Integrating palaeocaves into palaeolandscapes: An analysis of cave levels and karstification history across the Gauteng Malmani dolomite, South Africa

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Abstract
The Drimolen Palaeocave System in the 'Fossil Hominid Sites of South Africa' UNESCO World Heritage Site is well known for numerous remains of early hominins such as Paranthropus robustus and early Homo. These hominin fossils, along with bone tools and notably diverse accumulation of non-hominin primates and fauna, have all been excavated from the 'Main Quarry' area of the site where extensive lime-mining took place. Here we report the first radiometric age of 1.712 ± 0.269 Ma for hominin bearing deposits associated with the DNH7 Paranthropus robustus cranium in the Main Quarry area of the site, which is consistent with recent biochronological estimates. This age is similar to recent estimates for Swartkrans Member 1 Hanging Remnant (somewhere between 2.3 and 1.8 Ma) which also contains Paranthropus and early Homo. Simultaneously, we integrate the newly radiometrically dated Main Quarry deposits with a new fossil deposit, the Drimolen Makondo, discovered in 2013, that is situated some 50 m up the hill to the west from the Main Quarry. It has experienced only limited disturbance from mining but much more extensive erosion. Preliminary excavations and analysis have revealed that the Makondo infill is older than the Main Quarry, dating to 2.706 ± 0.428 Ma. Its greater age is confirmed by biochronology. The Makondo thus overlap with the suggested end of deposition of Australopithecus bearing Sterkfontein deposits, although it is yet to yield any hominin remains. These new dates for the two Drimolen Palaeocave System deposits indicates that, contrary to prior age estimates, the Drimolen site as a whole records the critical hominin and faunal turnover in South African palaeocommunities that occurred around 2.3-1.7 Ma. Finally, as the Drimolen Makondo represents a rare example of a pre-2 Ma fossil bearing deposit in the Gauteng exposures of the Malmani dolomite, we also integrate our results into the greater South African record of palaeodeposit formation (most of which occur between ~2.0 and 1.0 Ma). An analysis of the age of palaeocave infillings across the Malmani dolomite suggests that, as is classically the case with karst, the height within the dolomite is broadly correlated to their age, although with some notable exceptions that are likely related to localised geological features. Our analysis also indicates that most caves have undergone some form of secondary karstification related to a younger phase of cave formation, contrasting with models that suggest the cavities all formed at the same time and that infill is related to erosion and the opening up of cave passages. As such, the reason that few pre-2 Ma deposits have been identified in the Gauteng exposures of the Malmani dolomite is probably because these older caves have been eroded away. Identifying such early caves is critical in understanding

1. Introduction

The early hominin bearing palaeokarst of the Bloubank Stream Valley (aka Sterkfontein Valley1; Sterkfontein, Swartkrans, Kromdraai) situated in the Gauteng Province exposures of the ~2.6 Ga Malmani Dolomite have been the subject of extensive research for over 80 years (Broom, 1936) (Fig. 1). However, until recently little was known about early hominins outside of this single stream valley in South Africa, other than the holotype skull of Australopithecus africanus from Taung (Dart,1925) and the small collection of the same species from the Makapansgat Limeworks in Limpopo Province (Dart, 1925, 1948, Fig. 1). This started changing in the 1990s with the discovery of early hominin fossils outside of the Bloubank Stream Valley at cave sites that had been known about since the 1940s (e.g., Gladysvale; Berger et al., 1993, Fig. 1) and the 1970s (e.g. Gondolin; Menter et al., 1999); alongside new early hominin sites such as Drimolen and Haasgat in the 1990s (Keyser and Martini, 1991; Keyser et al., 2000; Leece et al., 2016), Malapa in 2008 (Dirks et al., 2010) and Rising Star in 2013 (Berger et al., 2015) (Fig. 1). This has led to these sites being incorporated into the 'Fossil Hominid Sites of South Africa' UNESCO World Heritage Site, often referred to as the 'Cradle of Humankind' (Fig. 1).

These discoveries have led to an increasing understanding of early hominin and early Pleistocene faunal biogeography within this very restricted karst area of 270 km2 that spans the border between the Gauteng and North West Provinces (Fig. 1), but has provided little data on early hominins and other mammalian fauna in the region before 2 Ma or further back into the Pliocene. The oldest hominin deposits (Australopithecus africanus bearing Taung Dart deposits and Makapansgat Limeworks Member 3) are both somewhere between ~3.0 and ~2.6 Ma (Herries et al., 2013) and lie outside the Gauteng exposures of the Malmani dolomite (Fig. 1).

While the Stw 573 Australopithecus skeleton has been suggested to date to somewhere between 3.7 and 2.2 Ma, the age of this fossil is contentious (see discussion in Herries et al., 2013; Granger et al., 2015). While new sites are being found on a more regular basis (Adams et al., 2010; Dirks et al., 2010; Dirks et al., 2017) and many of the sites remain undated, there are few confirmed instances of such pre-Pleistocene deposits in the Gauteng Malmani dolomite (GMD).

The majority of sites and deposits such as Kromdraai B, Cooper's D, Swartkrans, Malapa, Sterkfontein Member 5, and Gondolin are all dated to the period between ~2 and ~1 Ma (Herries et al., 2006a,b; Adams et al., 2007; de Ruiter et al., 2009; Dirks et al., 2010; Herries and Shaw, 2011; Pickering et al., 2011a; 2011b; Herries et al., 2009, 2010; 2013; Herries and Adams, 2013). Moreover, other sites such as Goldsmith's, Plover's Lake, Kromdraai A, Drimolen, Gladysvale and Motsetse are also considered to be within this time range based on biostratigraphy (Thackeray and Watson, 1994; Keyser et al., 2000; Lacruz et al., 2002; Berger and Lacruz, 2003; Herries et al., 2009, 2013).

The paucity of securely dated pre-2 Ma hominin-bearing palaeokarstic deposits in the Gauteng Malmani dolomitic region raises the question of whether this reflects a geological bias (e.g., lack of open karstic systems prior to 2 Ma, erosion-mediated obliteration of deposits), and/or the lack of a hominin record prior due to them not occupying the local GMD palaeohabitats prior to this time period. Because addressing this question requires primary data from GMD palaeocave systems with early Pleistocene deposits, here we report on new data critical to interpreting the Drimolen Palaeocave System including the first radiometric (electron spin resonance) dates from the Paranthropus robustus and early Homo bearing Main Quarry deposits (Keyser et al., 2000; Adams et al., 2016, Figs. 1 and 2). We also provide the first primary description and radiometric dates of a newly discovered fossil deposit at Drimolen which we have termed the Drimolen Makondo (Figs. 1 and 3). Finally, as a key hominin-bearing locality located outside the Bloubank Stream Valley and the highest site yet discovered within the GMD (1543 m amsl; Fig. 1; Table 4), we integrate this new data on the Drimolen deposits with an analysis of local geological structures to establish why the site formed where it did on the landscape and discuss the implications for understanding both regional karst formation models and the formation of the local fossil record during the early Pleistocene; something critical for understanding the biogeography of the region.

The various palaeocaves sites are rarely set within their surrounding palaeolandscape or discussed in relation to each other to show the variability of cave forming processes across the GMD.
Only through such an analysis can we better understand why they occur where they do, when they do and how they infilled. An overemphasis in this regard to Sterkfontein and Swartkrans, two sites located a km apart in one single stream valley (Fig. 1), has led to a very specific view about the South African palaeocaves sites. i.e that they are all quite similar and formed by similar mechanisms with great complexity in their deposition. Sterkfontein in particular is really the exception, not the rule with regards the formation and infill of the South African cave systems.

2. The Drimolen site stratigraphy and chronology
2.1. Drimolen Main Quarry (DMQ) The hominin bearing palaeocave system of Drimolen was first discovered in 1992 (Keyser et al., 2000) and lies approximately 5.5 km north east of the Australopithecus africanus, Paranthropus robustus and early Homo bearing sites of Sterkfontein and Swartkrans, and 9.4 km south west of the site of Australopithecus sediba bearing site of Malapa (Fig. 1). Near continuous excavation since 1992 has yielded numerous fossils of Paranthropus robustus, including the most complete P. robustus skull yet found (DNH 7), early Homo, and a range of other mammals; (Keyser, 2000; Keyser et al., 2000; Moggi-Cecchi et al., 2010; Adams et al., 2016). The site has also produced the largest collection of purported bone tools from any of the Plio-Pleistocene early hominin bearing sites with over 100 currently known; although to date only a small number have been fully studied (Backwell and d'Errico, 2008). A small collection of stone tools have also been recovered and are consistent with mode 1 technology. All this material originates from the Drimolen Main Quarry (DMQ; Fig. 1; 2) where lime miners concentrated their efforts in extracting speleothem from the palaeocave system in the early 20th Century, opening up exposures deposit had originally been considered to be between 2.0 and 1.5 Ma based on biochronology (Keyser et al., 2000) and thus of a similar age to Swartkrans and Kromdraai B (Herries et al., 2009).
With the dating of sites like Cooper's D to <1.6 Ma (de Ruiter et al., 2009) and because of East African correlations of the supposedly younger D. aff. piveteaui it had also been suggested that the site maybe at the younger end of this timescale or even younger (O'Regan and Menter, 2009; Herries and Adams, 2013). However, based on the most recent analysis of the fauna and the first identification of the supposedly older Dinofelis cf. barlowi and younger D. aff. piveteaui in the same deposit, the DMQwas envisaged to have been deposited towards the older end of this timescale (Adams et al., 2016); but till now, no radiometric dates have existed for the site.
The depositional sequence within the Main Quarry is extremely simple when compared to sites like Sterkfontein or Swartkrans, with no evidence for deposits that formed at vastly different time periods. The site is interpreted as a single large cavern that has a thick contiguous basal flowstone deposit that is exposed at the base of the depositional sequences on both the northern and southern side of the palaeocavern. overlain by a central debris cone of clast supported breccia (‘blocky breccia’ of Keyser et al., 2000, Fig. 2) that has been the source for almost all the hominin and macrofaunal remains (Keyser, 2000; Keyser et al., 2000; Moggi Cecchi et al., 2010; Adams et al., 2016). This central debris cone accumulated from the opening up and continuing collapse of what appears to have been a vertical entrance shaft based on the very steep slope of the talus cone as showing against the western wall of the palaeocavern (Fig. 2B). At the edges of the Main Quarry palaeocavern fine-grained siltstone and sandstone (Cave Siltstone of Keyser et al., 2000, Fig. 2) has accumulated due to winnowing of this central debris cone by water flowing into the cave shaft. Between the central clast supported breccia at the base of the Central Debris Cone and the Siltstone and Sandstone is an area of sandstone and siltstone matrix supported breccia which grades between the two deposits (Fig. 2B). These deposits have very rare macrofauna and are dominated by microfauna that is of a similar size and mass to the clasts within it. The only secondary cave forming processes that have been identified is on the southern side of the palaeocavern where a vertical entrance cave (calledWarthog Cave) has formed at the interface between the dolomite and the fossil bearing palaeocavern deposits. The sediments that fill this cave are uncemented, dark brown in

colour and contain no bones or fossils, except in sediments that sit directly on the palaeocave sediments. A single Paranthropus robustus tooth (DNH 122) has been recovered at this interface to date. The sediments are completely unlike the palaeocavern fill and completely identifiable, but do illustrate why such secondary karstification needs to be identified so that the potential for mixing can be evaluated (see Herries and Adams, 2013 for more discussion).

The biggest disturbance to the DMQ, is from early Twentieth Century limemining, which has collapsed sections of the deposits as they were undermined by mining (Fig. 2), mostly affecting the eastern side of the palaeocavern where deposits consist of mostly mining debris. In contrast the deposits along the western wall of the palaeocavern are intact. And usefully provide a complete section through the depth and north-south breadth of the original cavern deposits The collapsed block from which the DNH 7 P. robustus cranium was recovered lies in the centre of the main excavation area at the site, which has consisted of the excavation of both insitu deposits and collapsed deposits, mostly targeting decalcified sediments but also the removal of breccia blocks (see SOM for excavation methods). The DNH 7 block has collapsed from a higher position in the stratigraphy and would thus represent some of the youngest layers within the DMQ sequence, compared to the deposits exposed to its west which represent insitu basal breccia cone (Fig. 2). Because the collapse of the DNH 7 Pinnacle happened in recent times due to limining decalcification of this Pinnacle has also occurred recently and thus excellent preservation of fossils in decalcified contexts occur. In contrast, decalcified deposits within makondo features (see below) are more weathered or have been dissolved entirely because the process of decalcification has been ongoing since the cave was calcified and unroofed.

Identifying suitable in-situ teeth that could be sampled for Electron Spin Resonance (ESR) dating and their dosimetry measured has been a challenge as the Main Quarry deposits are dominated by isolated primate teeth and bovid teeth are relatively rare (Adams et al., 2016). However, a suitable bovid tooth was identified and recovered from the DNH 7 Pinnacle (Fig. 2) during sampling for other analyses and this has been used to provide an age estimate for that deposit (and thus the derived DNH 7 P. robustus fossil). It should be noted that this block has collapsed from a point higher up in the sequence and thus represents the youngest layers of the central debris cone in the Drimolen Main Quarry. The DNH 7 block is large enough that it has been possible to undertake accurate dosimetry calculations from both the block itself, and the origin point from where the block fell off. Given the fact that the block fell within the last 100 years or so dosimetry measurements are extremely similar at its origin point and within the block (see Supplementary Online Materials [SOM]). The final age estimate for the tooth based on ESR was 1.712 ± 0.269 Ma (Table 1 and see SOM) suggesting it was deposited sometime between ~1.98 and ~1.44 Ma, concordant with previous biochronological analysis (Adams et al., 2016).

2.2. Drimolen Makondo

A long trench (Fig. 1) excavated in the 1990s stretches from the western lip of the Main Quarry up the hill for about 50 m (Keyser et al., 2000, Fig. 1). This so called 'Keyser's Trench' connected all the known outcrops of palaeokarst as exposed or minimally excavated into by the lime miners who concentrated their efforts on the DMQ deposits. A second trench (Menter's Trench), crossing Keyser's Trench at its midpoint, was excavated north to south in the early 2000s. These cross trenches have exposed extensive 'makondokarren' (Brink and Partridge, 1980; Herries and Shaw, 2011) consisting of rounded solution features eroded into dolomite and palaeokarstic sedimentary deposits that represent the infill of old cave systems that have since become indurated with calcium carbonate.

The makondokarren features form due to groundwater flow beneath the hillside colluvium that creates vertical solutional features (makondos; often referred to as solution tubes but see below), particularly around treeroots, within both the dolomite bedrock and the siltstone, sandstone and breccia deposits of the old cave systems; which simply act as a host rock for their formation, like the surrounding dolomite. Keyser's Trench terminated at its western end at just such a ~3 m deep makondo feature that had been dissolved into a fossil rich palaeocave infill (Fig. 3). A small excavation by lime miners into the northern side had also exposed a basal flowstone and wad (residual insoluble material from the dolomite) formed within the palaeocave. This deposit is now formally termed the Drimolen Makondo (DMK) to differentiate it from the deposits of the Main Quarry (DMQ) where all previous fossils have been recovered (Keyser et al., 2000; O'Regan and Menter, 2009; Moggi-Cecchi et al., 2010; Rovinsky et al., 2015; Adams et al., 2016).

The DMK deposit was first explored in July 2013 when a small rescue excavation was undertaken on decalcified sediment adhering to the walls of this makondo feature (Main Makondo; DMK-MM; Figs. 3-6); excavation techniques presented in SOM) as these were in danger of collapsing due to decalcification. This material was densely fossiliferous and contained a number of articulated skeletal elements as well as suid and carnivore remains from taxa previously unknown in the Drimolen Main Quarry (Keyser et al., 2000; Rovinsky et al., 2015; Adams et al., 2016). To the north of DMK-MM is a SE to NW trending solution feature formed along a fault in the dolomite, termed here the North West Rift (DMK-NWR; Fig. 3), with further palaeocave deposits preserved on its western and southern walls forming the known extent of the deposit at the end of 2013. Digging at the base of the Main Makondo in 2014 allowed access into an adjacent covered makondo (the West Makondo; DMK-WM; Fig. 3) and it was shown to contain further articulated fossil remains in its walls including an articulated primate hindlimb. The covering colluvium of DMK-WM was removed in 2015 and 2016 to reveal the full extent of the ~3mdeep solution tube. Work was also undertaken to remove overburden from around these Makondo features to reveal what now appears to be the full area extent of the Makondo deposit (Fig. 3).

Stripping of colluvium to the east of the DMK-MM soon identified a second makondo feature dissolved into the same palaeocave deposits, subsequently termed the Eastern Makondo (DMKEM; Figs. 3-5). These two features have been the source of the majority of recovered fossil fauna from the site as the unindurated sediment that exists in these makondo features represents decalcified breccia deposits where the makondo feature in essence is a solutional process that has decalcified part of the original palaeocave sediments (Rovinsky et al., 2015, Figs. 3-5). However, this is not the case in all the makondo features as more recent cave forming processes can essentially drain these makondos due to collapse or fluvial action. In such cases they are often refilled with more recent colluvium. It is important to note which is the case as the former will contain fossils contemporary with the palaeokarst whereas the other will contain younger intrusive fossils, which could explain a lot of the mixing noted at other palaeocave sites in the region (Blackwell, 1994; de Ruiter, 2003; Reynolds et al., 2007; Herries and Adams, 2013).

Now that the entire DMK deposit has been revealed from under the covering colluvium it can be seen that the central fossil rich area of the deposit thatwas first excavated is the only area of dense fossil bearing breccia (Fig. 3), although more could be revealed at depth within the makondokarren features. A small area of breccia also occurs at the very south-eastern end of the deposit but contains few fossils in comparison; perhaps representing a basal portion of the breccia closer to an entrance. The rest of the palaeocaves sediments unearthed are horizontally laminated siltstone and sandstone deposits which are again dominated by microfauna and have been winnowed from the entrance breccia. However, unlike in DMQ these siltstone and sandstone deposits do contain articulated macrofaunal remains that cannot have been washed to their location because of their size or have been deposited vis gravity down a slope as they occur in completely horizontally stratified deposits.

There is no suggestion of a talus forming from a vertical entrance that could have produced a death trap deposit as so often suggested for deposits with abundant articulated remains (e.g. Dirks et al., 2010). In the breccia itself complete primate crania occur with articulated jaws (Fig. 4c) as well as a lot of articulated postcrania (Fig. 4e). The accumulation of larger elements within fine grained deposits suggests that the material was brought into the cave and the morphology of the cave suggests it likely had a more horizontal entrance. There is therefore a distinct contrast between the two Drimolen deposits. DMQ is a large cavern infilled by a vertical entrance, whereas DMK is more of a maze cave like system that seems to have developed more horizontally. DMK is also much more significantly eroded and much of the siltstone remains only as small remnants on the dolomite walls of the cave passages (Fig. 3).

The secondary makondokarren can be seen to have formed because of the preferential solution and erosion of the palaeocave deposits rather than the dolomite. This happens because they are easier to dissolve because they are cemented by purer calcite than the harder dolomite. This is a common feature in GMD caves where rekarstification of palaeokarst occurs, often with younger caves forming within older palaeocaves.

The entire depth of the palaeocave deposits (basal dolomite, wad, flowstone, basal breccia and covering siltstones, and sandstones) appears to be represented in the currently exposed makondo sections (Fig. 6). It has become apparent that only a relatively shallow (~3 m deep) remnant of the Drimolen Makondo cave infill remains compared to the deposits preserved in the Drimolen Main Quarry. The most representative profile is located in DMK-MM; Fig. 6, and has been used as reference for the whole site.

The base of the DMK infill can be seen in both the DMK-MM, as well as the western wall of DMK-NWR). At the base of the deposits a dark-grey wad exists that represents the insoluble residue from the dissolution of the host rock dolomite. This is overlain by a ~15 cm thick, laminated flowstone speleothem that steeply dips from north-west to south-east. In the base of DMK-MM, where it is at its lowest point, the flowstone is overlain by up to 100-120 cm-thick layer of coarse rubble, which in-fills the low points in the cave floor's topography (Fig. 6). This breccia deposit is clast-supported with a reddish sandy loam matrix, and comprises of unsorted (up to 70-80 cm) sub-angular dolomite and angular chert clasts; these are poorly oriented, gently dipping from north to south and more steeply from west to east, sometimes imbricated and with some vertical elements. The unit is moderately and locally cemented by calcite. On the northern wall of DMK-MM this unit contains a massive fallen dolomite block (around 1 m wide) most likely the result of roof collapse. This unit is not as bone-rich as the overlying siltstones and sandstones but does contain large identifiable fossil specimens, including an in situ bovid horncore.

The basal talus cone layer is then overlain by 2-3 m (depending on section location) of fossil rich matrix supported breccia with layered siltstone, sandstone and grainstone. In some areas this unit directly overlies the basal flowstone. To the south-east of DMK-MM this grades to a matrix supported breccia with denser and denser block inclusions (Fig. 6), while to the west of DMK-MM the sequence is dominated by macro-fossil poor, well laminated siltstone, sandstone and grainstone. The texture of the matrix and non-brecciated layers consists of sandy loam to gravelly sand with loam, including variable amounts of unsorted and chaotically dispersed coarse clasts (up to 15-20 cm), mostly comprised of angular chert with some sub-rounded dolomite (Figs. 6 and 7).

Finely layered or roughly laminated beds occur in the lowermost horizons, whereas graded trough cut-and-fill bedding characterises the layers overlying the breccia, indicating an east to west flow direction and winnowing from an entrance talus that has almost entirely been eroded away. The breccia is in fact a wedge-like body with maximum thickness in the south eastern part of DMK, thinning down and gently dipping towards the north. This breccia comprises of unsorted chert and some dolomite rubble and is locally clast-supported, with elements lying roughly parallel to the layering planes. The whole unit -breccia and finer sediment- is very strongly cemented by calcite (Fig. 7). Excavation has shown that this deposit contains a large number of partially articulated limbs that tend to be concentrated within particular horizons and many have seemingly been crushed by the deposition of later deposits.

The long bones are generally well preserved and lie parallel to the bedding planes, whereas the pneumatised ones and the crania are crushed and collapsed in-situ (Fig. 4). The uppermost preserved layers contain a dense micromammal accumulation that is most likely an owl roost deposit. Adjacent to this owl roost a bovid tooth was recovered while taking samples for other geologicalanalysis and was used for ESR dating returned an age of 2.706 ± 0.428 Ma (Table 1 and SOM; Fig. 8).

2.3. Fauna and biochronlogy

Further evidence for the pre ~2 Ma age of the Drimolen Makondo deposit and its earlier formational history relative to the Main Quarry comes from the fauna (Tables 2 and 3). The DMK faunal sample published by Rovinsky et al. (2015; Table 2) consists of faunal material almost exclusively recovered from decalcified deposits on the edges of DMK-MM in 2013 and DMK-EM in 2014 (Fig. 5); although a few remains were also recovered from the Southern Makondo (DMK-SM; Fig. 5). Due to the density of fossils in DMK-EM (Fig. 5) excavations had only progressed some 40 cm in depth over an area with a diameter of ~1 m by the end of 2016. One concern when excavating such makondo features, though not something that is regularly discussed in the literature of these S.

African palaeokarst sites, is the potentially high likelihood of mixing of fossils of different ages; as envisaged by Brink and Partridge (1980). This can occur due to direct decalcification of bone from the surrounding palaeocave deposits, as well as fossils being brought into drained makondo features due to later colluvial infilling. It is thus important to assess this when excavating a site, especially if no comparative in situ palaeocave sediments are also being sampled for fossil extraction, as has been the case at a number of similar palaeokarst sites in the region. A lack of identification of such processes may have led to the apparent mixing of different aged fossils at some sites like Swartkrans (see Herries and Adams, 2013) and would significantly affect known species lists for certain sites and the biochronology inferred from them.

At the DMK many of the articulated remains from the edges of DMK-MM and DMK-EM were interned within both the decalcified sediments and continued into the still calcified sediments. This indicates that the fossil material present in the decalcified sediments is derived from the neighbouring calcified deposits and is not a mixture of older residual material with younger fossils. It was also notable that in the still infilled DMK-EM, all the bones were concentrated around the edge of the feature, with the central area being sterile (Fig. 5). This is an artefact of fossils being completelydissolved in the central portion of the makondo, close to the inception point for decalficiation and before it expanded to its current area. The densest area of fossils in both the 2014 and 2015 season have been in the NE corner of DMK-EM within a small area known as the Rhi2 Pocket (Fig. 5). This dense accumulation of fossils can be explained by the position of this deposit against the eastern dolomite wall of the cave, into which more buoyant bones and fine sediments would have been winnowed (Pickering et al., 2007); although it is also an artefact of the fact it is a hollow within the breccia itself and so is in the early phases of decalcification.

It is again important to identify such effects during excavation and 3D plotting with a total station so that they can be considered in taphonomic analyses.

There is no evidence for in-fill by more recent colluvium in DMK-EM, however, this is not the case for all the makondos now revealed and excavated. DMK-WM was entirely filled with colluvium and no fossils were recovered from the loose fill, except against the very southerly wall. This appears to be the case here because a more recent palaeokarstic conduit that runs under DMKWM and DMK-MM has drained the majority of former decalcified infill from these makondo features. This void has then been infilled with sterile, winnowed fine-grained sediment at the base and colluvial infill towards the top and in the centre of the makondo feature. This shows the potential complexity of secondary karstification of such palaeokarst that is crucial to identify during excavation.

A primary description and analysis of the current Drimolen Makondo macromammalian faunal assemblage has been provided in Rovinsky et al. (2015; Table 2) and will only be briefly summarised here with an emphasis on comparisons with the DMQ faunal assemblage described by Adams et al. (2016; Table 3). The majority of the excavated fossil specimens, as at other comprehensively sampled calcified and decalcified palaeokarst-derived fossil assemblages from the region, consists of indeterminate (largely diaphyseal) fragments (49.5%) and identifiable (largely epiphyseal or craniodental) elements (50.5%) with only a smaller fraction (35.0%) of the specimens taxonomically attributable to Order or below (Rovinsky et al., 2015, Table 2). Despite the currently small sample size and high proportion of indeterminate specimens there are several sets of articulated element sets, from the partial skeleton of a Class III (sensu Brain,1974) large-bodied bovid through a crushed cranial skeleton of a ~3 kg canid (Vulpes chama) and medium-sized cercopithecoid primate upper limb (Rovinsky et al., 2015).

While there is overlap in the representation of mammal families between the DMK and DMQ, the overall assemblage composition differs in several key respects. Both deposits include remains of the extinct colobine Cercopithecoides, but no attributable papionin or hominin remains were identified from DMK despite their substantial representation in the DMQ assemblage (Keyser et al., 2000; Adams et al., 2016). Three families of Carnivora are recorded in the DMK sample, representing 12.9% of the recovered specimens, and all the three carnivore genera (Chasmaporthetes, Dinofelis, Vulpes) representing these families are found in both deposits (O'Regan and Menter, 2009; Adams et al., 2016).

The DMK Dinofelis sp. specimens, which consist solely of postcrania, are metrically and morphologically dissimilar to specimens that had originally been described from the DMQ and attributed to Dinofelis aff. piveteaui (O'Regan and Menter, 2009; Rovinsky et al., 2015). While initially viewed as a point of contrast between the two deposits, the recent analysis of the DMQ assemblage faunas by Adams et al. (2016) described a partial right maxillary canine attributable to Dinofelis cf. barlowi; the first instance of two Dinofelis populations to be recorded within a single South African site deposit. The youngest established occurrence of Dinofelis barlowi is from Malapa at ~1.98 Ma (Kuhn et al., 2016a,b; Pickering et al., 2011b). Thus the occurrence of this species in the DMQ may suggest that parts of this deposit are close in age to 2 Ma, or that the last appearance date of Dinofelis barlowi was slightly younger than previously identified. The fact that both Dinofelis species occur in the DMQ does not mean they were contemporary on the landscape, but could simply mean that the DMQ formed over a long time period. The ESR age from the DNH 7 Pinnacle, and thus upper layers of the DMQ deposits, at 1. 712 ± 0.269 Ma (somewhere between 1.981 and 1.415 Ma) does allow for these deposits to fall within this time range and in theory the basal deposits of the DMQ (and thus parts of the collection studied by Adams et al., 2016) could be as old as those in the DMK.

Unfortunately, the DMK ungulate sample is limited, highly fragmentary, and unidentifiable to the generic or specific levels (Rovinsky et al., 2015). At the Tribe level, the occurrence of alcelaphins and antilopins in the DMK is consistent with the dominance of those groups in the DMQ assemblage (Adams et al., 2016). The identification of the genus Hippotragus in the DMK through a partial horn core is novel for Drimolen, but simultaneously the DMK lacks oreotragin or tragelaphin remains that are well-represented Tribes in the DMQ (Adams et al., 2016). Equids are extremely rare within both Drimolen deposits, which is somewhat surprising given the ubiquity of equid remains across other penecontemporaneous eastern and South African deposits (Bernor et al., 2010). While the near absence of equid remains is more significant for interpreting the larger DMQ assemblage, it is interesting to note that the single Equus quagga ssp. individual from DMQ reflects a recent, separate evolutionary lineage from the DMK hipparion specimen (cf. Eurygnathohippus cornelianus) (Rovinsky et al., 2015; Adams et al., 2016).

The best biochronological indicator for the DMK assemblage is a single suid maxillary third premolar (DNM 57; Metridiochoerus sp.), which to date represents the only suid craniodental specimen from across the site deposits (Rovinsky et al., 2015; a single immature suid third metatarsal exists from the DMQ, see Adams et al., 2016, Table 3). This Metridiochoerus specimen is morphologically and metrically aligned with early Metridiochoerus andrewsi specimens from the Makapansgat Limeworks Member 3 deposits (3.03-2.58 Ma; Cooke, 2005; Herries et al., 2013; Rovinsky et al., 2015), as opposed to specimens from post ~2 Ma to ~1.8 Ma sites like Gondolin and Swartkrans (Herries et al., 2006a; Adams et al., 2007; Adams, 2010; Herries and Adams, 2013). While the Makapansgat Limeworks Member 3 represents the first appearance date for M. andrewsi in South Africa (as deposits containing this species at Bolt's Farm are as yet undated), it also represents the most definitive last appearance date of the more primitive Stage I (sensu Harris and White, 1979) M. andrewsi population. The actual last appearance date of this more brachydont M. andrewsi group can only currently be inferred by the occurrence of the significantly more derived (Stage III) M. andrewsi prior to the formation of deposits like Swartkrans Member 1 and Gondolin GD 2 (Herries et al., 2006b; Adams, 2010). Gondolin GD2 is dated to somewhere between 1.95 and 1.78 Ma, but likely closer to 1.8 Ma (Herries et al., 2006b; Adams et al., 2007; Herries and Adams, 2013). The Swartkrans Member 1 Hanging Remnant is perhaps slightly older with an expected age range somewhere between 2.3 and 1.8 Ma (Pickering et al., 2011a,b; Herries and Adams, 2013). Unfortunately no good data exist for this species from Sterkfontein and as discussed above few other sites cover the time period between the end of deposition of the Makapansgat Limeworks Member 3 and Swartkrans Member 1 and Gondolin; except perhaps the earlier internal parts of Gladysvale from ~2.4 Ma (Herries et al., 2013) and Haasgat from ~2.33-1.95 Ma (Herries et al., 2014). The dating of DMK to sometime between 3.134 and 2.278 Ma (~2.7 Ma) is entirely consistent with the presence of Stage 1 M. andrewsi.

2.4. Setting Drimolen within a regional chronological framework

The age of the youngest layers of the Paranthropus robustus, early Homo and archaeological bearing Drimolen Main Quarry at 1.712 ± 0.269 Ma makes it comparable in age to Swartkrans Member 1 dating to somewhere between 2.3 and 1.7 Ma (Pickering et al., 2011a,b; Gibbon et al., 2014, Fig. 8). Whether Swartkrans has deposits older than 2 Ma is still difficult to access as the dating is based on uranium-lead (U-Pb) dating of underlying and capping flowstone speleothem and thus the age of the deposit is only somewhere between this age range. Herries and Adams (2013) have noted that the 2.25 ± 0.05 Ma flowstone underlying the Member 1 Hanging Remnant is heavily eroded before the deposition of the hominin bearing deposits and that the deposit is thus likely closer to the younger end of this age range. This is also suggested by ESR ages between 1.96 and 1.80 Ma for this deposit (Herries and Adams, 2013). Whether the Earlier Stone Age bearing Member 1 Lower Bank contains older deposits remains to be seen.

U-Pb dating dates it to sometime between 2.3 and 1.7Ma (Pickering et al., 2011a,b), whereas using cosmogenic nuclide burial dating Gibbon et al. (2014) have suggested that some of the deposits are as old as 2.19 ± 0.08 Ma based on the age obtained from an unmodified quartzite cobble. This would mean they overlap with the younger age estimates (~2.07-2.01 Ma; Herries et al., 2013) for deposits from the Australopithecus africanus bearing Sterkfontein Member 4. However, a much younger age of 1.80 ± 0.09 Ma was obtained from quartz bearing sediment that was recovered from deeper in the section than the quartzite cobble. Thus the ages are inverted and the difference could be related to the very different types of samples, or the fact that total burial depth cannot be accurately measured because of the removal of the Swartkrans Cave roof. It has often been assumed with cosmogenic dating that once a sample is in a cave it is shielded from cosmogenic rays, but many of the fossil sites are large caverns with fossils coming from talus cones developed below what may have been large open shafts.

Thus the samples would not be shielded the same was as in a deep cavern environment. Potential older burial and reworking of quartz is also a significant issue that can be fully evaluated without understanding what the former landscape once looked like.

Parts of the Paranthropus robustus bearing Kromdraai B also date to this time period, but there remains questions as to whether any of these deposits are hominin bearing because Braga et al. (2017) have suggested the stratigraphy was more complex than envisaged by Brain (1981), Vbra (1981) or Partridge (2000). Herries et al.

(2009) originally followed their views that all the hominins came from Member 3, which according to Partridge's Member system should have been younger than 1.78 Ma based on Member 2 deposits having normal magnetic polarity (1.95-1.78 Ma as interpreted by Thackeray et al., 2002) and Member 1 reversed polarity (interpreted as >1.95 Ma by Thackeray et al., 2002). Braga et al.

(2017) state that Herries et al. (2009) miscorrelated Thackeray et al.s (2002) palaeomagnetic data and ignored the KB stratigraphy noting that the reversed polarity speleothem sampled by Thackeray et al. (2002) is actually younger than Member 3. Thackeray et al.

(2002) however, do not make this statement and suggest that all the samples they measured were from Member 1 and 2 on the east side of Kromdraai B and hence Herries et al. (2009) interpretation. More recently, and post Herries et al., 2009 interpretation, Braga et al. (2013) have suggested that of the hominin material recovered from breccia, rather than Brain's decalcified deposits, two time periods are represented; the oldest of which represents Member 3.

Member 3 is then separated from an overlying normal polarity deposit that Braga et al. (2013) suggest is the source for the Paranthropus type specimen TM1517, by a reversed polarity flowstone. This might suggest that at least part of what has been known as Member 3 is older than the Olduvai SubChron at 1.95 Ma and that the type specimen is of Olduvai age at 1.95-1.78 Ma, or that the deposit is much younger, being of Jaramillo SubChron age around 1.07-0.99 Ma. P. robustus is thought to occur down to about 1 Ma based on cosmogenic and ESR dating of Swartkrans Member 3 (Herries and Adams,2013; Gibbon et al., 2014); although Herries and Adams (2013) do caution whether the P. robustus remains could simply have been reworked from the older Member 1 deposits. The occurrence of Dinofelis piveteaui in the non-hominin and archaeological site (defined as Acheulian by Kuman, 2007 despite there being no bifaces), Kromdraai A has been used in the past to suggest a younger age for the site in a similar manner to Drimolen Main Quarry based on the age range of that species (<1.4 Ma) at Konso-Gardula and Kanam East in East Africa (Werdlin and Ewer, 2001). (Herries and Adams, 2013). This viewwas bolstered by the dating of the P. robustus and Dinofelis cf. piveteaui bearing Cooper's D to between 1.6 and < 1.4 Ma (de Ruiter et al., 2009). However, the dating of the Drimolen Dinofelis aff. piveteaui to 1.712 ± 0.269 Ma and its apparent 'co-occurrence' with D. cf. barlowi (Adams et al., 2016) means that its occurrence does not necessarily infer a particularly young age, although Drimolen Main Quarry now potentially represents the first and last appearance date of these two species respectively. The P. robustus site of Gondolin between 1.95 and 1.78 Ma (Herries et al., 2006a,b; Adams et al., 2007) is also within the age range of DMQ, but is interpreted as being closer to 1.8 Ma and so likely a little younger than DMQ. At ~1.98 Ma the Australopithecus sediba bearing Malapa site is also within the potential time range of DMQ. Other potential sites within this time range are Motsetse (Berger and Lacruz, 2003), whichwas originally considered to date to between 1.64 and 1.0Ma based on the occurrence of Dinofelis cf. piveteaui, but the dating of DMQ now means it need not be of that age.

In contrast to the P. robustus and early Homo bearing DMQ, the age of DMK (<3.13->2.28 Ma) puts it at an age when we might expect to find Australopithecus in the deposits. Compared to earlier Paranthropus and Homo bearing sites, there are few sites that have yielded Australopithecus, especially within the GMD (Herries et al., 2013). The site of Haasgat has been estimated to date to between 2.3 and ~1.9 Ma based on biochronology and palaeomagnetism (Adams, 2012; Herries et al., 2014), but could simply be around 1.95 Ma based on the expected occurrence of the reversal at the base of the Olduvai within the deposits. Haasgat has recently yielded a partial tooth of either early Homo or Australopithecus (Leece et al., 2016). Given the age of the site this would make it either a very late occurring Australopithecus or one of the oldest examples of Homo in South Africa. Parts of Gladysvale also date to as early as 2.4-2.0 Ma based on electron spin resonance (ESR) age estimates and Australopithecus cf. africanus teeth have been recovered from the breccia dumps at the site (Berger et al., 1993; Herries et al., 2013).Sterkfontein (Member 4, Silberberg Grotto and Jakovec Cavern; Partridge et al., 2003; Pickering and Kramers, 2010; Herries and Shaw, 2011; Granger et al., 2015) has yielded the bulk of Australopithecus fossils in the region and DMK overlaps in age with the Au. africanus bearing Member 4 deposits between 2.6 and 2.0 Ma (Pickering and Kramers, 2010; Herries et al., 2009, 2013) and perhaps the Australopithecus bearing Silberberg Grotto and Jacovec Cavern deposits, although there are considerable debate over the age of these deposits (Herries et al., 2013; Granger et al., 2015).

Jakovec Cavern Australopithecus fossils have been dated by cosmogenic nuclide burial dating to ~4.3-3.5 Ma (Partridge et al., 2003) but have also been suggested to contain Equus (Reynolds and Kibii, 2011), that is not known older than ~2.3 Ma in Africa (Geraads et al., 2004), but is known from the Member 4 deposits at Sterkfontein between 2.6 and 2.0 Ma (Herries et al., 2013).

Older Pliocene deposits have been suggested to occur in the GMD but apart from the Silberberg and Jakovec Cavern ages the majority of sites do not contain hominins and remain dated based on biochronology alone. Some of the deposits at Bolt's Farm, such as Waypoint 160, are also suggested to be some of the oldest in the GMD based on micromammal biochronology (~4.5 Ma; Gommery et al., 2012); however, this interpretation is based on the occurrence of a novel muroid rodent species with intermediate morphology and no occurrence other than atWaypoint 160. A more conservative biochronological interpretation is that the occurrence of this rodent reflects a depositional age somewhere between Langebaanweg at ~5.15 Ma (Roberts et al., 2011) and the Rodent Corner of the Makapansgat Limeworks, which is undated, although deposits at the site have been dated between 3.6 and < 2.6 Ma (Herries et al., 2013). As such, the sites need not necessarily fall midway in age between these two deposits given the lack of an established first or last appearance date. Bolt's Farm as a whole is not Pliocene in age as many of the pit deposits contain Equus and are thus <2.3 Ma (Badenhorst et al., 2011). Hoogland has also been suggested to date to as old as 3.1 Ma based on biochronology and palaeomagnetism, although it occurs in a highland area of dolomite a lot closer to Pretoria and with no other documented fossil sites (Adams et al., 2012). This unique location, like Taung and Makapansgat may thus mean older sites are preserved.

3. Setting Drimolen in an evolving palaeolandscape

3.1. South Africa's geological bias in fossil preservation

Why so few Pliocene and early Pleistocene fossil sites seem to exist has an important bearing of whether the sites and data that we have can be considered representative of human evolution in South Africa throughout the Pliocene and earlier Pleistocene. Our view of early hominin biogeography in South Africa certainly still suffers from a significant geological bias, in that all known pre 1.1 Ma hominin fossil sites are restricted to exposures of the karst landscapes of the Malmani dolomite of northern South Africa. As such, the clustering of early hominin sites in this region and northern South Africa in general is likely a geologically-imposed geographic bias rather than a true representation of hominin biogeography given that we have evidence of australopiths at the Buxton-Norlim Limeworks (aka Taung) and Makapansgat Limeworks, some 360 km south-west (Ghaap Plateau) and 230 km north-east (Makapansgat Valley) of the Gauteng sites respectively; but no evidence in between. However, these two sites remain the only Australopithecus sites outside of Gauteng and have a limited number of fossils both dating to the period between ~3.0 and ~2.6 Ma (Herries et al., 2013); making them the earliest definitive hominin sites in South Africa. Our understanding of the biogeography of earlier Homo in South Africa is only slightly improved since the recent find of a ~1.1-1.0 Ma tooth from fluvial deposits at Cornelia-Uitzoek in the Free State, some 180 km to the SE (Brink et al., 2012).

No understanding of hominin variability can be disassociated with an understanding of the degree of preservation from different time periods as well as regions. The vast majority of the sedimentary infill of palaeocaves in the Gauteng Province exposures of the Malmani dolomite (GMD) are between 2.0 and 1.0 Ma; (Herries et al., 2009, 2010; 2013; Herries and Adams, 2013) meaning that either: 1) older cave infills have simply not been identified to date, despite 80 years of research in the region; 2) cave formation in the region is primarily a Pleistocene phenomenon; 3) older caves and their infills did once occur but have been eroded away. Dirks et al.
(2016) have suggested that erosion rates are relatively constant (~3 m/Ma) across the Gauteng Malmani dolomite and that subsequently the physical character of the landscape changed little over the last 3-4 Ma and as such older caves simply did not occur in the region because it has been eroding very gradually. However, this does not mean that the topography of the current landscape was the same as in the past as much greater erosion rates of up to ~53 m/Ma have been recorded for some geomorphic features near the sites of Gladysvale and Malapa in the northern part of the dolomite (Dirks et al., 2010).

The idea that little has changed in the South African landscape since the early Pleistocene seems to be a reoccurring assumption of many papers with views of the climate as being ‘similar to today’ or drier than today being the most common conclusion (see Rayner et al., 1993). This makes little sense from a geomorphic perspective and when compared against the environmental history of the region where the palaeocaves often contain thick flowstone speleothem that cannot be seen forming in the region today. A situation where caves only begin to form as the region undergoes greater aridity during the early Pleistocene seems at odds with the climate records that do exist (Dupont et al., 2005; Hopley et al., 2007). These basal flowstones are often undated, but are suggested to have formed significantly before any sediments infilled the same cavities being composed in most cases of quite pure calcite or aragonite (Herries et al., 2006a,b; Hopley et al., 2009) and thus while the sedimentary infill of the palaeocaves is mostly post 2 Ma, the basal flowstones and thus caves must have formed prior to this. The sediments found in the caves also attest to significant water bourn deposition (fluvial and hillwash) that is unlike that seen in caves in the region today. The sedimentary sequences often contain speleothem formations associated with significant pools of water or relatively continuous water flow such as cave pearls.

Further afield at the Makapansgat Limeworks, massive amounts of what is likely very old speleothem occurs that is consistent with the even wetter climates of the Miocene-Pliocene (Latham et al., 1999, 2003). Moreover, large quantities of tufa also formed during the Pliocene at Taung (Hopley et al., 2013; Herries et al., 2013; Doran et al., 2015) and older tufa deposits also exist that could be earlier Pliocene in age, or earlier (Kuhn et al., 2016a,b).

One possibility that has been suggested to explain the dominance of sediment infills younger than 2 Ma is that the caves had formed prior to this, but were simply not open to the surface until after 2 Ma because the dolomite was covered by older Karoo cover strata (Dirks and Berger, 2012). If true, this would have a significant effect on other studies that have been undertaken and that have assumed a similar exposure of geology in the past as today. In particular, strontium isotope studies on South African hominin teeth that have been used to suggest landscape use (Copeland et al., 2011) whose conclusions would be significantly impacted by such changes in surface geology. This highlights the need to look outside the deposition within the cave and try and understand the evolution of the palaeolandscapes that surrounded them; something equally important for understanding hominin and mammalian variability and change through time.

3.2. Drimolen's geological setting & intrusive volcanics

Drimolen is located at a high point in the Malmani dolomite landscape at ~1543-37 m above mean sea level (amsl; Fig. 1; Table 4) and is ~ 5-7 km north east of the Bloubank Stream Valley sites of Sterkfontein, Swartkrans, Coopers, Kromdraai and Rising Star, and 9-10 km south west of the fossil sites of Malapa, Gladysvale and Motsetse. It thus occurs in a relatively barren part of the GMD landscape with regards fossil sites and is the only hominin site known in a ~121 km2 stretch of the GMD between the classic Bloubank Stream Valley sites and the newly discovered Nash Nature Reserve sites (Fig. 1). Drimolen is closest to the fossil site of Plover's Lake, located in the eastern end of the Bloubank Stream Valley ~2.3 km to the SE of Drimolen at 1446 m amsl (de Ruiter et al., 2008) and this may have been an ancient resurgence from water draining from Drimolen, although the deposits there are much younger, dated to the last <1 Ma (Thackeray and Watson, 1994; de Ruiter et al., 2008, Fig. 9). Like Sterkfontein, and in contrast to Drimolen, Plover's Lake (1443 m amsl) is still an active cave system, likely draining input water from the active Wonder Cave System, located 1.5 km east of Drimolen and 1 km north of Plovers Lake at 1511 m amsl (Fig. 9). This likely also explains the complexity of the Plover's Lake with deposits of various ages superimposed on each other and with both palaeokarst and modern passages and sediments reflecting generations of karstification.

The multiple stratified deposits at Plover's Lake suggest itmay have been a resurgence for quite a long period of time. While deposits only as old as 1 Ma have been noted here to date, these are very eroded for deposits of this age and perhaps suggest that older deposits would once have occurred but that they have been eroded away by the retreat of valley sides that lead sharply up to Wonder Cave (Fig. 9).

Wonder Cave is probably a good analogy for what the Drimolen Main Quarry Palaeocavern was once like and may help to explain the relationship of the Main Quarry and Makondo deposits.
Wonder Cave is a large cavern and is entered today down a vertical shaft at the bottom of which is a large talus cone stretching down into the depths of the cave and which transitions to mud floors at the edge of the cavern. At the very eastern end of the cavern is a second talus cone deposit that is not connected or related to the first, but is from an earlier, now sealed entrance. It is possible that such a relationship existed between the two palaeocave fills at Drimolen in the past, although the morphology of DMK suggests it is rather a series of narrow passage infills rather than the infill of a single large cavern like DMQ. Drimolen would have been a similar water sink for the same area of karst as Wondercave and may also have draining towards Plover's Lake. However, today surface water drains into the Bloubank Stream Valley further to the west of Plover's Lake. Drimolen also lies close to the top of a hill that marks the separation between two watersheds, the one just described that drains to the south east and into the eastern end of the Bloubank Stream Valley and the second which drains into a valley to the south west and eventually the western part of the Bloubank Stream Valley near Kromdraai.Weather similar drainage occurred ~2.3-1.9 Ma when Drimolen was infilling cannot be accessed without a better understanding of variation in the local erosion of the landscape. Drimolen does not lie in an extensive river channel today and occurs close to the top of a hill with an elevation of 1588 m amsl, and one of the highest points in the GMD. Clues as to why Drimolen is located in this rather unique location, with few other recognised fossils sites close to it, can be found on the opposite hillside to the east (Fig. 10), where a large subvolcanic intrusion of microgabbro (often referred to as dolerite or diabase in the literature; Obbes, 1994, 2000; Ingram and van Tonder, 2011) is exposed. This has been confirmed by petrographic thin section analysis (Fig. 11). This microgabbro appears to be a large laccolith-like structure based on its morphology, which seems unlike many other volcanic intrusions noted in the region, which often occur as sills or dykes (Obbes, 2000; Ingram and van Tonder, 2000). Thousands of such intrusive volcanic features (dolerite, syenite and diabase dykes and sills) have been suggested to occur across the GMD (Martini and Kavalieris, 1976; Obbes, 2000, Fig. 10). Drimolen occurs on a geological map of such intrusives produced by Obbes (1994) where the site is located in what he terms the Rietpuits Member of the Monte Christo Formation. The microgabbro intrusion noted in the field is not identified on the Obbes (1994) map, which instead suggests the occurrence of a large diabase intrusion to the west of the site in the adjacent Crocodile River Member of the Monte Christo Formation (Fig. 10). However, this cannot be identified by ground truthing in the field. The Broderstroom Area Geology Map 2527DD (Ingram and van Tonder, 2011) instead maps a ring of such intrusive volcanics around the area of Drimolen and thus suggests another morphology to these outcrops, again unrelatable on the ground.
Part of the problem is that much of this geological mapping has been determined by vegetation coverage and features on aerial images, rather than on the ground (Obbes, 1994; Ingram and van Tonder, 2011).
The ‘dolerite’ intrusives have been suggested by Obbes (1994) to be Karoo Age (~184-176 Ma; Obbes, 2000; Ingram and van Tonder, 2011) when numerous dolerite intrusions are recorded to the South East (Neumann et al., 2011). Obbes (1994) considers the ‘diabase’ to be Pilanesburg Age (~1.19 Ma). Ingram and van Tonder (2011) have further suggested that some of the intrusives in the region may be related to the intrusion of the Bushveld Igneous Complex (~2.06 Ga; Yudovskaya et al., 2013), which also tilted the dolomite. As such, they are much older than the hominin bearing palaeocaves themselves.
However, their intrusion into the dolomite would have caused faults and structures that would still have an influence on speleogenesis and cave development. Moreover, given the microgabbro intrusion northwest of Drimolen would have intruded at depth within the dolomite and not extruded, its influence on erosion near the surface, speleogenesis and karstification would have been more prevalent within the time period of the formation of Drimolen. The intrusion of the microgabbro would have faulted and fractured the older dolomite as it intruded up beneath it,

through it and into the dolomites bedding planes, creating the fault lines along which the Drimolen palaeocave has formed. These fault lines run SE-NW through the dolomite at the site, radiating around and away from the microgabbro intrusion. In the Main Quarry at Drimolen a more southern fault can be seen running westwards and it is along this radiating fault line that the Drimolen Makondo is partly formed. Other clues to the effects of subvolcanic intrusions come in the form of quartz outcrops on the top of the Drimolen hillside. One such intrusive forms the cap to a large cave shaft on the southern side of the hills summit. It is possible that such subvolcanic intrusions are much more extensive at depth in this area and this may in itself explain the elevation of the dolomite in this part of the Gauteng Malmani dolomite. While mapping the area around Drimolen looking for cavities using Ground Penetrating Radar (GPR) we identified a series of large domed features on the 50 MHz radargrams that may also represent deeper intrusives within the dolomite (Fig. 10).

It has been noted that in other areas of the dolomite these intrusives occur as dykes that compartmentalise the dolomite, having a major effect on hydrology and thus cave formation (Martini et al., 2003; Dirks and Berger, 2012). In areas the major tensional joints along which caves have formed can be seen to be associated with intrusive quartz formation (Kavalieris and Martini, 1976). Certainly these intrusive events appear to have had amajor influence on cave development through diverting water flow, but also likely due to the formation of tension fractures in the dolomite and perhaps also localised uplift, as is likely the case at Drimolen. The occurrence of such igneous intrusives could also be responsible for cave formation in itself and a hypogenic origin for cave formation through rising deep hydrothermal water or mixing of deep water with shallow water has been suggested (Martini et al., 2003).

3.3. Variation in cave morphology across the GMD

While it is often suggested that only heavily jointed maze caves exist in the Malmani dolomite this is simply not the case, as shown by sites such as the river cave of Sudwala and the caves of the Ghaap Plateau such as Wonderwerk and Bushmansgat. While complex maze caves do exist, like Sterkfontein and Rising Star, palaeocaves such as Drimolen, the Makapansgat Limeworks and Historic Cave appear to have been large caverns like Bushmansgat and likely developed after phreatic solution due to subsidence and collapse.

There is actually little evidence that much of the palaeokarst formed like the currently active maze cave systems of the region, but seem often to be large caverns. While it has been suggested that hydrological flow and linkage between the Gauteng cave systems is limited (Wilkinson, 1983), this may not have been the case in the past and some of the caves seem to clearly fit the morphology and character of stream sinks (at the top of hills) and others stream resurgences (within valleys). The amount of speleothem found in the base of many of the caves in the region itself suggests that the climate was significantly different and likely much wetter in the past compared to today, or even between the Pliocene and Pleistocene.

Thus the degree of speleogenesis and cave development may have changed significantly through time, as evidenced at the Makapansgat Limeworks by massive amount of speleothem deposition prior to the cave opening; something not seen in any South African cave today.

The occurrence of two different aged palaeocave deposits in such close proximity at Drimolen allows us to address outstanding questions about how caves have formed and developed in this part of the GMD through time when compared to other sites in the region. There is good data to suggest that caves that formed in the Bloubank Stream Valley would have formed very differently to somewhere like Drimolen, occurring as it does at the highest point of today's GMD landscape, or to sites in the northern, chert capped upland area such as Haasgat (Fig. 1). Our understanding of Pliocene to Pleistocene karstification of the GMD has focused very heavily on a few sites that are within a kilometre of each other, most notably that of Swartkrans (Brain, 1958) and the most studied system, Sterkfontein (Partridge, 1978, 2000; Martini et al., 2003). There has been a tendency to take models that were developed for a particular site (e.g., Brain, 1958 model for Swartkrans) and try to apply it to multiple sites, even though they have different geological settings and life histories of speleogenesis and development. While Sterkfontein Cave is a maze cave that has developed along a series of major fault zones and is related to an active fluctuating piezometric surface (Wilkinson, 1983), other sites do not follow this pattern. For example, Herries et al. (2014) have suggested that Haasgat is a remnant of a larger cave system that once occurred in what is now a steep sided V-shaped valley outside the cave, itself formed by the collapse of the cave system that would have had its speleogenetic origin at the interface between the Eccles Formation dolomite and the Diepkloof Formation (Obbes, 2000) chert breccias that occur on the hilltops in this region. The Diepkloof Formation was originally mapped as part of the Rooihoogte Formation (Obbes, 2000) but the latter description has continued to be used by authors such as Dirks and Berger (2012). Such a speleogenetic origin has also been envisaged for the initiation of the Makapansgat Cave Systems at the contact between the Black Reef Quartzite and Malmani dolomite (Latham et al., 1999, 2003; Latham and Herries, 2004). Such speleogenetic origins, like the formation of caves at the interface between the dolomite and the palaeokarst, occurs in part due to the mixing corrosion effect (B€ogli, 1964) between meteoric waters of different chemistry. In a similar vein the occurrence of such insoluable rock of such different chemistry to the dolomite will help the inception of caves and will also have a significant influence on their morphology and evolution, with insoluable beds often forming the roof or floor of caves. Even thick chert layers within the Malmani itself will effect cave development.

Dirks and Berger (2012) have suggested a similar influence for cave formation near Malapa. Haasgat thus consists of a remnant cave passage that may once have been more of an active stream cave, again unlike the large palaeocavern of DMQ or the small maze-like cave of DMK. A very similar water sink system occurs today in the next valley, again close to the top of the hill, where a vertical shaft leads down to a series of breakdown chambers and then into a streamway. This streamway changes its morphology from a high and narrow rift at its start to a low and wide bedding plan close to its sump. This streamway is strewnwith recent bone from a variety of animals and shows how fossil deposits can form in the very distal part of cave systems, well away from the entrance down which the bone was original deposited. For understanding the taphonomy of these cave systems an understanding of the caves morphology and developmental history really needs to be accessed and tied back to the sedimentology of its deposits.

So while many of the caves in the central and northern part of the dolomite seem to have acted more as water sinks many of the caves that occur in the Bloubank StreamValley are resurgence caves where water exits the valley into the Bloubank Stream. It is this character that makes them more multigenerational in character. In contrast to the water input systems, which often have a simple stratigraphy or consist of multiple deposits scattered across a hillside that have formed as the topography and drainage has changed, the resurgence caves are often complex multi-period systems.

Classic examples of these are the Makapansgat Limeworks Cave further to the north or Plover's Lake within the Bloubank Stream Valley itself.

4. Karstification models and phases of karstification across the GMD A lot of the literature (e.g. work of Keyser, Martini, Partridge, and Dirks; Keyser and Martini, 1991; Partridge, 2000; Martini et al., 2003; Dirks and Berger, 2012) surrounding the caves of the Malmani dolomite has focused on how the formation of caves does not follow a Eurasian model of cave formation and how the caves are maze caves driven by faulting with dissolution having taken place due to slowly phreatic circulation close to the ‘watertable’ (Martini et al., 2003). However, a classic model in karst landscapes is where older caves are found at higher elevations because of water base level lowering and thus the abandonment of older passages and the initiation of newer ones beneath them (Ford and Williams, 1989).

The relationship of the Main Quarry versus the Makondo at Drimolen does conform to such a model where the older deposit is at a higher elevation and is significantly more eroded. Moreover, part of the reason that some of the makondo features have been drained and refilled with colluvium is that

another more recent cave (Porcupine Cave) has formed beneath it on its southern side. Marker and Moon (1969) suggested early on that a number of cave formation levels occurred within the Malmani dolomite (but across the whole of South Africa) that were related to specific erosional surfaces (e.g African/Post-African), although this is at a much larger scale.
4.1. Relationships of sites and deposits The occurrence of potentially different aged deposits or different aged caves in close proximity to each other on the landscape is well documented (Partridge, 1978, 2000; Herries et al., 2009) but in many cases the relationships and ages of the different deposits has been hard to determine (Herries and Adams, 2013). At sites such as Plover's Lake, and also Sterkfontein there is a clear relationship between depth and age, but unlike the classic models of Partridge (1978, 2000), greater depth does not relate to greater age, as current active cave deposits occur beneath the palaeokarst. At Sterkfontein more recent infills (e.g the <1.8 Ma Oldowan and Acheulian bearing Member 5; Herries and Shaw, 2011) have been deposited in cavities formed within older deposits (>2 Ma Member 4; Herries et al., 2013) by the collapse of older deposits into lower cave passages (see Stratford et al., 2012, 2014). This may have occurred on a number of occasions with >2 Ma Member 4 material making way for ~1.8-1.6 Ma Stw 53 Infill material and then the <1.4 Ma Oldowan and Acheulian bearing Member 5. Layered deposits in the lower Name Chamber and Milner Hall attest to both Member 4 and Member 5 aged deposits having been reworked (Stratford et al., 2012, 2016). This may also account for australopith bearing deposits in both the Silberberg Grotto and Jacovec Cavern. It has become apparent that much of the deposits in the lower chambers at Sterkfontein are reworked, which has a bearing on the chronology of these deposits. This has an effect on the suggested ~3.67 Ma cosmogenic ages for the Stw 573 australopith skeleton (Granger et al., 2015) because redeposition and mixing of landscape and cave sediment that previously occurred in higher chambers close to the surface would affect the age modelling, which has been suggested to be <2.8 Ma (Kramers and Dirks, 2017). Palaeomagnetic analysis (Herries and Shaw, 2011) would be dating the age of redeposition rather than the age of the interned fossils and U-Pb dating would also be dating speleothem laid down during this redeposition. As such, all that can be said at the moment is that the Stw 573 australopith skeleton is likely between 3.7 and 2.2 Ma, although its assignment to the same species (Au. prometheus; Clarke, 2013) as documented in the 2.6-2.0 Ma dated Member 4, which does not appear to suffer such reworking issues, perhaps makes an age of between 2.6 and 2.2 Ma more likely. Similar issues of reworking occur at Swartkrans where cavities formed through the 2.0-1.8 Ma Member 1 were infilled with younger Member 2 and 3 deposits (Herries and Adams, 2013).
In contrast to these classic sites the different aged deposits at Drimolen have a clear separation today. Whether this was true in the past remains to be answered as heavy erosion has obscured the original relationship of the two deposits to each other. The vertical and lateral difference between the two deposits could easily be accounted for by variation in the floor topography seen within the nearbyWonder Cave, which itself contains two separate talus cones at either end of a large cavern. A similar level of erosion as seen at Drimolen, when applied to Wonder Cave, may create similar palaeocave remnants, although both deposits at Wonder Cave would clearly have formed within a large cavern setting, unlike Drimolen. Many other sites which today are not stratigraphically linked, such as Kromdraai A and B, could once have been part of the same cave system but perhaps, like Wonder Cave, represent input from different entrances or at different times related to reshaping of the caves morphology. It is often forgotten that the morphology of caves, especially large breakdown caverns, can change dramatically through time and that most caves are dynamic in that they are constantly changing shape through dissolution by water, entrance, wall and ceiling collapse, as well as subsidence. One of the most extreme examples is when more recent cave passage forms through older palaeokarst that formed along the same fault lines. In such situations newer caves will often form within old palaeocaves sediments, it being easier for the water to dissolve the purer calcite matrix of the palaeokarst sediments than the dolomite itself.
At other sites, multiple aged palaeocaves infills still occur but they have not formed within each other but as separate caves, forming complexes of related deposits. Good examples of this are the

Coopers Caves (A-D). In other cases, such as Kromdraai A and B the deposits are not interstratified but due to the erosion that has occurred since they were active caves it is hard to assess if these deposits were once part of the same cavern. The establishment of erosion rate estimates at sites (Dirks et al., 2010, 2016) is beginning to establish this more firmly so that such relationships can be made.

4.2. Understanding erosion histories and reconstructing cave morphology

In general, age-depth relationships of fossil deposits have been examined on an intra-site basis, rather than at a regional scale. Part of the problem is that it is hard to work out whether sites such as Kromdraai A and B (Herries et al., 2009), Drimolen Main Quarry and Makondo (Rovinsky et al., 2015; Adams et al., 2016), or the Pits of Bolt's Farm (Thackeray et al., 2008; Gommery et al., 2012), that appear to contain deposits of different ages, were separate caves or different fills within the same cave due to extensive erosion. In his early work, Partridge (1978) considered that at least 10 m of deposits had been eroded from Sterkfontein, although Granger et al.
(2015) now estimate this to be ~ 3 m/Ma. Recent cosmogenic work by Dirks et al. (2010, 2016) indicated that in valley tops the erosion rate was around 3-4 m/Ma, whereas in valleys it was as much as 53 ± 9 m/Ma. This suggested that significant erosion has occurred to the landscape in some areas that may have significantly changed the topography of the landscape but that little may have changed in the upland areas with perhaps only 12-10 m having been removed since the oldest caves in the region were infilling.
Dirks et al. (2016) use the low average basin erosion rate to argue that the lack of older caves in the region may thus be because they never formed, rather than that they have been eroded away, because the upland part of the region should not have been significantly different in the past. This is significant as there is a question as to whether hominins occurred in southern Africa prior to 3.0-2.6 Ma (the oldest age for hominins at Taung and Makapansgat) or whether this is because older caves did not exist, or have been eroded away, thus creating amajor geological bias to the fossil record that significantly effects biogeographical interpretations (Stone et al., 2016). The survival of the older Makondo deposit at Drimolen may suggest that in fact pre-2 Ma deposits did more readily occur on the landscape but they have suffered significant erosion. Other significantly eroded cave remnants that may be older do also occur in the region, such as close to hilltops near Hoogland (~1500-1490 m amsl). These are 30-40 m below the highest point of the hills today, perhaps suggesting significantly more erosion has occurred in specific upland areas than suggested by Dirks et al. (2016) study. Part of the issue maybe that little erosion has occurred in the upland parts of some areas, especially those in the northern sector of the GMD around Haasgat, due to extensive capping insoluable chert features related to the Diepkloof Formation (Obbes, 2000), the Leeuwenkloof Member capping the Eccles Formation, as well as a potentially undescribed ‘massive blue-green chert’ that maybe related to hydrothermal alteration associated with the ~2.2 Ga Ukubambana Event or the ~2.05 Ga Bushveld Igneous Complex (Obbes, 2000; Kositcin et al., 2003; Dankert and Hein, 2010; Gleason et al., 2011). Recent dates suggest that the Bushveld Igneous Complex caused regional-scale hydrothermal activity circulating 700 km outward from its margins (Gleason et al., 2011).
One issue when it comes to caves and their erosion is that flat water tables do not occur in karst, although due to mine drainage this seems to be the case in the region today. In fact piezeometric surfaces often occur whereby the water level in the karst is at a greater height within hills compared to at resurgences in valleys.
Thus two cave sites of the same age can be active at the same time and thus depositing sediments, but be at very different altitudes.
For this reason it is again useful to understand the palaeokarst in terms of sinks or resurgences. A distinction must also be made between parts of caves formed under entirely phreatic conditions compared to vadose modification, the later likely being the main driver in the palaeokarst. Thus modification of systems can have occurred long after dewatering due to any base level changes and still before active opening and sediment accumulation occurred into the systems. The nature of

water sinks and resurgences is very different and thus it would be expected to see such differences in the palaeokarst, although in some cases the same cave can act as both where there is limited height differences between input and output (e,g as envisaged by Adams et al., 2007 for Gondolin). 4.3. The effect of tectonics on cave formation If an erosion model is correct with regards why older sites do not generally exist across the GMD but significantly older deposits do occur in certain areas, most notably Sterkfontein and Bolt's Farm at the western end of the Bloubank StreamValley, then there needs to be distinct local geology to allow these deposits to survive. One possibility is that the NW trending fault that Sterkfontein formed along (Martini et al., 2003) allowed sediment to accumulate at greater depth than in other areas and thus resist erosion. This may explain the apparent older age of the Bolt's Farm deposits, which seem to have developed along a similarly trending major fault line as Sterkfontein. While these faults and caves are, like Drimolen, associated with volcanic intrusions, other possible reason for large faults in the region maybe due to tectonic folding during the 2.2-2.0 Ga Ukubambana Event or deformation related to the ~2.02 Ga Vredefort Meteorite Impact, the effects of which distorted the Malmani dolomite as far as the GMD outcrops in question (Dankert and Hein, 2010). The extensive nature of such folding, intrusive and impact events in the GMD explains why palaeokarst is so prevalent in this region over other exposures of Malmani dolomite such as the Ghaap Plateau, where the dolomite remains relatively unfractured or tilted.

The South African caves have been suggested to be 'hyperphreatic' in origin whereby deeper parts of cave systems develop close to the interface (within 10 m) between the phreatic and vadose zone as base levels lower (e.g. Partridge, 2000). This is suggested to be mainly driven by recent Pliocene uplift (Partridge and Maud, 1987; Partridge, 2010), although changing environmental factors obviously also have an effect. There has also been considerable debate about how much uplift may have occurred (de Wit, 2007). Martini et al. (2003) have noted that at Sterkfontein the passages remain very similar in size with depth that would mean that during lowering in the piezometric surface the dissolution intensity would need to have remained approximately the same over the entire life history of passage formation, which seems unlikely.

4.4. An evaluation of the deep phreatic karst model

Another hypothesis, a 'deep phreatic karst' model, suggested by Wilkinson (1983) and followed by Dirks and Berger (2012) suggests that the entire depth of the cave systems were formed prior to them being open to the surface as the caves all form within a restricted height zone (1400-1420 m amsl). This is rather a simplistic model as it also assumes that all the caves in the region were formed at the same time and that the age of the deposits in the caves is related to when they break through to the surface. In such a model, caves that are eroded into by valleys open up and are infilled first due to greater erosion rates and those that formed in areas that became hilltops were opened later. Cave infill, and thus the age of the fossil deposits inside would thus be driven by geological factors that promoted (e.g major faults, geological contacts) valley formation, or inhibited it (e.g. capping chert breccia of the Rooihoogte Formation).

Dirks and Berger (2012) have also suggested that chert breccias and other features are often in close association with caves, although this is not the case at Drimolen.

The age of infill into caves may have been further influenced by Karoo cover strata that has since eroded away (Wilkins et al., 1987).

It has been suggested that this occurred around 1550 m, which represents the reconstructed height of the African erosion surface (Partridge and Maud, 1987; Dirks and Berger, 2012). However, Dirks and Berger (2012) also note that the African surface has likely been structurally dismembered since the Miocene and possibly earlier, along numerous small faults, and it is not a continuous surface as generally assumed. While Dirks and Berger (2012) envisaged this Karoo cover as protecting caves that existed from infilling until the late Pliocene/early Pleistocene, Martini et al. (2003) instead suggested this Karoo cover would have stopped dissolution of the dolomite and thus cave formation prior to this period. However, rather than the landscape being significantly covered by Karoo strata in the mid Pliocene with caves sealed below it as envisaged by Dirks and Berger (2012), Dirks et al. (2016) instead suggest that significant exposures of dolomite must have occurred as far back as the early Pliocene based on erosion rates of 3-4m/Ma. Dirks and Berger (2012) do note differences in distributions between fossil bearing caves and non-fossil bearing caves that in itself may be explained by the fact that they formed at different periods with the fossil sites representing palaeokarst that is unconnected to the later phases of karstification.

In the deep phreatic karst model, caves at greater altitude would be considered to have younger infill as per Dirks and Berger (2012; Fig. 9) model. Dirks and Berger (2012) do not completely apply an age-depth relationship across the dolomite and suggest that caves would have opened first in the northern part of the Gauteng Malmani dolomite and that in general the age of cave sediments would be younger. While one of the oldest sites does occur in the north, at Hoogland (>3.1 Ma; Adams et al., 2010) sites at Bolt's Farm in the southern area are also considered to be some of the oldest in the region (Gommery et al., 2012). While many sites in the Bloubank Valley fall within the period between 2.0 and 1.0 Ma, this is related to the formation of that valley, rather than it being in the south per se. Gondolin is also a northerly site but also falls in this time range at ~1.8 Ma (Adams et al., 2007). Overall there seems no apparent age relationship north-south across the Gauteng Malmani dolomite (Fig. 1) but the age of sites is related in part to height within the GMD as well as the sites relationship to river and stream systems.

The Bloubank Stream Valley's formation is heavily controlled by streams flowing off the Black Reef Quartzite and Witwartersrand Supergroup rocks to the South. In contrast the northern sites are controlled by drainage off the dolomite and into the developing Magalies River that runs along the Timball Hill shale between the dolomite and the harder Daspoort Quartzite.

4.5. Cave formation levels across the GMD The other issue with Dirks and Berger’s (2012) model is that caves do not just form within their suggested restricted height range across the landscape or down to that level. As Table 4 shows, the vast majority of fossil bearing caves occur at altitudes between 1480 and 1500 m amsl and while there is a good correlation between the height of the cave and its age, older sites actually occur at greater altitudes in the landscape. This is similar to what would be expected in a typical Eurasian karst model where older caves are formed and abandoned by down cutting and new ones form at lower altitudes. Such relationships between cave levels and erosional surfaces have been postulated by Marker and Moon (1969), although their approach looked at southern Africa wide levels and correlated them to erosional surfaces rather than strictly at overall height in the landscape versus age. There are some exceptions to the height-age correlation and this shows where a simplistic model of landscape evolution cannot explain the distribution of caves and palaeokarst.

Gladysvale is suggested to have first opened up as early as perhaps 2.4 Ma based on electron spin resonance dates (Herries et al., 2013) and continued perhaps continuously until perhaps half a million years ago (Lacruz et al., 2002); although it should be noted that Gladysvale also has a currently infilling cave system that has eroded through these older palaeocaves deposits. Malapa at ~1.98 Ma and Gondolin at ~1.8 Ma are also perhaps lower than sites of a similar age in other parts of the landscape. Notably, these caves all occur in erosional drainage towards the Magalies River on the very northern edge of the dolomite. While Gladysvale remains more intact, occurring into the side of a hill with a horizontal entrance, Malapa and Gondolin consist of heavily eroded remanets of caves and perhaps had vertical entrances to their systems.

Gondolin, the lowest cave also occurs in between the Magalies and Crocodile Rivers and thus a heavily eroded area of the dolomite. In contrast Haasgat is much higher in the dolomite in this area, but is also the oldest site. As such, within this local area the model of older caves at higher altitudes is consistent; but, apart from Haasgat, can't be compared directly with the sites in the Bloubank Stream Valley.

Within the Bloubank Stream Valley height and age again have a good correlation with Plover's Lake at <1 Ma being the lowest (1440 m amsl), and the supposedly Pliocene caves of Bolt's Farm being the highest (1490-1510 m amsl). Of course the degree of erosion should also be taken into account and in this regard the Bolt's Farm sites are some of the most heavily eroded in the landscape and the highest; fitting with a suggested Pliocene age.

However, there are also caves at Bolt's Farm (Bolt's Farm Cave) that are active and contain much younger deposits, but also with remnants of palaeokarst. This does not fit with a model where caves are passive sediment traps through one stage of karstification and infill.

It suggests at least a two phase karstification of the landscape whereby caves have formed in the Pliocene and early Pleistocene and become relict karst. Later karstification has then occurred and formed more recent cave passages. This can clearly be seen at many sites, such as that described above for Warthog Cave in the Drimolen Main Quarry. In fact the reuse of palaeokarstic conduits is very common in the region because it is easier for caves to form within the palaeokarst that is cemented with purer calcite than the dolomite itself. This contrasts with Sterkfontein, where Martini et al. (2003) suggested that the fossil bearing deposits were not strictly palaeokarstic because they believed the lower passages formed at the same time as the fossil deposits such as Member 4.

Now this may be true because Sterkfontein is an active cave system developed along a well-developed fault that would have allowed sediment to penetrate to a greater depth within the dolomite at this location, but as outlined above most of the fossil bearing deposits in the lower chambers are potentially reworked.

Drimolen is another site that does not conform to the height-age model across the landscape, as it is the highest site in the Gauteng Malmani dolomite. Until the discovery of the Makondo deposit it was maximally 2 Ma (Keyser et al., 2000), but as outlined above this can now be extended back to at least 2.3 Ma. At 1543 m amsl and given its eroded nature the Drimolen Makondo is within 10 m of the estimated height (~1550 m amsl) of the African erosion surface and the base of the Karoo cover strata. The dolomite on Drimolen hill behind the site itself reaches a height well above this of 1589 m/ amsl. Unlike the areas around Malapa and Gladysvale this hill has no chert cover strata that might inhibit erosion and a preliminary erosion rate of 10 m/Ma for quartz on the edge of the Drimolen hill (3 times Dirks et al., 2016 3 m/Ma basin estimate for the dolomite as a whole) would suggest that erosion from the top of the hill could have taken 3-4 Ma. This is roughly in keeping with Dirks and Berger (2012) view that given erosion rates and the height of the Karoo cover strata that sites older than the mid-Pliocene are unlikely in the region, but it does also suggest that sites as old as the mid-Pliocene may once have existed in the area and have since been eroded away except in some exceptional cases.

Hoogland at 1493 m amsl, which lies in an area of the dolomite (Schurveberg) close to Pretoria is one of the oldest sites in the region with deposits stretching back to before 3.1 Ma (Adams et al., 2010). The site is relatively well preserved because it is formed in the side of a 1546 m amsl hillside. Nearby small remnants of caves survive at altitudes of 1502 m that could be even older. As is the case in comparing the northern and southern edge of the dolomite it is also difficult to directly compare age-depth relationships across to the Schurveberg where the terrain is again very different. These localised differences may be related to the fact that the dolomite in these areas belongs to different Members, the Bloubank sites being in the Monte Cristo Formation and the northern sites being in the Eccles Formation and the relationships of the dolomite to surrounding strata as well as drainage histories and the occurrence of more weather resistant rock.

5. Conclusions

Which of these karst formation histories is correct, along with other factors such as the presence of suggested protective Karoo cover strata may explain why earlier Pliocene deposits are yet to be found within the Gauteng Malmani dolomite. But understanding this complex geological context of the hominin bearing caves is critically in evaluating biases in the preserved record of the region and thus coming to an understanding of whether Australopithecus only inhabited South Africa after 3 Ma, or if we simply do not, or perhaps will never have the sites that are significantly older than this to tell. At the Drimolen Makondo only a small portion of the original depth of the deposit (~3 m) is seemingly preserved on the landscape and this greater erosion is not related to being in an area with high erosion rates like a stream or river valley. Erosion of such older sites may have been increased in some areas due to localised uplift related to features like the microgabbro intrusion to the east of Drimolen. While the <3.1->2.3 Ma DMK and 2.0-1.4 Ma DMQ deposits appear not to be interconnected at Drimolen, this new deposit does provide more evidence of the repeated formation of caves of different ages at the same point on the karst landscape of Gauteng Province. It also demonstrates how a site that has been excavated for 25 years, which was previously considered to contain only one age of deposit, can be more complex and yield new material from previously undocumented time periods. Given the complexity of understanding long excavated sites with complex overlapping multi-generational infills like Sterkfontein and Swartkrans, Drimolen now provides an alternative, compartmentalised record of the period when Australopithecus went extinct and Paranthropus and early Homo first occur in South Africa; moreover in a very different setting to previously discovered sites.

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Tables

Sample	DMK	DMQ
Enamel		
Dose (Gy)	2107 ± 143	1658 ± 64
U (ppm)	1.46 ± 0.24	2.05 ± 0.41
234U/238U	1.4134 ± 0.0649	1.1881 ± 0.0338
230Th/234U	0.8076 ± 0.0093	0.8980 ± 0.0401
Thickness (m)	950 ± 147	1112 ± 156
Water (%)	3 ± 1	3 ± 1
Dentine		
U (ppm)	19.19 ± 1	17.1 ± 1.5
234U/238U	1.2018 ± 0.0094	1.0805 ± 0.0460
230Th/234U	0.8882 ± 0.0165	0.9577 ± 0.0243
Water (%)	5 ± 3	5 ± 3
Sediment		
U (ppm)	0.65 ± 0.22	1.9 ± 0.5
Th (ppm)	1.35 ± 0.45	3.02 ± 0.2
K (%)	0.21 ± 0.19	0.29 ± 0.05
Water (%)	15 ± 10	15 ± 10
External dose		
Beta Dose (μGy a^{-1})	31 ± 17	53 ± 11
Gamma Dose (μGy a^{-1})	335 ± 68	323 ± 39
Cosmic (μGy a^{-1})	220 ± 65	97 ± 50
Internal dose		
Internal dose rate (μGy a^{-1})	116 ± 78	347 ± 131
Beta Dose rate dentine (μGy a^{-1})	77 ± 52	148 ± 56
P enamel	4.6359 ± 0.7708	0.80 ± 0.25
P dentine	1.8967 ± 0.3315	−0.27 ± 0.08
Total Dose rate (μGy a^{-1})	779 ± 134	968 ± 156
Combine US-ESR age		
Age (ka)	**2706±428**	**1712±269**

Table 1 Combined US-ESR ages and associated data.
The age was calculated using the 234U and ThO decay from Cheng et al., 1998, the enamel and dentine density of 2.95 and 2.85 respectively from Grün (1986), alpha efficiency factor of 0.15 ± 0.02, U8-U4 alpha dose (260 mGy/ka) from Grün (1987), U4-Th0 alpha dose (295 mGy/ka) from Grün and Invernati, (1986a), and an average sediment density of 2.69 ± 0.04 g.cm-3. Data and Ages are expressed with a 2-sigma error.

Taxon	NISP	MNI
Order Primates		
Family Cercopithecidae		
Subfamily Colobinae		
Cercopithecoides sp.	2	2
Cercopithecidae indet.	13	1
Order Carnivora		
Family Canidae		
Vulpes chama	14	1
Family Felidae		
Dinofelis sp.	3	1
Family Hyaenidae		
Chasmaporthetes ?nitidula	7	1
Order Artiodactyla		
Family Bovidae		
Tribe Alcelaphini		
Alcelaphin indet.	2	1
Tribe Antilopini		
Antilopin indet.	1	1
Tribe Hippotragini		
Hippotragus sp.	9	1
Bovidae indet.	133	1
Family Suidae		
Metridiochoerus sp.	1	1
Order Perissodactyla		
Family Equidae		
cf. *Eurygnathohippus cornelianus*	1	1
Total	186	12

Table 2. Listing of fauna from the Drimolen Makondo macromammalian assemblage.

Taxon		NISP	MNI
Order primatesa			
Family Cercopithecidae			
Subfamily Colobinae			
Cercopithecoides williamsi		22	8
Tribe Papionini			
Papio hamadryas robinsoni		260	45
Cercopithecidae indet.		272	4
Order Carnivora			
Family Canidae			
Vulpes chama		1	1
cf. Vulpes chama		1	–
Canidae indet.		5	1
Family Felidae			
Subfamily Machairodontinae			
Dinofelis aff. piveteaui		17	2
?*Dinofelis* sp.		1	–
Dinofelis cf. *barlowi*		1	1
Megantereon whitei		2	1
Machairodontinae indet.		1	1
Subfamily Pantherinae			
Panthera pardus		5	1
cf. *Panthera pardus*		3	1
Panthera sp.		1	–
Subfamily Felinae			
cf. *Caracal caracal*		1	1
Felis silvestris lybica		3	1
cf. *Felis silvestris lybica*		4	2
Felidae indet.		31	–
Family Herpestidae			
aff. *Suricata suricatta*		1	1
cf. *Cynictis penicillata*		3	1
Family Hyaenidae			
Chasmaporthetes nitidula		1	1
Lycyaenops silberbergi		1	1
Hyaenidae indet.		7	2
Carnivora indet.		15	–
Order Cetartiodactyla			
Family Bovidae			
Tribe Alcelaphini			
Connochaetes sp.	2		2
Damaliscus sp.	2		2
Megalotragus sp.	4		2
Indeterminate (Class II/III)	34		9
Indeterminate (Class III)	11		4
Tribe Antilopini			
Antidorcas recki	25		16
Antidorcas cf. *recki*	26		2
Raphicerus sp.	1		1
Tribe Oreotragini			
Oreotragus sp.	12		9
Tribe Reduncini			
Redunca cf. *fulvorufula*	3		3
Tribe Tragelaphini			
Tragelaphus sp.	11		6
Indeterminate	2		–
Bovidae indet.	538		–
Family Giraffidae			
Giraffidae indet.	1		1
Family Suidae			
Suidae indet.	1		1
Order Perissodactyla			
Family Equidae			
Equus quagga ssp.	3		1
Order Proboscidea			
Family Elephantidae			
Elephantidae indet.	1		1
Order Hyracoidea			
Family Procaviidae			
Procavia sp.	5		3
Order Lagomorpha			
Family Leporidae			
Pronolagus sp.	1		1
Leporidae indet.	36		5
Order Rodentia			
Family Hystricidae			
Hystrix sp.	1		1
Order Tubulidentata			
Family Orycteropodidae			
Orycteropus cf. *afer*	1		1
Total	**1380**		**147**

Table 3. Macromammalian species from DMQ after Adams 2012.

Site	Height of entrance or palaeokarst exposure on surface (amsl)	Age	Reference
Drimolen Makondo	1543 m	<3.1->2.3 Ma	this paper
Drimolen Main Quarry	1533 m	2.0–1.4 Ma	Keyser et al., 2000; Herries and Adams, 2013
Wonder Cave	1511 m (Chamber roof at ~1500 m and floor at ~1470 m)	Later Pleistocene infill	
Bolt's Farm -Elephant Cave	1509 m	unknown	
Motsetse	1508 m	unknown	
Bolt's Farm Cave	1504 m	active	
Haasgat	1498 m	2.3–1.95 Ma	Herries et al., 2014
Bolt's Farm – Waypoint 160	1495 m	5.2–2.6 Ma	Gommery et al., 2008
Hoogland	1493 m	3.1–2.6 Ma	Adams et al., 2010
Bolt's Farm - Aves Cave	1492 m	unknown	
Rising Star	1484 m	335-236 ka	Dirks et al., 2017
Sterkfontein Member 4	1483 m	2.6–2.0 Ma	Pickering and kramers, 2010; Herries and Shaw, 2011; Herries et al.,2013
Swartkrans	1482 m	<2.3->1.8 Ma	Pickering et al., 2011a,b; Herries and Adams, 2013
Kromdraai B	1481 m	2.0–1.6 Ma	Thackeray et al., 2002; Herries et al., 2009.
Bolt's Farm- Cobra Cave	1478 m	Pleistocene and active	
Coopers D	1474 m	1.6–<1.4 Ma	de Ruiter et al., 2008
Plovers Lake	1443 m	~1 Ma (estimate)	Thackeray and Watson, 1994
Gladysvale	1433 m	2.4–0.6 Ma	Lacruz et al., 2002; Herries et al.,2013.
Malapa	1421 m	1.98 Ma	Pickering et al., 2011a,b
Gondolin	1390 m	~1.8 Ma	Herries et al., 2006a,b; Adams et al., 2007

Table 4. Elevation (above mean sea level; amsl) of the Cradle Fossil sites versus their age in millions of years (Ma).

Figures

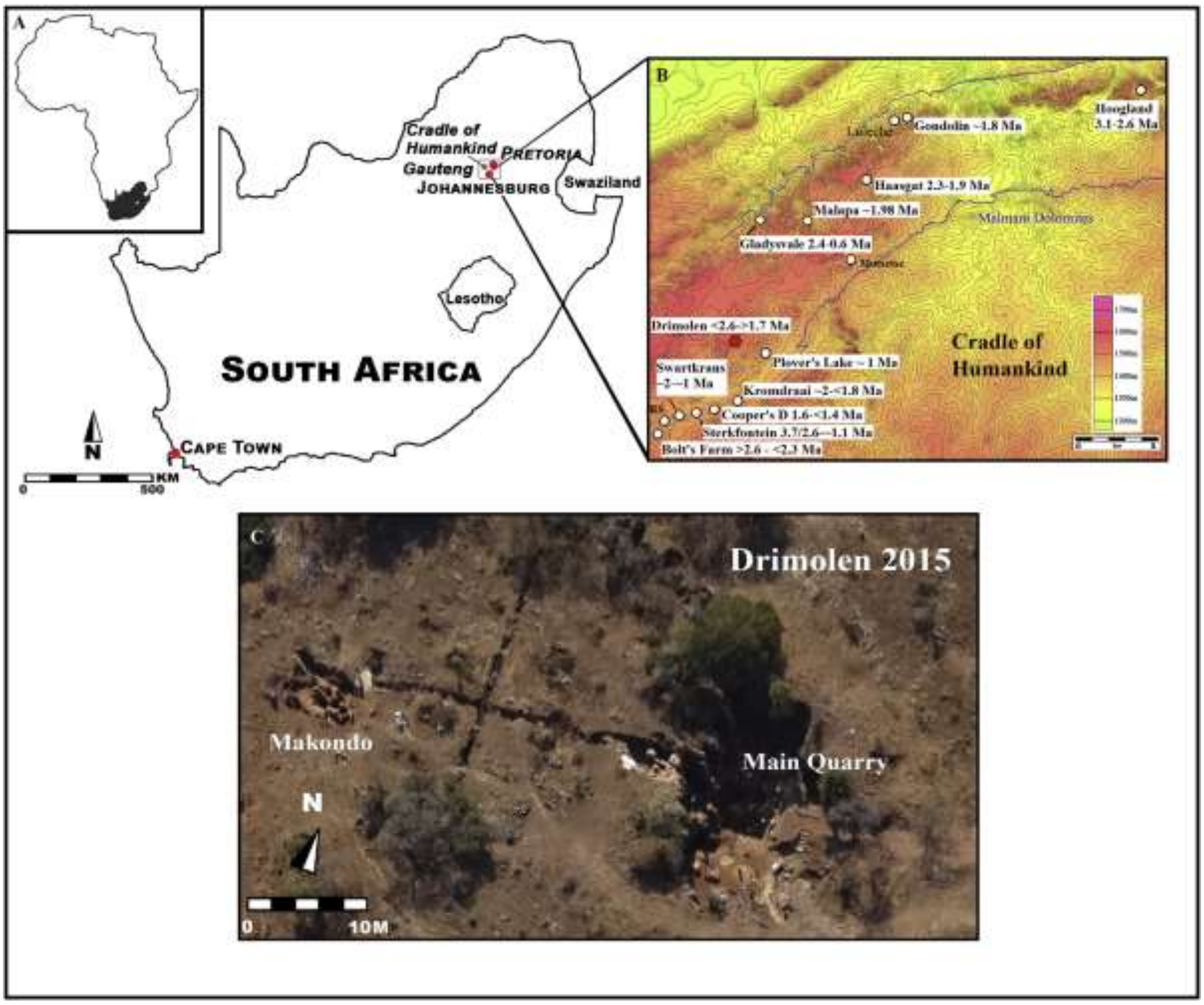

Fig. 1. A) The location of the Cradle of Humankind portion of the Hominid Fossil Sites of South Africa UNESCOWorld Heritage Site, compared to other early hominin sites in South Africa; B) The location, height and age of early hominin and other fossil sites in the Gauteng Province exposures of the Malmani Dolomite; C) The relationship of the Makondo to the Main Quarry at Drimolen.

Fig. 2. The deposits of the Drimolen Main Quarry: A) as envisaged by Keyser et al. (2000; After Adams et al., 2016) showing the location of the ESR sample in the DNH7 collapse block; and B) a photo of the Main Quarry excavations and stratigraphy from the same perspective. The location of the ESR sample to the DNH7 Paranthropus robustus fossil is shown, the latter recovered from a position about 1 m above the current level of the top of the DNH7 collapse block.

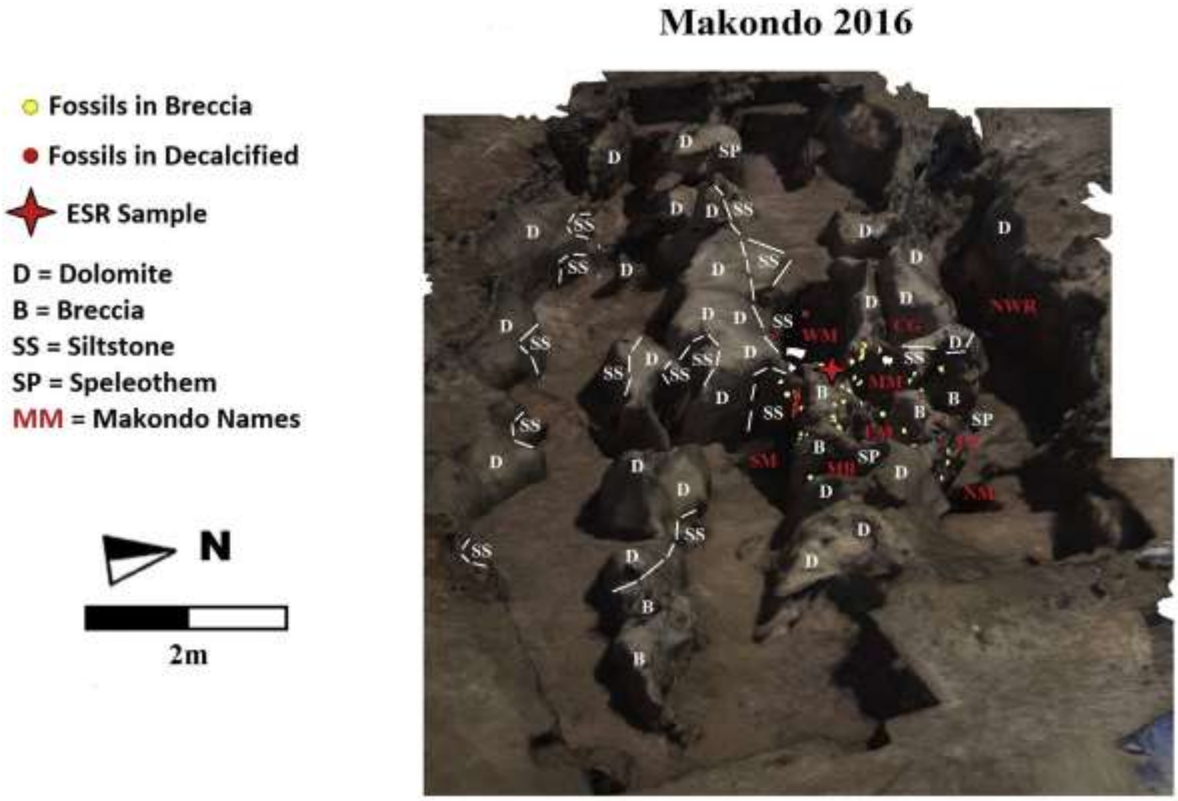

Fig. 3. Photogrammetry model of the Drimolen Makondo at the end of the 2016excavation season. The location of the ESR age is shown along with the location of fossils excavated from decalcified sediments and those still embedded in breccia. These are all concentrated in the centre of the site and a close up of this is shown in Fig. 4. The sedimentological nature of the outcrops is also shown. The methodology for creating the photogrammetry model is outlined in Armstrong et al. (2017).

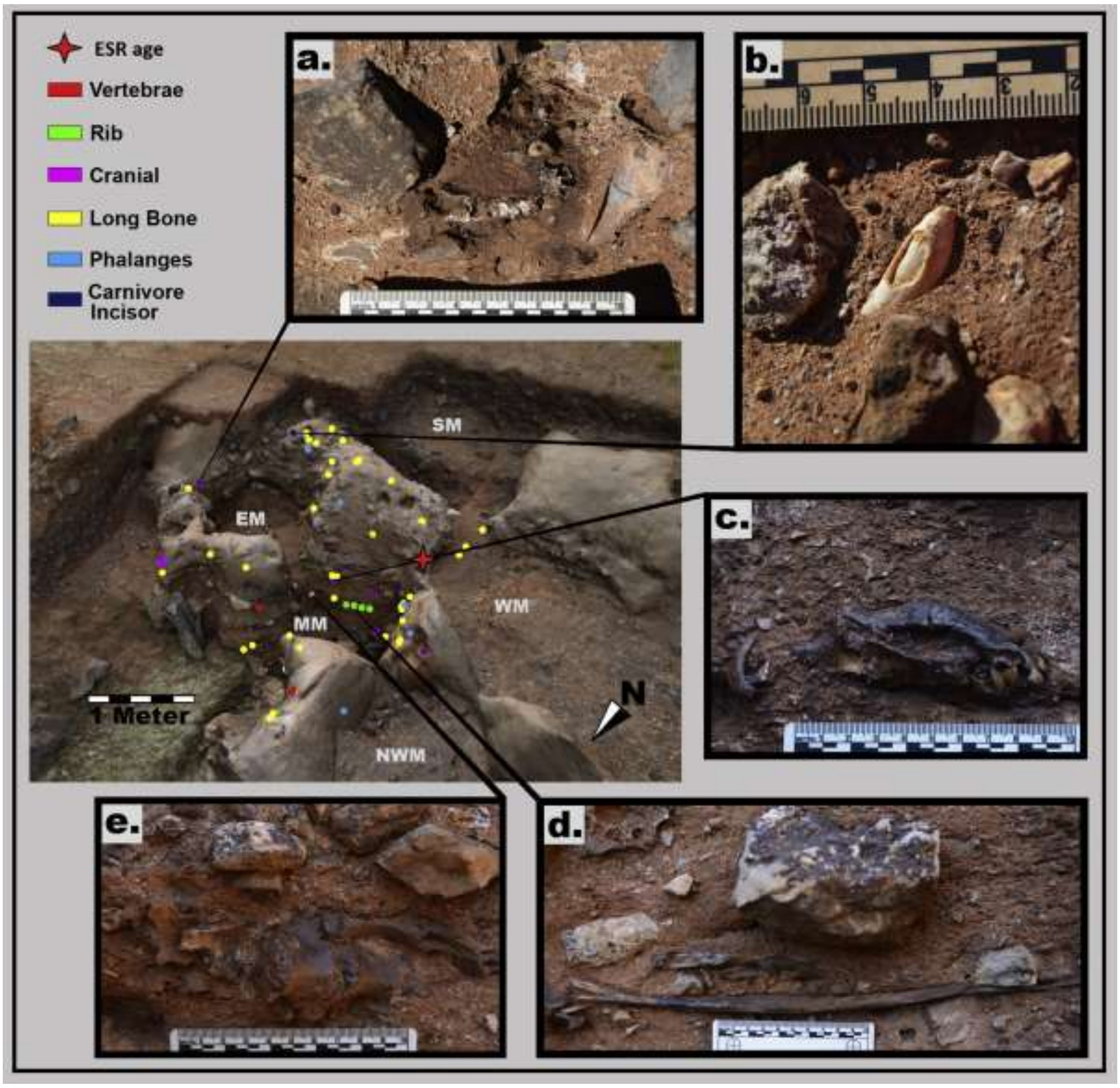

Fig. 4. DMK Main Makondo photomosaics of west and south profiles. 1: slightly cemented coarse dolostone and chert rubble, with red earth matrix. 2: strongly cemented and bone rich siltstone/sandstone, with chert and dolomite clasts.

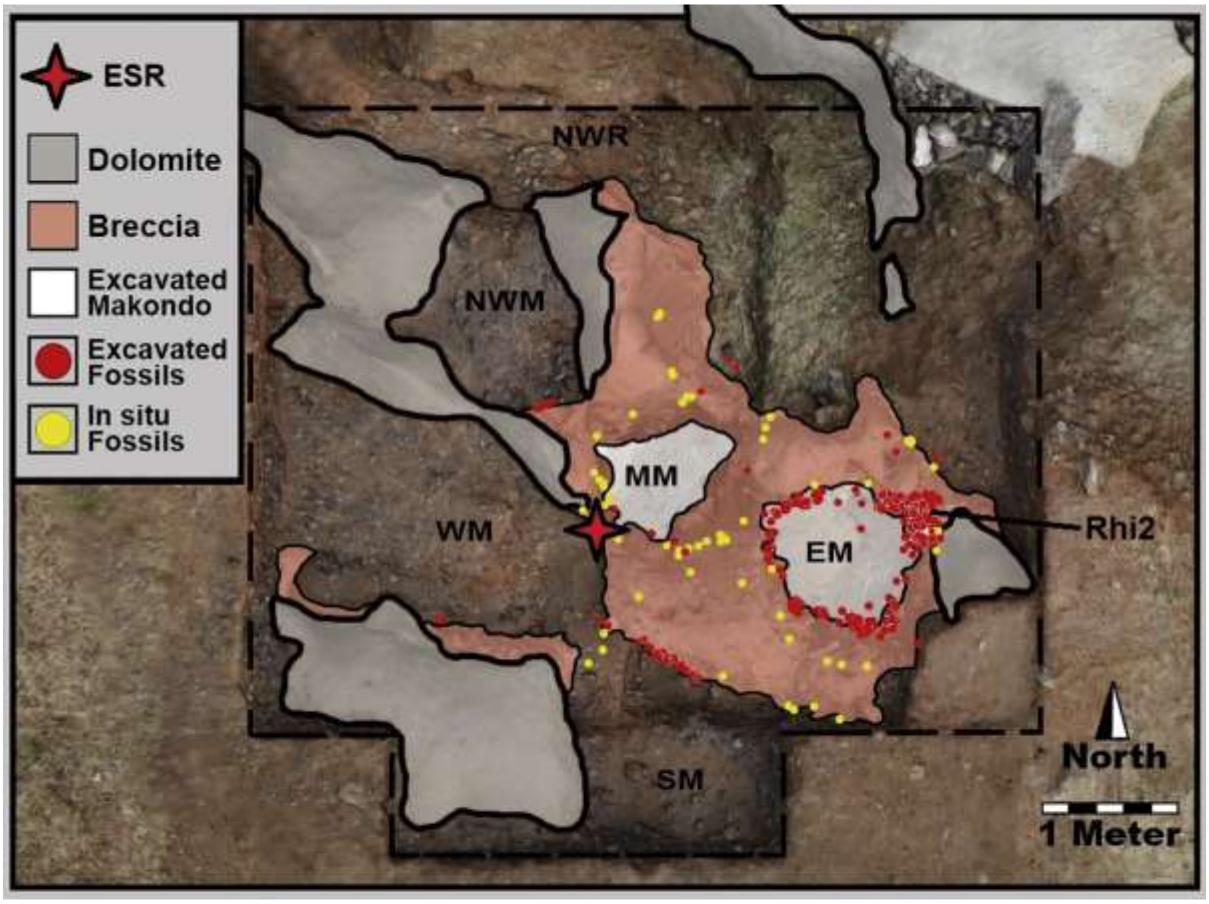

Fig. 5. A photomontage and GIS drape of point provenienced excavated fossils and fossils still in-situ in the surface of the makondo palaeokarst deposits looking rom the north-west to the south-east. Examples of in-situ articulated fossils are also shown: a) primate mandible; b) carnivore tooth; c) monkey skull and mandible; d) ribs of a large class 3 bovid; e) articulated vertebrae of a large class 3 bovid. The designations of the various makondo features is also shown (MM = main makondo; EM = east makondo; WM = west makondo; NWR = north-west rift).

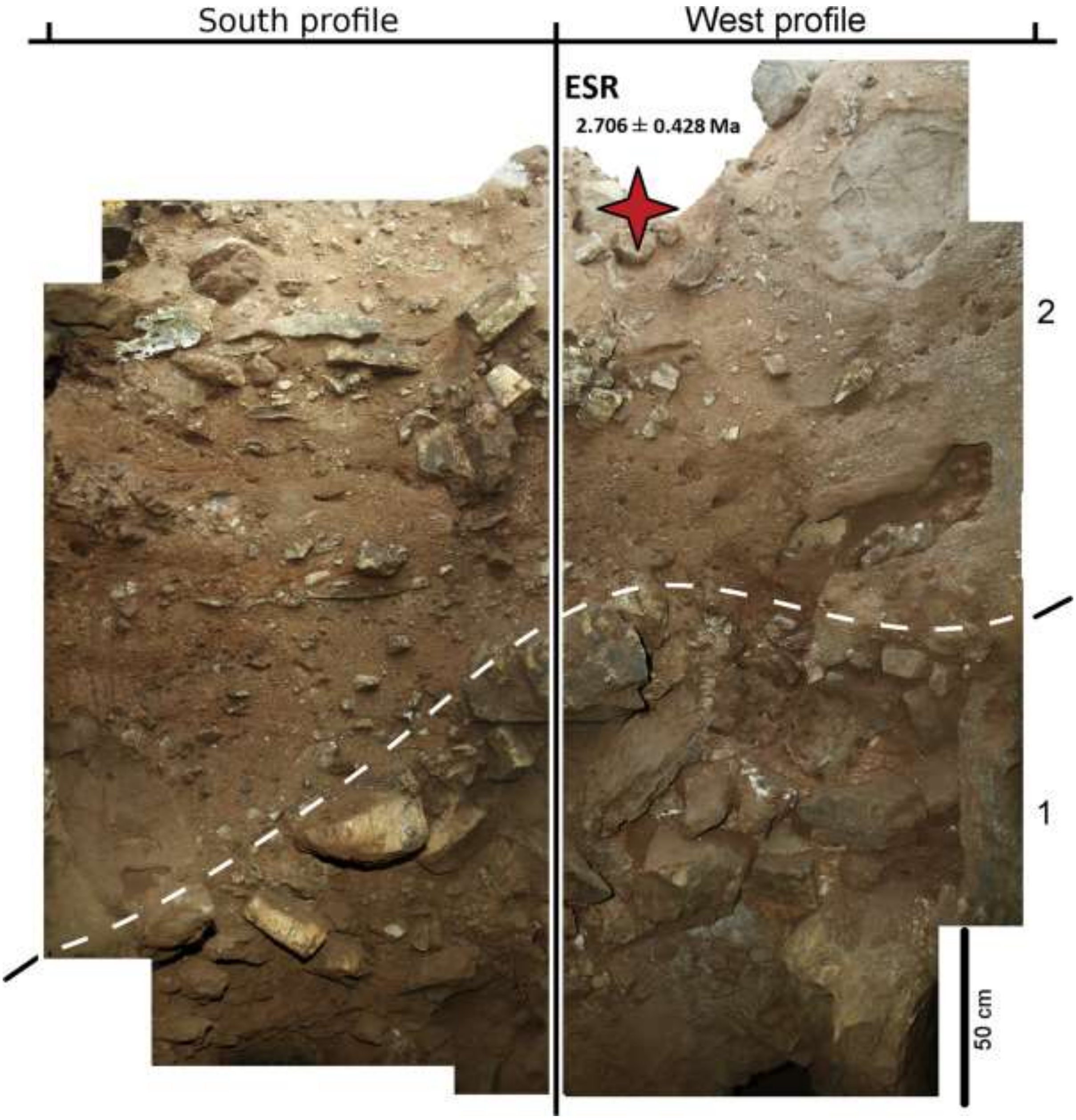

Fig. 6. A plan of the Drimolen Makondo deposits at the end of the 2014 excavation season showing the horizontal relationship of the piece plotted fossils from the Eastern Makondo as described in Rovinsky et al. (2015). All the fossils plot around the edge of the makondo feature with none in its centre.

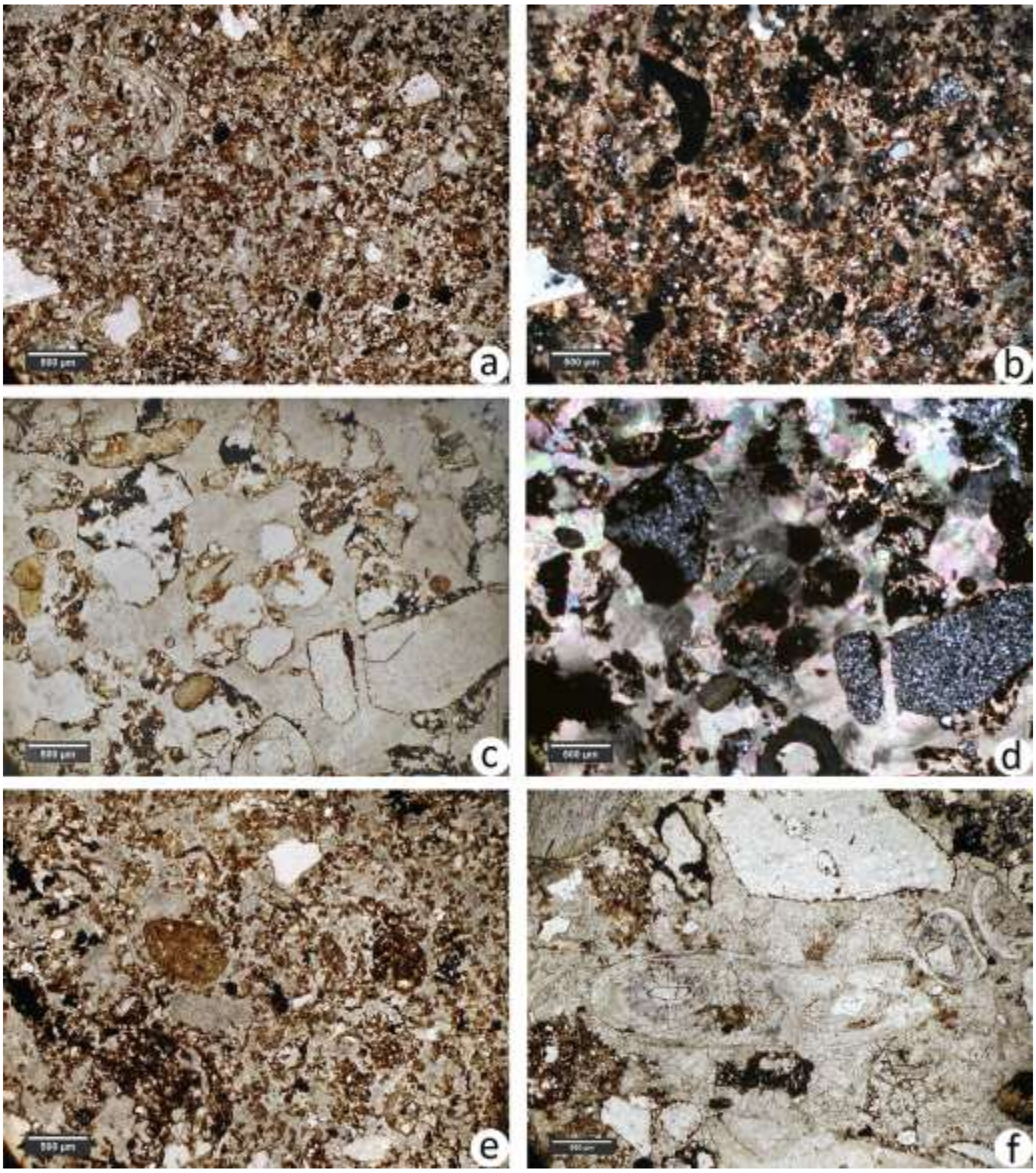

Fig. 7. a: sample DMK-MM1. Fine granular microstructure with enaulic coarse/fine related distribution pattern, strongly cemented by medium-size dirty sparite crystals. Few fine to medium sand-size monocrystalline and very few polycrystalline quartz. Fe-oxide coatings cover some coarse grains (upper centre and upper right). Frequent rounded aggregates of fine material, stained by Fe-oxides. One altered bone fragment (upper left). PPL, 2.5   objective. b: as before, XPL, 2.5   objective. c: sample DMK-MM1. Single-grain microstructure, with very few fine fraction organised in enaulic related distribution pattern. Coarse- to very coarse sand-size chert grains, moderately altered. Discontinuous Fe/Mn-oxide coatings over almost all grains. Few Fe/Mn-oxide infillings in cracks within mineral grains. One slightly altered bone fragment (bottom, centre). PPL, 2.5   objective. d: as before. Cement composed of large-size sparite crystals. XPL, 2.5   objective. e: sample DMK-MM1. Fine granular microstructure, with enaulic coarse/fine related distribution pattern. Rounded aggregates of fine material, with Fe/Mn-oxide stain (centre left and centre right). Complex nodular amorphous Fe/Mn-oxide pedofeatures stain the micromass (lower left corner). Note tiny quartz grains within the rounded aggregates. Cement composed of medium to fine-size sparite crystals. PPL, 2.5   objective. f: sample DMK-MM2. Moderately altered bone fragment; micromammal mandible, with in situ upper part of tooth roots. Coarse sediment, including very coarse sand-size chert grains and few aggregates of fine material. Thin Fe-oxide coatings on mineral grains. Anhedral to subhedral sparite cement, locally forming a pavimentous pattern with triple joints PPL, 2.5 objective.

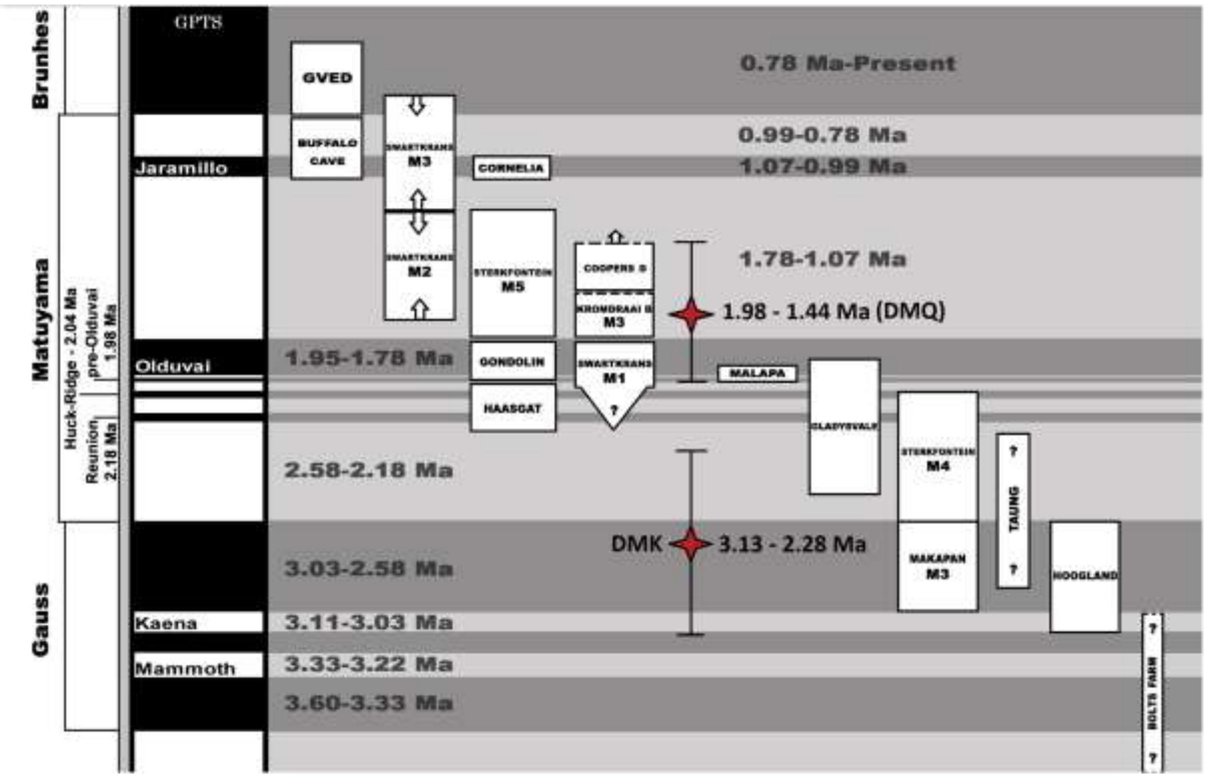

Fig. 8. The age for the Drimolen Makondo (DMK) and Main Quarry (DMQ) compared to other hominin and other fossil sites in South Africa.

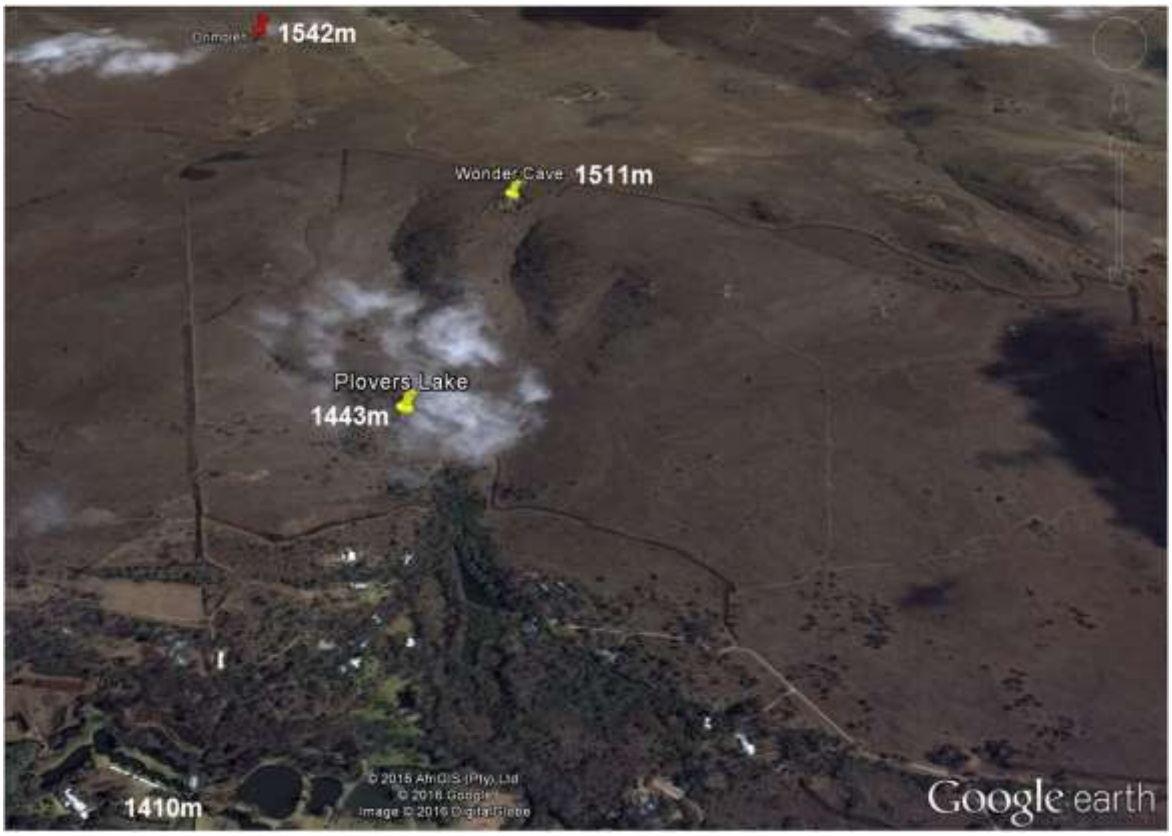

Fig. 9. Google Earth image showing the relationship of Wonder Cave, Plover's Lake and Drimolen with a steep erosional slope rising up from the Plover's Lake resurgence to the groundwater input of Wonder Cave. (data provided through © Google Earth by © Google, © 2016 AfriGIS Pty Ltd, and © 2016 DigitalGlobe).

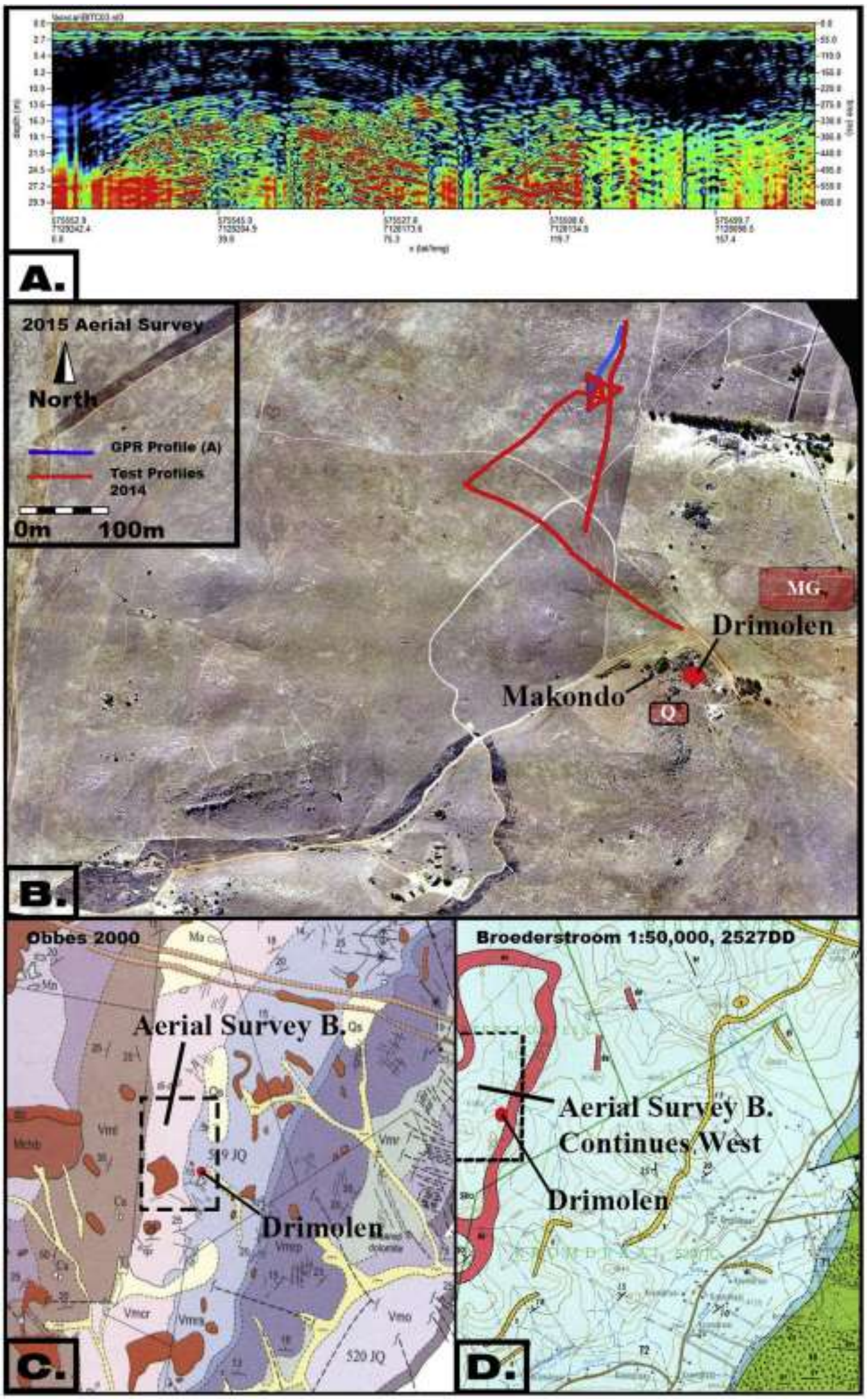

Fig. 10. A) GPR survey showing large domed features that may represent intrusive microgabbro undertaken using a Mala© GPR ProEX Systemwith a 50 Mhz antenna that penetrates to a depth of ~30 m. B) The location of the GPR profile in A (in blue) compared to the Drimolen Palaeocave System and surface outcrops of volcanic intrusives (MG: is microgabbro shown in thin section in Fig. 7; Q: quartz). C) Geological map for the Drimolen area as produced by Obbes (2000) and showing volcanic intrusives (red); and D) Geological map for the Drimolen area as produced by Ingram and van Tonder (2011) and showing volcanic intrusives (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

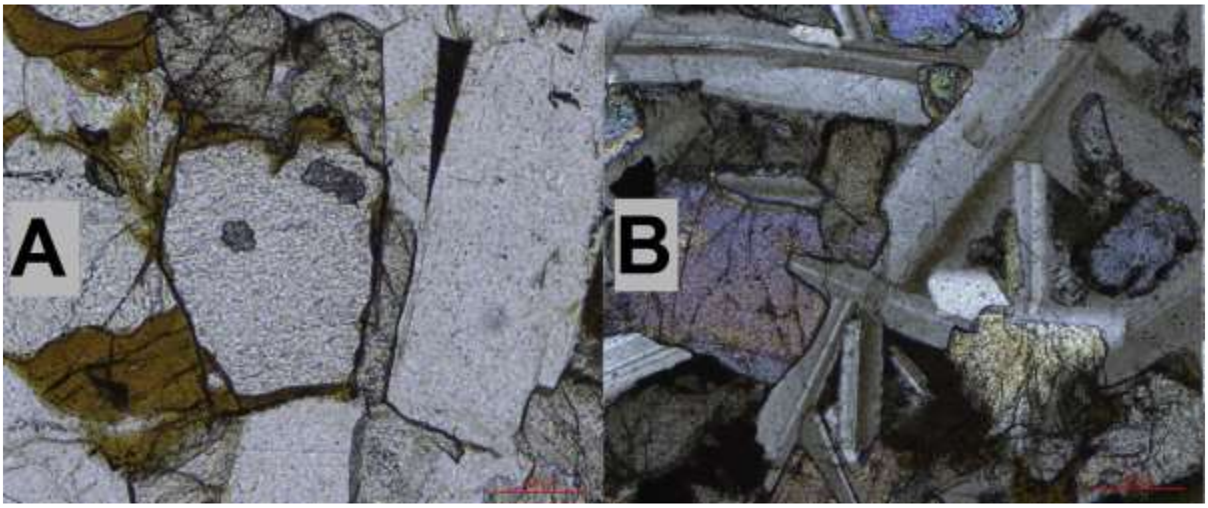

Fig. 11. Sample DNB01 is holocrystalline with a seriate fabric, where the texture is intergranular to ophitic. Presence of a very weak foliation throughout, which is visible via the lack of well orientated feldspars. Size of minerals range, however primarily sit within the medium grained classification (1-5 mm in length). The mineralogy primarily consists of plagioclase feldspar, olivine phenocrysts, pyroxenes and trace iron oxides (constituting less than 5%). Plagioclase laths average 1.5 mm in length and are clearly distinguishable through polysynthetic twinning. Anhedral pyroxenes primarily fill space between plagioclase laths and appear secondary in their crystallisation. Olivines distinctive through third order birefringence colours and euhedral to subhedral crystal habit. Mineral characteristics and size of this specimen confirms rock as a medium gained, mafic intrusive. Previous classification of dolerite (also ref. diabase/microgabbro) is supported through this study.