of sites of varying ages in close proximity has been well documented. This is particularly the case throughout sites within the Blaaubankspruit Valley (Fig. 2). However, little research has been carried out to assess relationships between these sites and age-depth relationships of fossil deposits have only been extensively examined on an intra-site basis rather than a regional basis. Filling these gaps has significant implications for understanding the complex geological context of hominin bearing caves. This is critical for evaluating biases in the preserved record of the region; i.e., addressing whether *Australopithecus* only inhabited South Africa after 3.7 Ma (Granger et al., 2015; Stratford et al., 2017) or 3.0 Ma (Herries et al., 2013), or whether a regional geological bias exists that has resulted in the erosion of older cave sites (Herries et al., in press).

Marker and Moon (1969) have suggested that cave formation was directly linked to various phases of erosion in South Africa, while others (Keyser and Martini, 1991; Partridge, 2000; Martini et al., 2003; Dirks and Berger, 2013) have suggested that South African caves did not follow typical Eurasian karst models and rather formed by dissolution along pre-existing structures, such as observed at sites such as Sterkfontein (Martini et al., 2003). However, little effort has since been given to substantiate these discussions. Most geological mapping projects in the region have been carried out on larger, tectonic scales, typically geared toward resource exploration. This has led to a gap in research at local geological scales targeting karst formation in relation to the associated geology throughout the CoH.

Only a few studies (e.g., Latham et al., 1999; Martini et al., 2003; Bailey et al., 2011; Reynolds et al., 2011; Dirks and Berger, 2013; Makhubela et al., 2017) have attempted to bridge the broader geological context with karst formation. Specifically, recent studies by Dirks and Berger (2013) link site-specific geology to local karst formation. However, their model is largely based on the local geology at Malapa and lacks wider geological interpretations on the dynamics of karst formation in the region. Their conclusions argue for a uniform karstification model, forming caves contemporaneously and in direct association with the Rooihoogte Formation (i.e. chert breccia; supplementary figure). Though it is acknowledged that this unit has been locally linked to karst formation elsewhere in the CoH (e.g. Sterkfontein; Stratford, 2017), a uniform karstification model presented for Malapa cannot be generalised for the region; whereby multiple sites have clear evidence of multi-generational and multi-faceted karstification phases. For example, Drimolen Main Quarry cavern vs. Warthog cave; a far later karstification phase that forms at the interface of the palaeocavern and the dolomite (Fig. 4). Here, the sediments that fill Warthog cave are uncemented and contain no fossil or bone material, with the exception of sediments that lie directly on the contact with the underlying palaeocave sediments. Lastly, the conclusion that the Rooihoogte Formation is directly correlated with phases of cave formation is also untrue for sites including Drimolen and Haasgat (Herries et al., in press). Consequently, models should be examined and conclusions drawn on a site by site basis in relation to the surrounding geology, which will better inform age-depth relationships of fossil deposits within the site itself. Data gathered from non-fossiliferous karst in the region, would also aid in providing an unbiased dataset to be utilised in conjunction with known fossiliferous sites. This would likely facilitate a better understanding on the regional geomorphological evolution and more specifically, the timing of karstification phases throughout the CoH.

The first stage in doing this is to expand the discussion to encompass geological formation in relation to local and regional karst formation and interpretation. Although some attention is given here to the Gauteng exposures of the CoH (Fig. 1), we do not confine this synthesis to a specific area or to specific units, as only 2% of the area of southern Africa is underlain by carbonate rocks. Other lithologies need to be considered in the formation of karst in addition to structural or orogenic processes that have contributed to the formation these rock units. Relevant tectonic and igneous events elaborated here include the

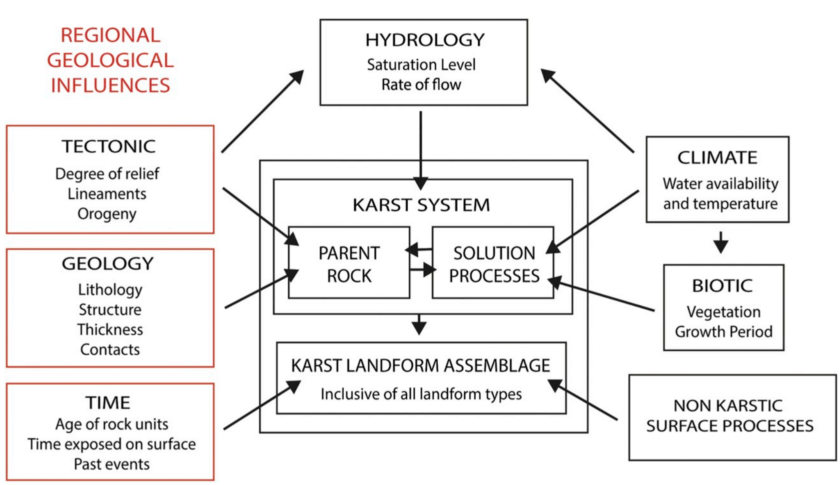

Fig. 3. Image adapted from Marker (1980) showing relationships between regional influences and karst formation.

Fig. 4. A (left): Image west facing of the Drimolen Main Quarry palaeocave, showing central talus cone and the location of the Warthog Cave to the south of the site. B (right): Close up image of the Warthog Cave (displayed in the white box in Fig. 4A): showing uncemented, darker sediments that were deposited during a much later karstification phase (X). Y indicating lighter, cemented palaeocave sediments that winnowed from the Main Quarry talus cone. Photo credit: A. Murszewski, 2017.

emplacement of Bushveld Complex, formation of the Vredefort Impact structure and extensive deformation related to emplacement of Karoo dolerite dykes and sills (see Section 4.8.1). Our goal is to outline the geological drivers of karst formation in dolomitic units within the north-northeastern provinces of South Africa, including sites outside of the Gauteng Province.

4. Regional geological formation of the CoH

Due to the lengthy geological history of southern Africa and associated nomenclature in the literature, a synthesis of the bedrock stratigraphy in the CoH has yet to be undertaken. Here we contribute a systematic framework for the geological evolution of the region, so that relevant geological knowledge can be integrated into modern interdisciplinary research on karst sites in the region. Since comprehensive studies linking geology to karst formation are relatively novel in the CoH, a secondary objective of this new synthesis is to promote routine adoption of multi-scale geoarchaeological analyses for understanding the formation of hominin-bearing palaeokarst.

As South Africa has a relatively well-preserved, stratigraphic record, a considerable amount of geological information exists on the Archean basement rocks (Kapvaal Craton) to the most recent sedimentary deposits. This synthesis focuses on rocks that are exposed within the north and north-eastern provinces of South Africa, namely the area encompassing the CoH (Fig. 1; 2). To promote consistency and to simplify the comparison of the ages and stratigraphic positions of different rock units, a comprehensive geological history is provided within the supplementary figure, while the distribution of geology is displayed in Fig. 1. Sequences such as the Transvaal Supergoup (specifically the Malmani Subgroup) and the Bushveld Complex are particularly relevant to the geological evolution of the karst landscape in the CoH, hence these will be discussed in greater detail, following an overview of the regional stratigraphy. To provide a complete stratigraphic account, every major super-group that outcrops in the north and north-eastern provinces of South Africa is briefly discussed.

4.1. Early Archean Successions

Archean rocks in South Africa are characterised by a long history of accretionary tectonics beginning with the formation of the Kaapvaal Craton, which contains granite-greenstone belts as old as ca. 3.75 Ga (De Wit et al., 1992; Delph and Porter, 2015). Ultramafic and mafic volcanic successions (komatiites, high-magnesium basalts and tholeiites) (Anhaeusser, 1977, 1992) within the greenstone belts and their underlying and surrounding tonalite-trondjemite-granodiorite (TTG) gneisses have been strongly metamorphosed and migmatised, and are intruded by later 3.3–3.1 Ga Archean granites (Robb and Anhaeusser, 1981; Poujol and Anhaeusser, 2001; Arndt, 2014). Most of these units are well preserved to the east and northeast of the CoH, with outcrops extending to the northern border of South Africa (Fig. 1). The Paleoarchean was followed by a period of tectonic quiescence, uplift and erosion prior to deposition of the Dominion Group and the Witwatersrand and Ventersdorp Supergroups.

The Dominion Group is a sequence of volcanics and metamorphosed clastic sedimentary rocks, lying uncomformally on the Paleoarchean granite-greenstone basement of the central Kaapval Craton (Crow and Condie, 1987; Marsh, 2006). The group comprises three lithostratigraphic units; Rhenosterspruit, Rhenosterhoek, and Syferfontein Formations with an age range of 3076 Ma (Armstrong et al., 1991) (Fig. 1).

4.2. Witwatersrand and Ventersdorp Supergroups

The Witwatersrand Basin of South Africa is an Archean sedimentary basin filled with clastic sediments of the West Rand and Central Rand Groups (2.87–2.94 Ga) (Fig. 1). These successions host the richest gold camps in the world, with mineralization occurring within 1 to 2 m thick tabular conglomerate layers of the Witwatersrand Supergroup (Fig. 1), which extends in an east–west direction over a strike length of some 45 km (Naicker et al., 2003). These deposits have been a major driver of mineral exploration (Davenport and Saunders, 2000) and the discovery of extensive gold deposits in this region were the primary motivation for the development and location of Johannesburg. Today, numerous exploration drilling programs and open-cut mine workings occur within the CoH World Heritage Site. This is particularly relevant in the southernmost areas of the Blaaubankspruit Valley (Fig. 2). The proximity of gold mining to palaeokarst resulted in the exploitation of speleothem (i.e. lime) from *in-situ* cave deposits through the late 19th and into the 20th century. This disturbance of stratified palaeokarst deposits still impact the contextualisation of fossil finds in modern day palaeoanthropology throughout the CoH (refer to section 6).

4.3. Transvaal Supergroup

The overlying Proterozoic Transvaal Sequence is preserved within two structural basins in South Africa, the Transvaal Basin and the Griqualand West Basin. Deposition took place under epeiric marine conditions ca. 2.55–2.00 Ga ago and comprises a mixed carbonate-siliclastic ramp grading upwards to a carbonate platform (Walraven and Martini, 1995; Catuneanu and Eriksson, 1999; Sumner and Beukes, 2006; Stratford, 2015). The sequence includes up to 15,000 m of low-grade metamorphic mudstones, sandstones, volcanics and dolomites. The drowning of the platform coincides with the widespread deposition of banded iron formation (BIF) across the Kaapval Craton (Sumner and Beukes, 2006). The supergroup is divided into four primary groups based on age and lithology (Wronkiewicz and Condie, 1990), from oldest to youngest these are the Wolkberg Group, the Chuniespoort Group (inc. Malmani subgroup), the Pretoria Group, and the Rooiberg Group (Sup. Fig).

The sedimentary lithologies within the Transvaal Supergoup (specifically the Malmani Subgroup) form one of the most famous karst landscapes in the world. Following the discovery of hominin- bearing palaeokarst in the early twentieth century, this sequence has been highlighted due to its palaeoanthropological significance (Dart, 1925; Broom, 1938, 1949).

4.4. Chuniespoort Group

The Chuniespoort Group consists of the Black Reef Formation, the Malmani Subgroup (Fig. 5A, B and C), the Diepkloof Formation, the Penge Iron Formation and the Duitschland Formation (Eriksson et al., 2006). A stratigraphical representation of the Chuniespoort Group, as well as the overlying Rooihoogte Formation, highlighting various basin wide unconformities and discontinuous units, are provided in fig. 6.

The Black Reef Formation, in many places, unconformably overlies the protobasinal rocks of the Ventersdorp and/or the Witwatersrand Supergroups. Conglomerates within the Black Reef Formation in this contact zone are typically discussed in its economic significance for gold exploration. Post the deposition Black Reef Formation, a period of tectonic tilting caused southward shift in the dip of the Transvaal basin surface upon which Chuniespoort Group sediments were deposited (Catuneanu and Eriksson, 1999; Ingram and Van Tonder, 2011). The Chuniespoort Group (mainly the Malmani Subgroup) is interpreted to have been deposited in a tidal flat environment (Truswell and Eriksson, 1973). Deeper water in the Transvaal basin saw high levels of soluble iron and manganese that reacted with free oxygen to deposit banded iron formations (Penge Iron Formation) and manganese rich beds (MnF) in discrete locations (Voëlwater Subgroup) (Beukes, 1983; Eriksson and Altermann, 1998; Schneiderhan et al., 2006).

Based on the relative abundance of interbedded chert (Fig. 5C), stromatolites and shales (Fig. 5B), the Malmani Subgroup has been subdivided into the Oaktree, Monte Christo, Lyttleton, Eccles and Frisco Formations (Truswell and Eriksson, 1973; Obbes, 2000; Eriksson et al., 2006). The formations most relevant to the hominin-bearing karst landscape of the CoH are; the basal chert-free Oaktree Formation (180 m thick), the overlying chert-rich Monte Christo Formation (700 m thick) and 3) the chert-rich Eccles Formation (Martini et al., 2003; Herries et al., 2006a). The Eccles Formation is capped by the Leeuwenkloof Member, which consists of angular to sub-angular chert fragments within a siliceous matrix. The majority of hominin bearing sites in the CoH lie within the chert-rich Monte Christo and Eccles Formations; specifically sites of Sterkfontein, Drimolen, Gondolin and Hasgaat (Fig. 2) occur at the boundary of the Oaktree and Monte Christo Formations, within the Monte Christo Formation, within the Eccles Formation and at the upper boundary of the Eccles Formation,

Fig. 5. A (top left): Shale outcrop capping roof of active cave. B (top right): Chertified stromatolites within dolomite outcrop. C (bottom left): Interbedded chert and dolomite within the Monte Christo Formation. D (bottom right): Chert breccia formation with a siliceous matrix. Photo credit: A. Murszewski, 2017.

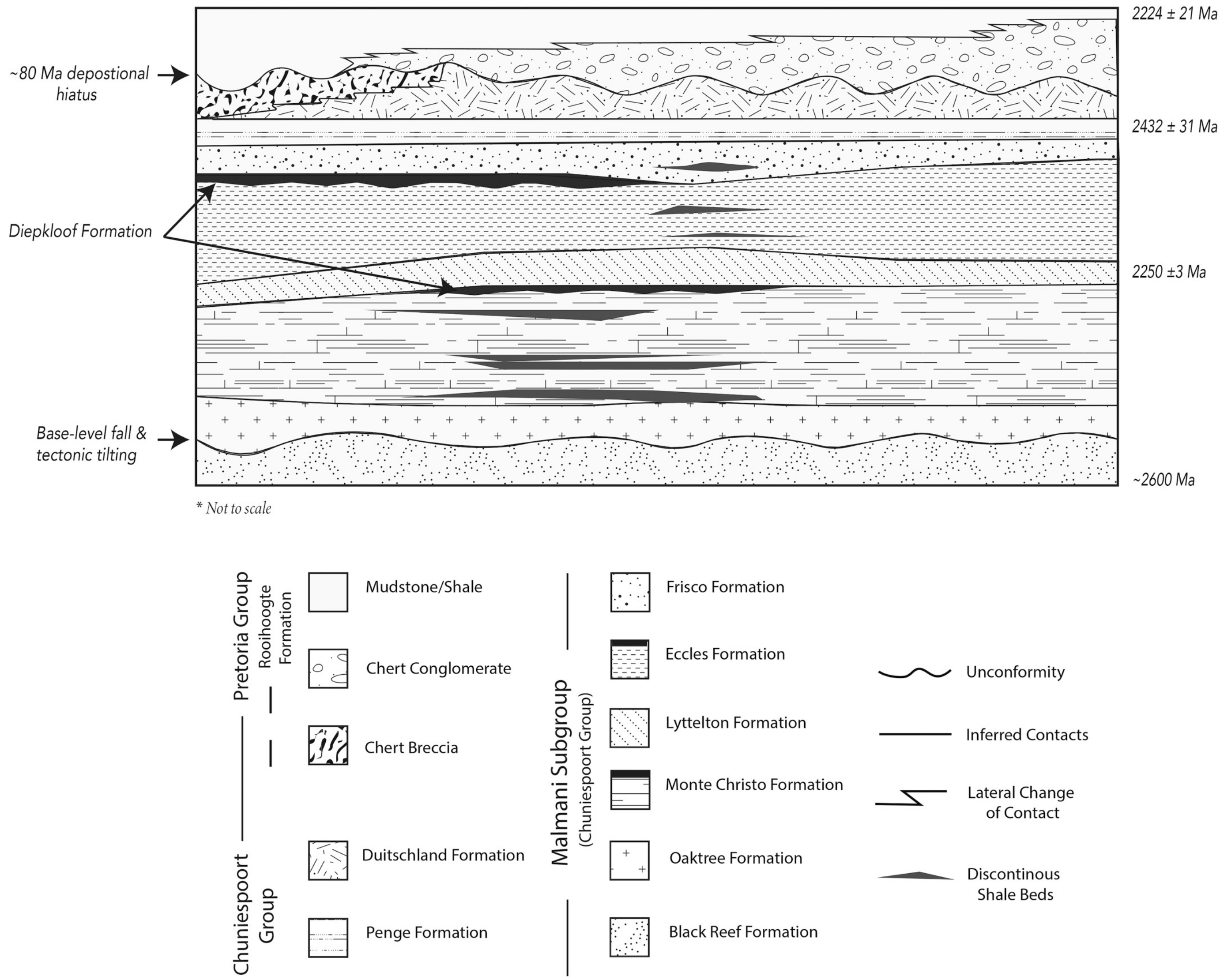

Fig. 6. A basin wide sequence stratigraphic interpretation of the units of the Chuniespoort Group and the overlying Rooihoogte Formation from the Pretoria Group. Unconformities are highlighted as well as lateral variation within facies.

respectively (Obbes, 2000; Martini et al., 2003; Herries et al., 2014).

The Diepkloof Formation unconformably overlies the Monte Christo and Eccles Formations and is described as a ‘chert breccia’; consisting of angular to subangular clasts of chert cemented by siliceous and ferruginous material (Obbes, 2000; Ingram and Van Tonder, 2011; Fig. 5D). It is argued that compressional events related to orogeny at 2.4 Ga exposed dolomites and cherts at the surface where rainwater and carbon dioxide formed a mild acid that reacted with dolomite (Reimold and Gibson, 2010 pp.42). This acid dissolved the dolomite but left the insoluble chert behind as a rubbly chert breccia, which caps topographically higher lying areas throughout the CoH. In some areas, the Diepkloof Formation unconformably overlies the aforementioned chert breccias of the Leeuwenkloof Member that cap the Eccles Formation. The composition and local proximity of these two units allow for the speculation whether the Diepkloof Formaiton and the Leeuwenkloof Member are one of the same.

4.4.1. Rooihoogte Formation

Although not within the Chuniespoort Group, the basal Rooihoogte Formation of the Pretoria Group, unconformably overlies the Malmani subgroup in some areas and is commonly referred to when studying stratified karst deposits. The majority of the Rooihoogte Formation consists of mudstones and an uppermost arenite unit. This material as well as iron formations of the Timeball Hill and/or Strubenkop Formations (refer to Sup. Fig.) has been identified within palaeocave deposits at Sterkfontein and Rising Star through $^{40}Ar/^{39}Ar$ dating (Makhubela et al., 2017).

The base of the Rooihoogte Formation comprises a reworked chert-breccia and chert-conglomerate unit (also referred to as the Beverts Member), that has also been discussed in karstification studies in the CoH (Eriksson et al., 1993; Obbes, 2000). Although slightly different in composition, the close proximity of the two chert breccia units resulted in the Diepkloof Formation mapped originally as part of the Rooihoogte Formation. This was rectified by stratigraphic studies by Obbes (2000), however confusion still results in the various ‘chert breccias’ (also inclusive of the Leeuwenkloof Member of the Eccles Formation) being discussed interchangeably. There has also been a great deal speculation about the mode of formation of the Beverts Member. Eriksson (1988) has proposed that these units formed as fault scarp talus deposits. Dirks and Berger (2013: pp.113) support this conclusion and refer to this formation as chert-breccia dykes and state “probably developed as a result of extension of the paleo-shelf and opening of the basin in which the Pretoria Group sediments were subsequently deposited.” This theory has then been used to uniformly model karst formation in the

CoH, based on the mere location of chert breccia and palaeokarst material on the landscape. Other concepts presented by Obbes (2000), Catuneanu and Eriksson (2002) and Ingram and van Tonder (2011) argue for regression model and subsequent subaerial exposure, thus removing dolomite from interbedded dolomite-chert units. This is supported by a depositional hiatus of ~80 Ma in between the Pretoria Group (beginning with the Rooihoogte Formation) and the underlying Chuniespoort Group, argued by Eriksson and Reczko (1995), whereby excessive erosion occurred. These successions are then argued to be the depositional product of a rifting cycle in the Transvaal Basin and accumulated during a stage of glacio-eustatic fall (Catuneanu and Eriksson, 2002). The contact between the chert breccias and overlying chert conglomerates are arguably the result of a major tilting event between the deposition of the two facies, separated by an aerial unconformity. Although chert breccias are still discussed as part of the Rooihoogte Formation (Ingram and van Tonder, 2011; Dirks and Berger, 2013) arguments have been made for the separation of these two units at the unconformity; where chert breccias cap the Chuniespoort Group, and the chert conglomerates form the base of the overlying Pretoria Group (Catuneanu and Eriksson, 2002; refer to Fig. 6). This latter depositional model is also supported by the relative abundance of this unit throughout the landscape.

4.5. Bushveld Igneous Complex

The ca. 2.06 Ga Bushveld Igneous Complex (BIC) is the largest known layered igneous intrusion in the world, comprising up to 600,000 km^3 of mafic rocks across an area of 65,000 km^2 (Walraven and Hattingh, 1993; Buick and Gibson, 2001; Cawthorn et al., 2006; Zeh et al., 2015). The BIC underlies the northern extremity of the Gauteng province, cropping out further into the southern Limpopo, northwestern Mpumalanga and north-northeastern North West Provinces (Fig. 1) (Zeh et al., 2015).

The intrusion consists of layered ultramafic and cumulate mafic rocks plus felsic roof zone granitoids (Trumbull et al., 2015). While the mode of formation and source of magma for the BIC is still contested (Vantongeren et al., 2010; Mungall et al., 2016), it is generally agreed that intrusion took place via the injection of multiple sill-like sheets, emplaced at a depth of < 6 km (Kruger, 2005; Cawthorn et al., 2006; Finn et al., 2015). The BIC significantly altered the lithosphere of the Kaapvaal Craton and is associated with an extensive contact metamorphism aureole that mainly affects sediments of the Pretoria Group (Cawthorn et al., 2006; Delph and Porter, 2015). Many rocks within the contact aureole experienced intense deformation that resulted in schistose rocks (Cawthorn et al., 2006). Intrusion of the BIC also affected several formations within the Transvaal, altering the mineralogy of the Penge Iron formation at peak temperatures between 500 and 550 °C (Sharpe and Chadwick, 1982) and causing supergene alteration of the lower Malmani subgroup that produced base and precious metal deposits, which have been targeted for exploration (Sumner and Grotzinger, 2004). Alexandre et al. (2006) report deformation structures and contact metamorphic hornfelses related to the emplacement of the BIC in the Pretoria Group.

4.6. The Vredefort Impact Structure

The Vredefort Impact Structure (VIS) is the result of a large meteorite impact thought to have occurred at ca. 2.02 Ga (Kamo et al., 1996; Moser, 1997) (Fig. 1). Although still contested, many geologists accept that the diameter of the Vredefort structure is approximately 190–250 km in the northeastern provinces, southwest of Johannesburg (Reimold and Gibson, 2010). Due to the nature and scale of this impact event, the underlying rocks (particularly the sedimentary successions of the Transvaal Supergoup) underwent widespread deformation and contact and regional metamorphism (Reimold and Gibson, 2010). The Vredefort Dome at the center of the impact structure is the oldest and largest impact event preserved on Earth and, as such, was declared a World Heritage Site by UNESCO in July 2005 (Gibson, 2011).

The Vredefort Dome is surrounded by a 50 km wide zone of downwarped sediments, referred to as the Pochefstroom Syncline (Bisschoff, 1969; McCarthy et al., 1990; Alexandre et al., 2006). Within the dome itself, inward dipping pseudotachylite fault zones have been observed, indicating normal dip-slip displacement associated with the collapse of an impact crater (Killick, 1993; Gibson and Reimold, 2001). Although the extent of brittle deformation associated with the Vredefort impact event is still debated (Reimold and Gibson, 2010), studies have documented the occurrence of pseudotacylite veins as far north as the Witwatwersand Goldfields (Trieloff et al., 1994).

Various sources cite links between impact structures and the formation of karst in multiple terrains around the world (Matton et al., 2005; Buchner and Schmieder, 2007; Matton et al., 2005; Ghoneim, 2009; Schmieder et al., 2009; Monegato et al., 2011). The spatial proximity of the BIC and the VIS to the CoH (Fig. 7) likely contributed regional deformation within the CoH. These events and their potential links to karst formation are discussed in greater detail throughout section 5.0.

4.7. Waterberg Group

The Waterberg group is composed of three subgroups, which formed within a fault bounded basin during the Palaeoproterozoic (Barker et al., 2006). The Nylestrom, Matlabas and Kransberg subgroups were deposited in alluvial fans, braided rivers, and littoral shelf environments, respectively. These successions provided another source of mining activity in South Africa during the 20th century. Although lead is argued to be the most significant economic driver in the Waterberg group (Barker et al., 2006), others argue for rich sources of titanium, copper, hydrothermal zinc and manganese within the Cleremont, Skilpadkop, and Aasvoelkop formations (Eriksson and Altermann, 1998). These formations are frequently exposed in the landscape near Makapansgat, an important palaeoanthropological site north-west of the main Gauteng extents of the CoH.

4.8. Cape and Karoo Basins

The Cape Basin is host to the siliciclastic sediments of the Cape Supergroup (485–350 Ma), which formed within a rift valley basin over a period of 170 Ma (Truswell, 1977; Thamm and Johnson, 2006). Alternatively, Shone and Booth (2005) have argued that deposition occurred within a passive continental margin basin. Rocks of the Cape Basin are subdivided into the Table Mountain, Bokkeveld and Witteberg Groups (Thamm and Johnson, 2006). Although these units primarily are exposed in the southern and eastern extremities of southern Africa, they are also present in isolated outcrops in the north-eastern provinces (Fig. 1), and hence are briefly discussed here.

Overlying the stable crustal blocks of the Kaapvaal Craton (in the north) and the Namaqua-Natal Belt (in the south) is the retro-arc foreland basin known as the Karoo Basin (Dickinson, 1974; Johnson et al., 1997, 2006). The Karoo Basin hosts up to 12 km of sediments accumulated from the Late Carboniferous to the Middle Jurassic (Johnson et al., 2006). The major lithostratigraphic units within it are the Dwyka, Ecca, Beaufort, Stormberg and Lembomo (Drakensberg) Groups, which are present in the Eastern Cape Province. The Karoo successions are exposed over large portions of the South African landscape and are commonly encountered in regions encompassing sites of the CoH (Fig. 1).

Fossil bearing strata within the Karoo are of global significance for their geological characteristics. Intercontinental faunal assemblages (in Australia, South America, Madagascar, Falkland Islands, India and South Africa) support the original palaeogeographical basis for the existence and location of the Gondwana supercontinent (Du Toit, 1936; Johnson et al., 2006). While the sediments of the Karoo host the most

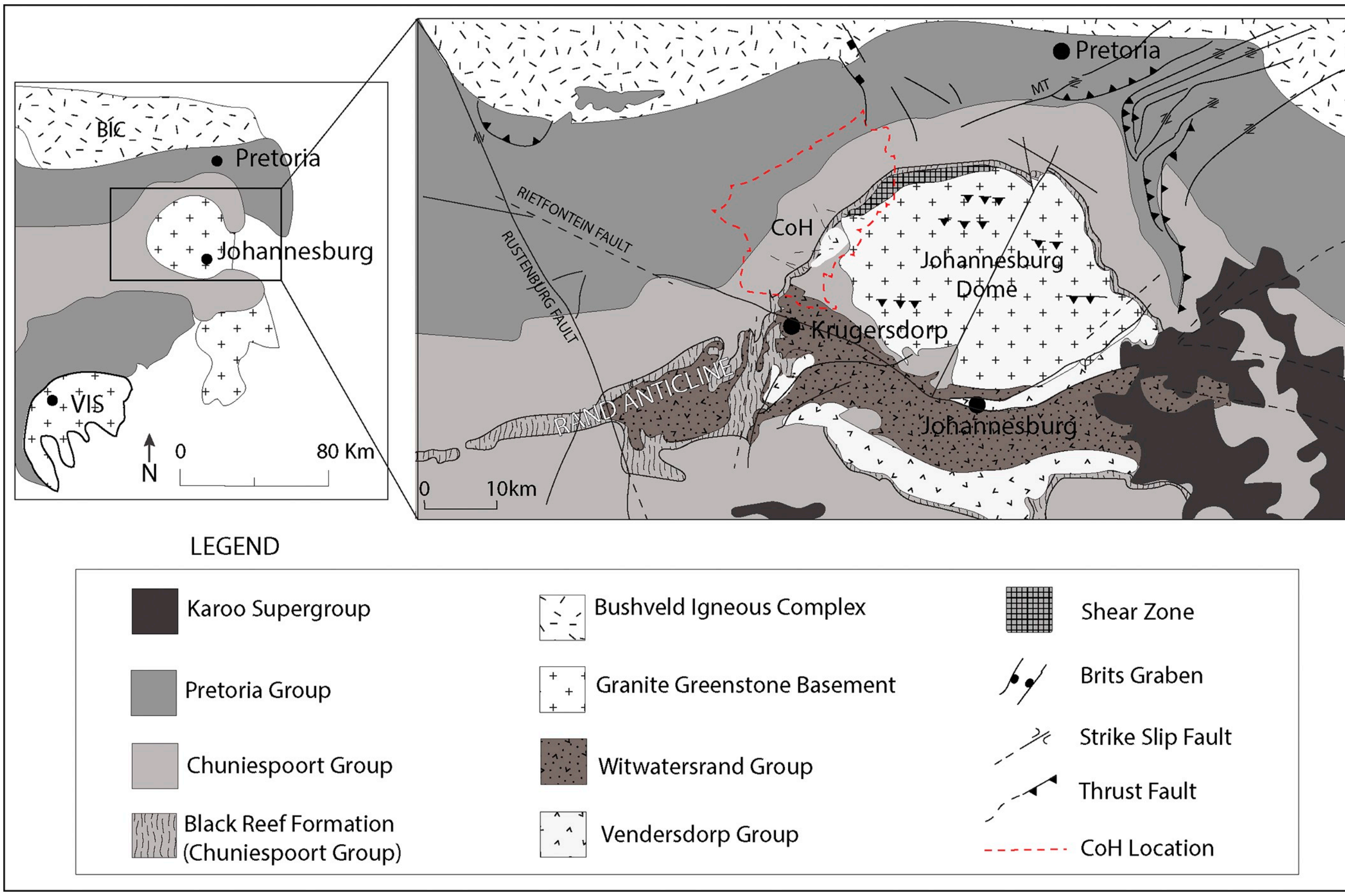

Fig. 7. Simplified geological map displaying the spatial proximity of the Bushveld Igneous Complex and the Vredefort Impact Structure to the CoH; identifying major structures and principal lithostratigraphic units. Adapted from Gibson et al., 1999 and Alexandre et al., 2006.

significant coal reserves in South Africa, other resources (such as uranium and molybdenum) are largely uneconomical (Rowsell and De Swardt, 1976; Christie, 1990; Cole and Wipplinger, 1991; Cadle et al., 1993; Snyman, 1998; Van Vuuren et al., 1998; Johnson et al., 2006).

4.8.1. *The Karoo Igneous Province*

Early Jurassic Karoo magmatism is associated with the emplacement of major sill complexes and associated dykes (The Karoo Igneous Province) into the Dwyka, Ecca and Beaufort sedimentary successions (Hobday, 1977; Svenson et al., 2006) (Fig. 1). The Karoo Igneous Province represents the archetypal Continental Flood Basalt province which was fed by a shallow feeder system represented by the Karoo Dolerite Suite (Duncan and Marsh, 2006). Locally, dolerite sills and dykes form up to 70% of the Karoo Basin stratigraphy where they intrude along a variety of lithological contacts (Neumann et al., 2011). While the Karoo Igneous Province and associated Dolerite Suite have not been identified within the sediments of the Transvaal or the CoH, the presence of dolerite dykes and sills of unknown age is noted in this area (Dirks and Berger, 2013).

5. Structural attributes of the Transvaal Supergroup

The Transvaal Supergroup, encompassing the palaeokarst of the CoH, has often been discussed as preserving a relatively simple basin geometry, with beds that dip toward the center of the BIC (SACS, 1980; Marker, 1980; Eriksson et al., 1995). However, there is a longstanding debate in the literature regarding the nature and timing of deformation within the Transvaal Supergroup, including the Malmani subgroup (McCarthy et al., 1986; Roering, 1986; Andreoli, 1988a, 1988b; Hillard and McCourt, 1995; Gibson et al., 1999). Here we evaluate the deformation that has been observed to affect the Transvaal Supergroup and its possible origins.

5.1. *The Transvaalide Fold-and-Thrust Belt*

A number of models have been proposed to explain the presence of north-verging structures observed within the area including northward thrusting of Witwatesrand and Ventersdorp Supergroups prior to the deposition of the overlying Transvaal sediments at 2.06 Ga (Roering, 1986; Hillard and McCourt, 1995), and the accretion of the Namaqua-Natal belt to the southern and western margins of the Kaapvaal Craton during the Kibaran Event and related Namaquan Orogeny at 1.03–1.00 Ga (Coward et al., 1995; Friese et al., 1995). Further studies in the northern Witwatesrand basin identified north trending cleavage and folds within the Black Reef Formation (McCarthy et al., 1986). An extensive survey of the lower Chuniespoort Group along the northern side of the Johannesburg Dome identified folds and axial planar cleavage similar to those identified within the quartzites of the Black Reef Formation (Gibson et al., 1999). Dolomites of the Malmani Subgroup exhibit widespread evidence of bedding plane reactivation indicated by slickenfibres of quartz within chert laminae. Several bedding sub-parallel shear zones were identified, characterised by intense planar phyllonitic fabrics parallel to shear zone boundaries. Overall, Gibson et al., (1999) documented shear zones, folding, cleavage and lineations that indicate a strong non-coaxial deformation event with top-to-the-north shearing. Although these ductile structures were previously attributed to the Vredefort impact event (Fig. 7), based on recent modelling of syn–impact structures along the outer edge of a crater

Alexandre et al. (2006) suggest that they should be extensional rather than compressional as reported by McCarthy et al. (1986) and Gibson et al. (1999).

Due to the spatial correlation, others have focused on the influence of the BIC (Fig. 7) on the Transvaal Supergroup (Eriksson et al., 1995), however, this does not account for the brittle-ductile nature of folds, cleavages and faults found throughout the Transvaal sediments of the Johannesburg Dome and more specifically, the CoH. An alternative compressional event was first proposed by Andreoli (1988a), which has been more recently supported by $^{40}Ar/^{39}Ar$ ages (Alexandre et al., 2006). To establish an age for these structures, Alexandre et al., (2006) sampled synkinematic muscovite bearing rocks from locations between the BIC and the Vredefort Crater. Lithologies sampled include a mylonitic slate and a tectonic breccia from the Chuniespoort Group (Monte Christo Formation), phyllitic slate and a grey phyllite from the Rooihoogte Formation, and two phyllites from the Timeball Hill Formation. $^{40}Ar/^{39}Ar$ analysis yielded two distinct ages of ca. 2.015 Ga and 2.042 ± 0.0029 Ga. While the latter is based on unambiguous plateau and pseudo plateau ages and thus considered reliable, the younger date is based on disturbed spectra and was dismissed as difficult to interpret by the authors. The 2.042 ± 0.0029 Ga age likely distinguishes this event from known metamorphism associated with either the BIC, which has a U/Pb and $^{207}Pb/^{206}Pb$ age of ~2.05 Ga (Walraven and Hattingh, 1993; Kinnaird et al., 2004; and reference therein) or the ~2.02 Ga Vredefort Impact event (Kamo et al., 1996; Moser, 1997). The generally ductile cleavages and folds are also not reconcilable with high strain rate and associated brittle deformation expected from an impact structure. The top age range of $^{40}Ar/^{39}Ar$ spectra in ooids and peloids within palaeokarst mudstone from Sterkfontein (2.059 ± 0.013 Ga) and Dinaledi (2.096 ± 0.013 Ga) fossil sites, also overlaps these reported ages of the BIC or the compressional event by Alexandre et al. (2006) (Makhubela et al., 2017).

Alexandre et al. (2006) concludes that these ages correspond to a separate tectono-thermal event first suggested by Andreoli (1988a) as the Transvaalide Fold and Thrust Belt (TFTB), which saw orogenic crustal compression extending laterally from Botswana to Swaziland. This compression event reactivated basement thrust faulting, which penetrated units from the overlying Transvaal Supergoup, resulting in additional folding, faulting and an assemblage of mesostructures (Obbes, 2000). Therefore, in addition to any influence the BIC and Vredefort Impact had on the structural geology of the region, it is highly likely that the effects of the TFTB have actively contributed to the karst formation of the Malmani Dolomites within the CoH. It is suggested that future research build on the work of McCarthy et al. (1986), Gibson et al. (1999) and Jamieson et al. (2004) to better elucidate the issue of structural controls on cave formation within the CoH.

6. Karst infill

While there are numerous Cenozoic deposits in South Africa, the most pertinent of these to research on the CoH are palaeokarst infill units, most of which date to < 2.6 Ma (Herries et al., 2018). These South African cave sites contain two main sediment types: allochthonous sediment (ranging from coarse, fossil bearing to fine and sterile) (Fig.8A) and speleothems (Fig. 8B). Speleothem formation is the product of the downward mobilisation of surface derived carbonic acid through the dolomitic country rock. Calcium carbonate minerals precipitate as a result of CO_2 degassing, once solutions reach open spaces (i.e. caverns), occurring mainly as thick basal flowstones and dripstone.

Precipitation of calcium carbonate occurs within a closed cave system, while the cave is still active (i.e. speleothem formation occurring [Monroe, 1970]). The term travertine has also incorrectly been used in earlier literature to define this unit (Vrba, 1981; Clarke, 1994). These are common in all palaeocaves (and active caves) in the region as calcite precipitation from surface and groundwaters is a product of weathering and dissolution of dolomites within the Malmani subgroup. Speleothem growth is expected to be positively related to environmental moisture and to CO_2 availability in underground water (Fairchild et al., 2008), which is in turn related to vegetation cover. There may be different climatic interpretations of these constraints (Pickering et al., 2007; Venter, 2017, and reference therein), but it is possible that a strictly European perspective relating flowstone to interglacials may not be fully valid in southern Africa. Furthermore, as the accuracy of Uranium-Lead dating of flowstones is generally on the order of hundreds of thousands of years, they are too large to be meaningfully paired to variations in orbital parameters (Pickering et al., 2011b). This can be problematic as glacial-interglacial cycling was generally less intense and glacial episodes shorter; notably even more so prior to ~2.6 Ma (Compton, 2011). However, in a simpler context, flowstone layers generally indicate local or generalised halts in clastic sedimentation and therefore are suggestive of cyclical periods of discontinuous cave filling. Alternatively, in relation to more complex, karstic networks, fractures and joints provide meteoric discharge, facilitating not only the localised speleothem formation, but also the

Fig. 8. A (top): Remnant talus cone comprising of course breccia material within at Drimolen. B (middle): Capping speleothem overlying siltstone, WAD and dolomite at Drimolen. C (bottom): Makondo karren formed within palaeocave deposits from Bolt's Farm. Photo credit: A. Murszewski, 2017.

dissolution of host rock and infills. The latter typically enlarges existing openings and facilitates further collapse. Thus, during this corrosive process allogenic sediment accumulates synchronously with speleothem formation local to fracture systems (Stratford, 2017). This more complex suite of processes can be observed in the spatial organisation of openings, re-karstification of sediments and multiple generations of intrusive speleothem growth. Here, broader geomorphological studies are required to determine the nature and distribution of speleothem growth.

Specific to the CoH, it is difficult to assess the range of speleothem that may once have existed as many of these deposits have been mined extensively. At sites such as the Makapansgat Limeworks, an extensive array of speleothem types can be seen with rare surviving examples of calcite rafts, and mammillary speleothem (cave clouds) (Latham et al., 1999, 2003). The massive basal speleothem at the Makapansgat Limeworks indicate formation during a wetter climate in comparison to modern day, and unlike the caves in Gauteng, may point to a much older formation history in the earlier Pliocene (Herries et al., 2013; Reed et al., in press). Speleothems are of great importance in these settings as they provide a means of absolute dating (U/Th, U/Pb; Hellstrom and Pickering, 2015), as well as environmental information from stable isotopes (Hopley et al., 2007). However, because of the prevalence of flowstones surviving over stalagmites, such sequences likely only preserve punctuated phases of calcite formation and thus climate history. When fossil-bearing, clastic units are bounded either side by dateable speleothems – i.e. FBU – flowstone bounded units (Pickering et al., 2007) – the resulting ages provide a maximum (basal flowstone) and minimum (capping flowstone) age bracket (Pickering et al., 2010, 2011b). Intrusive flowstones, however, occur post erosion of established clastic deposits and can be problematic when attempting to obtain reliable depositional age brackets. Here, additional microscopic analysis of the contact between units is required to further assess the depositional sequence and the relationship of speleothem formation with bounding clastic units. Other dating techniques applied to these sites include cosmogonic burial ages (Partridge et al., 2003; Granger et al., 2015) and Electron Spin Resonance (ESR) dating of teeth (Schwartz et al., 1994; Curnoe et al., 2001), whereas palaeomagnetic seriation of fine clastic sediments and speleothem (Herries, 2003; Herries et al., 2006a; Herries et al., 2006a; Herries and Shaw, 2011) in combination with high-quality radiometric dating provides high-accuracy estimates of cave fill formation timing (Pickering et al., 2011b). Flowstone dating was also used in tentative inter-site correlation, even if robust hypotheses can be achieved only by integrating different sources of stratigraphic data (Pickering et al., 2011a).

The coarser clastic material (dolomite blocks and chert blocks) originates from collapse of cave ceilings due to progressive weathering of the bedrock, and accumulates close to entrances or under shafts into underground chambers. These blocks form the framework of unsorted clastic units, which are mostly organised in talus cones. These clastic sediments vary in grain size from massive blocks to finer rubble mixed with much finer brownish to reddish sediment that mostly consist of sand- and silt-sized particles. These are mainly comprised of quartz granules and clay/iron aggregates, deriving respectively from the weathering of cherts and chert breccias, and combined erosion and colluvium of long-evolution soils. Although many literature sources refer to various clastic deposits of all sizes as “breccia” or “cave breccia”, the geological definition of this term only refers to larger angular fragments cemented within a finer matrix. Finer-grained sediments, (i.e., gravity flow deposits easily mobilised sand, silt, clays and muds) are winnowed out of the talus deposit into the lateral extents of the cave, typically developing layered siltstone and/or sandstone units. However, within such complex, dynamic systems, the in-wash of soil sediment is likely to continue, resulting in cyclical or sub-continuous replacement of gravity flow, thus create lateral and longitudinal variability in facies development (Pickering et al., 2007, 2011b; Dirks et al., 2010; Ford and Williams, 2013; Herries et al., 2018; Stratford, 2017). Recurrent thin graded sequences in sandstone/siltstone units may suggest short-period cyclical deposition connected to seasonal/thunderstorm events (Brain, 1995). Hominin and other macrofauna bones of large size are generally included within the “cave breccia” sediments, whereas only small bone splinters and microfauna remains can be found within the sandstone/siltstone units. This is, unless larger bones have been dragged into these areas of the cave by carnivores, or animals have died in these areas of the caves.

Multiple sites in the CoH have defined depositional units; referred to as ‘Members’, based solely on these basic lithological characteristics (i.e. grainsize, colour and matrix, < 15% clast vs. clast supported lithotypes) (Pickering et al., 2007). Thus, many of these defined ‘Members’ categorise probably similar, but potentially non-contemporaneous geological processes, as the limits of the lithological units may be time-transgressive. This has caused serious confusion in reconstructing depositional histories of palaeocaves, including the ages of the fossil remains interned within them. Such confusion has resulted in a shift in paleoanthropological research from a description based member system, to an allostratigraphic correlation with the development of depositional models crossed with chronological techniques discussed above (Herries et al., 2018). More recent geological units identified within the cave deposits include colluvium and infill of more recent material that was washed downslope into a natural depression or makondokarren (a karst pavement of solution pockets within the dolomite formed under colluvial cover) (Fig. 8C).

Lime miner's rubble forms distinctive markers in many palaeocave sites that were exploited for lime throughout the 20th century. Although this is not a natural phenomenon, it still forms a semi-continuous unit over a large portion of many of the sites and marking anthropogenic influence, thus should therefore be included as part of the cave stratigraphy.

7. Discussion

Current disparities in the fossil hominin record in South Africa, such as not being able to resolve the turnover or contemporaneity of specific hominin species, have arisen due to conflicting geochronological results from various dating methods and flawed interpretations of the depositional histories of palaeokarst within the CoH (Herries et al., 2013, in press; Herries and Adams, 2013). There has been a tendency in the palaeoanthropological community to utilise simplistic models of cave formation, based on either Brain's (1958) developmental model of cave development and infill, or the sedimentologically based Member systems of Brain (1976), Butzer (1976) and Partridge (1978; 1979; 1982; 2000). The problem with the latter is that it is built around a concept of identifying sedimentologically similar units, not chronostratigraphic infills. As such, lateral variation in cave processes are defined as different units, which in turn were given different ages.

The work of Latham et al. (1999, 2003) showed that the Member system as used at some sites (e.g. the Makapansgat Limeworks) was fundamentally flawed, while other researchers (Bruxelles et al., 2016) have opted to redefine the Member system of sites such as Kromdraai, while maintaining a similar sedimentological approach. The issue with these approaches is that there is a concentration solely on palaeokarst infill material, rather than the speleogenesis and development of the caves. In part, this is because this is no easy process as much of the original structure of the caves, particularly their ceilings have been eroded away over the last few million years (Fig. 8C). As such, new techniques and approaches are essential for understanding the formation of these sites (Herries et al., 2018).

The confusion over cave formation has been intensified by the advent of chronometric dating in the last two decades. While at certain sites, such as Swartkrans; the dating of different Members has produced complementary results and confirmed their stratigraphic sequencing (Pickering et al., 2011b; Herries and Adams, 2013), at other sites including Sterkfontein; the dating has caused more confusion over how the cave infilled (Partridge et al., 2003; Walker et al., 2006; Herries et al., 2009; Pickering and Kramers, 2010; Herries and Shaw, 2011; Granger et al., 2015; Kramers and Dirks, 2017a, 2017b). Yet, because of Sterkfontein's accessibility and publicity, it is often used as a model for all the palaeocave sites in the CoH. We argue here that there is a high degree of diversity within the Malmani caves. For example, sites like Drimolen Main Quarry consist of large caverns that represent water input points into the dolomite. This mode of formation is similar to the modern, nearby Wonder Cave system. However, sites like Plover's Lake, Rising Star, the Makapansgat Limeworks, represent valley bottom resurgence caves, which are often multi-generational (Herries et al., in press). It is essential to thus understand these differences and the overall speleogenesis of karst sites, rather than concentration solely on infilling characteristics.

This has necessitated a shift in research emphasis to incorporate robust multidisciplinary analyses, producing multi-stage, holistic geological data. Such an approach fundamentally aids in determining the chronology and context of hominin species identified within the karst landscape of the CoH. Since this transition to adopting a more holistic research methodology is in its early stages, the geological data that should be collected alongside these fossil discoveries is still limited. Particularly, large gaps exist at local scales that prohibit understanding of karst formation in relation to the surrounding geology. Most geological mapping in the region have been carried out on larger scales, driven by resource exploration and are subsequently not useful for local karstification studies, nor are they accurate for site-specific analysis.

Initial investigations carried out by Dirks and Berger (2013) at Malapa, modelled a uniform-karst formation model, associated primarily to the chert breccia deposits within the Rooihoogte Formation. Not only is this based on the assumption that these chert breccias are intrusive; it also lacks consideration of local variables that have influenced karst development over time. Time is specifically relevant here as antiquity of palaeokarst sites within the CoH extend to ∼ 3.2 Ma (Partridge et al., 2003; Crawford et al., 2004; Herries et al., 2013). Therefore, having been subjected to numerous, multifaceted geological processes, it should be unsurprising that palaeokarst in the CoH are unique and dynamic systems. Specifically, the landscape surrounding sites further north of the CoH have a different surface geology; including a dominance of silicified chert breccias from the Diepkloof Formation and the Leeuwenkloof Member (separate to the Rooihoogte Formation identified at Malapa; refer to section 4.4.1). Karst ceilings forming along shale and chert beds are also common at sites such as Drimolen and Rising Star, whereas Haasgat has eroded along the side of a large fluvial valley (Dirks et al., 2015). This shows a large variation in the overall speleogenesis of the cave and the surrounding landscape. Furthermore, due to the antiquity of the Malmani dolomite landscape (∼2.6 Ga), the question remains on whether older karst is still preserved in the region, or whether a geological bias exists, removing traces of older karst from the surface.

Intrusive features (i.e. dolerite, quartz) are also prevalent throughout the landscape in the CoH. Although the Karoo Igneous Province and associated dolerite suite have not been identified within the sediments of the Transvaal or the CoH, the presence of dolerite dykes and sills of unknown age are noted in this area (Dirks and Berger, 2013; Herries et al., in press). Specific to Drimolen; located at a high point in the GMD landscape at ∼1543-37 m above mean sea level (amsl) (Fig. 2), a large dolorite outcrop has been mapped in close proximity to the palaeocave deposit. Knowledge of such regional features are important to ascertain mode of karst formation, as factors that influence karstification are not only reliant on the solubility of the rock type, but also characterised by secondary fracture porosity and structure location. As the emplacement of intrusive bodies would have resulted in extensive deformation, geological markers are likely key to the evolution of the karstic landscape, especially at high altitudes.

Although pre-existing discontinuities may play a strong tectonic control on dyke geometry, sub-parallel jointing and intense fracturing zones (i.e. dyke-induced structures) are documented within the Karoo Igneous Province host rocks (Le Gall et al., 2005). Chert deposits within the Rooihoogte Formation have also been argued to be “chert-breccia dykes” present within the GMD (Dirks and Berger, 2013). The relationship between cave formation and chert-breccia deposits have been spatially linked for sites including Malapa and Gladysvale, where researchers have modelled caves forming as elongated fissure chambers along chert-filled fractures. On a regional scale, the composite profile of several mapping projects (Visser, 1969; Hall, 1910; Button, 1973; Klop, 1978; SACS, 1980; Greer, 1982; Eriksson, 1988; Hartzer, 1988; Van Der Nuit, 1990; Obbes, 2000; Catuneanu and Eriksson, 2002) highlight chert breccias in the Rooihoogte Formation as a continuous reliable marker bed throughout the landscape. Thus, the conclusion that these features are vertical dyke or filled fracture structures are not supported by three-dimensional studies. However, as chert breccias are more resistant to weathering than the surrounding dolomite, they likely influence local surface drainage and water geochemistry. Such insoluble chert beds are left standing, which is enhanced by the presence of fissures and joints that facilitate the movement of infiltrating water. Therefore, although site-specific, they may still play an important role during the in early phases and karstification.

Structures involving joints, bedding and foliation also exert noteworthy controls on weathering patterns within the landscape. Although these structures and tectonics may increase erosion, their effects are characteristically seen at the landform scale. Few events within the depositional and deformational histories of southern Africa have been identified here as likely contributors to early phases of karst formation. Firstly, the VIS is thought to have occurred approximately 500 Ma post the deposition of the Malmani Dolomite succession (Kamo et al., 1996; Moser, 1997). Not only is there a clear spatial link between the VIS and CoH (Fig. 7); where impact structures resulting on local karst formation are widely documented (Matton et al., 2005; Buchner and Schmieder, 2007; Ghoneim, 2009; Schmieder et al., 2009; Monegato et al., 2011), metamorphism possibly associated with either the BIC or VIS is clearly visible in the form of slate and slickenfibres of quartz throughout the dolomitic landscape (Gibson et al., 1999). Further studies in the northern Black Reef Formation (McCarthy et al., 1986) and the Malmani Dolomites (Gibson et al., 1999) identified north trending cleavage and folds thought to be associated with the VIS. This is further supported by N-NNE trending structures that have been argued to be associated with karst formation at Malapa (Dirks and Berger, 2013) and Sterkfontein (Martini et al., 2003). Surrounding Sterkfontein cave system, WNW deformation zones have been mapped and comprised of en-echelon elements that cross-cut the strata contacts of the Oaktree and Monte Christo Formations (Hobbs, 2011). Additional GPR and aerial photography confirmed a series of anticlines in the lower Monte Christo Formation. Whether these structural deformities are the product of the VIS, or in fact a compressional event (TFTB) as suggested by Andreoli (1988a) and Alexandre et al. (2006), it is highly logical that the effects of either the VIS, BIC or/and TFTB are related to karst formation in the CoH. Lastly, although the spatial distribution of these structures and the CoH are linked, there has yet to be detailed studies providing site-specific evidence to this.

8. Final remarks

Understanding the various events that contributed to karst formation and preservation can advise current palaeoanthropological studies, while also be useful for locating new, *in-situ* palaeokarst sites in South Africa. This is important, as most material from fossil sites in the CoH has been influenced by lime mining, used for production of local Witwatersrand and Ventersdorp aged gold deposits during the twentieth century. Although unmined sites present their own problems with regards to extensive colluvium cover and access to fossil-bearing units, analysing strata that is found *in-situ* enhances overall confidence of interpretations drawn. By locating untouched, *in-situ* palaeokarst reliable stratigraphic data can be gathered. This enhances contextual information able to be gathered for fossil- material.

Although previous work has been carried out on karst formation processes in the Malmani dolomite, this is the first comprehensive synthesis of the current literature that has focused on synthesising the regional geological history in relation to karst formation. In providing a systematic new synthesis of the literature, we aim to ensure that relevant geological knowledge can be easily incorporated into modern research of fossil bearing caves in the CoH. Research using the geological framework outlined here has already commenced at sites within the northern exposures of the Gauteng Province.

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