CHAPTER SIX
DISCUSSION AND CONCLUSIONS

6.1 Introduction

The aims of this study were: to document the three-dimensional internal stratigraphy of the Pleistocene cave fill fan at Gladysvale, which is uniquely exposed as a result of the activity of lime miners; to date the intercalated flowstone layers by Uranium-series dating; and to investigate the palaeoenvironment and climatic control of the deposit through the stable light isotopes of carbon and oxygen. The results of these three aspects have been presented in Chapters 3, 4 and 5 respectively, and are now synthesised in this chapter. The cave fill fan morphology and internal architecture are also discussed. The U-series data are used to investigate the timing of flowstone growth at Gladysvale, and model ages for the undated flowstones, and intercalated breccias are proposed. The stable light isotope data are used to reconstruct the changing vegetation growing above the cave. The three-dimensional stratigraphy and sedimentology, together with the U-series dates and isotope data, are used to reconstruct the conditions in the cave over the last 600 kyr. The timing of flowstone growth at Gladysvale and the palaeoenvironment of the deposit are used to produce a 500 kyr record of terrestrial climatic change for South Africa, which is compared to other similar records. The forcing mechanisms of these sequences are addressed. A model for the climatic control of South African hominin bearing caves is proposed, and compared to other published cave sedimentation models.

6.2 Morphology and sedimentology of the Pleistocene fill at Gladysvale Cave

6.2.1 Three-dimensional sedimentary architecture of the cave fill fan

The exposed faces, and the resulting section drawings and stratigraphic columns, of the two lobes of the younger internal deposit at Gladysvale Cave can be used to investigate and document the three-dimensional internal architecture of the deposit. Miall (1985) argues that in order to properly apply a facies analysis to fluvial deposits, vertical profiles are not sufficiently diagnostic, and that three-dimensional exposures are needed to interpret variations in the composition and geometry of a deposit. As already illustrated in Figures 2.1 and 3.2 and the preceding section drawings, the exposures created by the lime miners at Gladysvale make this an ideal site to investigate the internal structure of a cave fill fan.

The three-dimensional architecture of this deposit will be discussed from the proximal Hinge region, where sediments initially entered the cave, and were then spilt into two lobes around the large central stalagmite (Figure 3.2). The sections exposed by the trench made to remove this stalagmite, the WF1 and EF2, are then discussed as they formed adjacent to the stalagmite boss, and directly below the entrance sourcing the majority of sediment into the cave. The EF1 and WF2 are discussed next, as these faces expose the sediments accumulating on the outer edges of the two lobes, towards the bounding side walls of the cave. These sections are all longitudinal section through the deposit, exposing proximal to mid-fan changes in morphology. The SF1 is a cross-section through the eastern lobe, and provides the crucial third dimension, stressed by Miall (1985). The Peabody Chamber and extension sections are equally important, in that they are also cross-sections, and are the only exposures of the distal part of the deposit.

The Hinge section (Figure 3.17, 3.18, 3.19) consists of proximal sediments, which are backed up against the front, southern wall of the cave (Figure 2.1). The bulk of the sediment in the upper chamber of the cave was received from this area, which accounts for the elevated topography above of the Hinge section above the other areas of the deposit. The Hinge section is unusual in that FBU HL forms the uppermost unit, filling the cave to the roof directly above the Hinge, unlike in other sections of the cave, and the younger unit, FN is not present. It appears that after clastic sedimentation, producing HL ceased, the entrance through which these sediments had been sourced, was blocked off and the accommodation space directly in front of the entrance in the Hinge area was filled up. The flowstone layer capping HL then grew centimetres away from the cave roof, fed directly by the stalactites growing down from the cave roof above, and sealed this entrance off. HL is developed only in the Hinge section, and does not extend down into the wings on either side of the Hinge (Figure 3.29).The lack of FN and the raised topography of the entire Hinge section can be explained by the presence of the extra FBU MK.

In this extreme proximal region of the deposit, MK is exposed and is significantly thicker than the other FBU. MK disappears into the floor of the Hinge section, but continues across into the northern extension of the Hinge section, occurring in the limited space between the WF1 and EF2, where only MK is exposed; is also exposed in the southernmost exposures of these two faces (Figure 3.29, note: there is no vertical exaggeration in this figure, but the Western Face 1 and Eastern Face 2 have been swivelled round ~45° to appear in the same plane as the Hinge section). MK is the first sedimentary package of the younger sequence at

Gladysvale, and its limited exposure in only the Hinge and adjacent areas, suggests that early sediment was received through the cave entrance behind the Hinge section, where it rapidly built up and did not penetrate and spread out into the rest of the upper chamber of the cave. The cave floor at that time would have consisted of the top flowstone of the FBI 2, identified by Pickering (2002), and the major stalagmite, marked by the lime miners' trench (Figure 3.2). Brain (1958) argues in his model of cave formation for the South African hominin bearing caves, that during stage 3 (Figure 1.5), before the cave opened up to receive sediment input from outside, major stalagmite deposition would have taken place on the cave floor. MK was probably limited in extent by this large stalagmitic boss on the cave floor, which restricted its extent to the proximal region of the middle of the deposit, closest to the ancient cave entrance.

The relative position of later incoming clastic sedimentation through the Hinge section entrance was probably controlled by the presence of MK. The FBU clearly dip away from the Hinge section into the eastern and western lobes of the deposit. The Hinge section is not continuous with the WF1 and EF2 sections, which occur on either side of the trench below the Hinge section. This discontinuity is explained by the presence of reasonably small stalagmites, which have been reconstructed into positions on either side of the Hinge sediments (Figure 3.29). The presence of these small stalagmites on either side of the Hinge section explains the nature of the strata in the eastern and western extensions of the section - strata fan out, and dip angles of binding flowstones flatten out significantly. On the western extension, the remains of such a stalagmite were found. Sediments would have entered the cave through the entrance directly behind the Hinge sections, into the limited space above MK, and split around the major stalagmite (Figure 3.2), and then spread down either side to form the two wings of the Hinge. Accommodation space was limited by the two small stalagmites on either side of the Hinge, and sediments would have initially flowed around these to form the strata exposed in WF1 and EF2. As the accommodation space inside the cave filled up, and sediment input decreased with time, late sediments would have entered through the Hinge entrance and backup up against the small stalagmites.

The sections documented in WF1 (Figure 3.15, 3.16) and EF2 (Figure 3.21, 3.22) are exposed by the lime miners' trench, and would originally have formed on either side of the stalagmitic boss in the middle of the cave (Figure 3.2). The sediment supplying these sections would have been received from the entrance behind the Hinge section, and as discussed above, would have split into the two lobes on either upper or lower stalagmites in the Hinge area. The two sections show remarkably similar morphologies, despite being from two different lobes, suggesting that their morphology was controlled by their position in the middle of the deposit and the supply of sediment.

All six of the major FBU are present in WF1, including MK, which occurs only as a thin layer on the southern side of the section, and then disappears. As already discussed, this FBU (MK) was restricted to the proximal region of the deposit, and appears to have been limited from spreading out any further into WF1 by the presence of the basal stalagmite (Figure 3.16). LK is also found in the southern end of the section, and appears, in this section, to be limited in lateral extent by the basal stalagmite. BM and SR occur throughout the section, although BM is obscured by miners' rubble towards the northern side of the section. Both these units thin across the section and have a concordant relationship (Figure 3.16). JS has a very different morphology, where sediments appear to have initially flowed out across the section, showing a concordant basal relationship with underlying SR, but later sediments appear to have stacked up against the stalagmite growing up from the base of the section, making the unit much thicker on the southern side of the section. HL is then limited by the underlying morphology of JS, and downlaps into the space in front of the stalagmite. FN is then, in turn, limited by the formation of the underlying HL, and thickens across the section, reaching its maximum development on the northern side of the section.

On the EF2, MK is not restricted by a stalagmite, as in the WF2, and extends further across the section. LK and BM follow MK concordantly and extend across the entire section, but become progressively thinner (Figure 3.21, 3.22). SR downlaps into the space created by the sudden thinning MK and the concordant nature of BM and LK, extending across the section, also showing marked thinning into the distal part of the section. JS is considerably thinner than SR, but follows the underlying morphology of SR concordantly (Figure 3.21 inserted graph), and is the uppermost unit in the distal part of the section. HL and FN occur only in the middle of the section, where they downlap into the saddle created by the underlying units. HL is limited to only the top area of the Hinge section, and FN is absent altogether from the Hinge, suggesting that the entrance in the area was blocked up during the sedimentation of HL, and that the sediments of FN were received from other, smaller, lateral entrances to the cave. Sediments entering through these entrances would not be present in the Hinge area, and would have flowed down over the pre-existing deposit into the saddle like space in EF2.

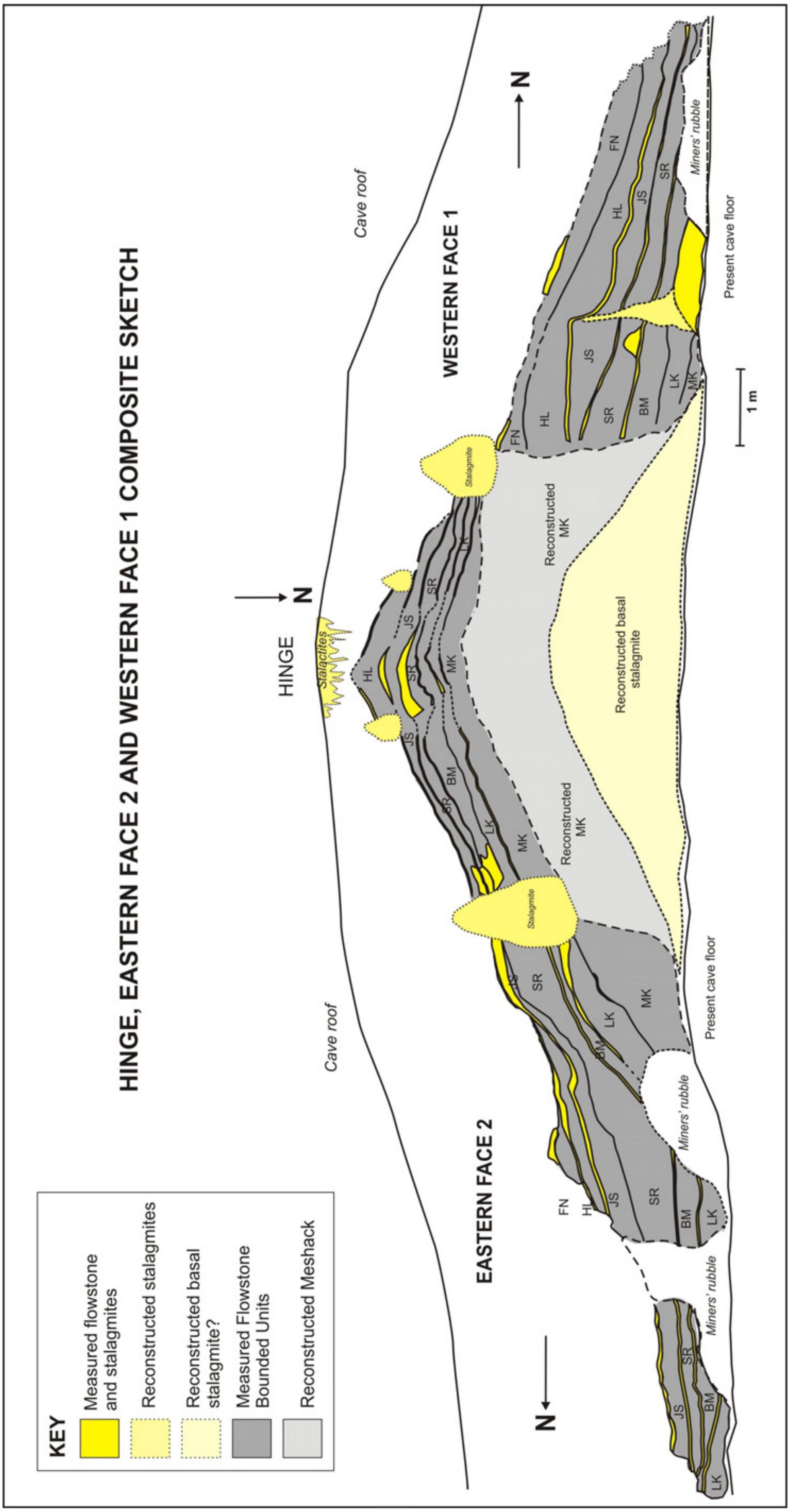

Figure 6.1. Composite sketch of the Eastern Face 2, the Hinge and the Western Face showing the relationship between these sections; note: there is some vertical exaggeration, by the EF2 and WF1 having been swung around ~45° to be in the same plane as the Hinge.

The last two longitudinal sections through the deposit are EF1 and WF 2, which expose the sediments on the edges of the two lobes, and are the furthest away from the main cave entrance in the Hinge section. EF 1 is well exposed in the present cave entrance, made by the lime miners, and previously sediments would probably have been adjacent to the side wall of the cave. The FBU show a very different overall morphology to the WF1 and EF2 sections, in that all FBU thin across the section, showing remarkable concordance with little to no downlapping relationships (Figure 3.10, 3.11, 3.12). The southern side of the section exposes the entrance into the cave for some of these sediments, but the lack of clear entrance morphology (such as seen in the Hinge section) suggests that this was not a major entrance, and may have been more like a narrow slit through which minor sediment supply was received. The overall morphology of these strata indicate that they were received from the Hinge area, and moved into and away from the central area of the cave into this more lateral region. The large dolomitic block in SR is covered in sediment, and sediments do not appear to have backed up against it, suggesting that sediment was not being received from an entrance directly above this block. The strata are cut off by the trench across the northern side of the section, which was made to remove a stalagmite (Figure 3.2). The flat angles of repose of the binding flowstone in this area suggest that sediment had been backed up against this stalagmitic boss.

WF2 has a similar morphology to EF1 in that the FBU thin almost uniformly across the section, and once again do not display any clear downlapping relationships (Figure 3.22, 3.23). However, this section is slightly different as the thickness of the sediments in the southern proximal region, and the presence of the same strata in the Porcupine Pit and against the far eastern side wall of the cave (Figure 2.1) suggests that sediment in this part of the cave was supplied through a second entrance, as well as the Hinge section entrance. Today there is an entrance directly above the Porcupine Pit. This was clearly enlarged by the lime miners but it is possible that they exploited a pre-existing entrance.

SF1 is a cross-section through the western lobe for the deposit (Figure 2.1) and links WF1 and EF1. It is important in that it provides a third dimension to the deposit. The middle of the section is not well exposed or preserved, suggesting that this area was not directly underneath a palaeodrip source, as were the two sides of the section, which are well calcified (Figure 3.13, 3.14). The midfan position of this section is indicated by the absence of MK, which, as already discussed, is found only in the proximal regions of the deposit. LK and BM thin across the section away from the eastern side, indicating that these units were receiving sediment through the Hinge entrance. SR shows a similar pattern of thinning away from the middle of the deposit, but, thickens slightly into the western end of the section as the unit downlaps into the space created by the thinning of BM and LK. JS and HL concordantly thin across the section, while overlying FN thickens dramatically as it downlaps into the space created by JS and HL on the western side of the section. Thus, this cross-section through the deposit demonstrates the same relationship between successive clastic sedimentary units as the longitudinal sections, where the oldest units are sourced from the Hinge area entrance, and thin across to the edges of the section, and are then followed by units which thicken across to the edges of the deposit, downlapping into the space created by the underlying units.

The Peabody Chamber and Peabody extension sections (Figure 3.26, 3.27) are also cross-sections through the western lobe of the deposit and are the only exposures of distal strata. As with SF1, the middle of the section is not well calcified and consequently not well preserved. On either side the sections are well calcified, well preserved and thicker. This morphology is most likely due to the large stalagmite, which would have, to some extent, filled the space between in SF1 and these sections (Figure 3.2). Incoming sediments would have been channelled around on either side of this stalagmite boss, where they were better calcified (and preserved) along the palaeodrip lines identified in Figure 3.2.

6.2.2 Facies changes through space

A set of nine different sedimentary facies have been identified within the flowstone bounded units of the deposit in the upper chamber at Gladysvale. The three-dimensional exposures of the deposit allow for an analysis of changes in these facies through space, within the confines of a single depositional horizon preserved as a FBU. The longitudinal sections through the deposit best expose such changes, and the EF1, WF1, EF2 and WF2 will be discussed as the best exposed and preserved sections. SF1 is the only cross-section of the mid-fan region of the deposit and is also discussed. The facies changes can be seen from the proximal to mid-fan to distal region of the deposit, with a general fining of sediments through the deposit from Facies D to Facies A to Facies C and Facies B in the Peabody Chamber. The spatial arrangement of these facies reflect the energy of their deposition, moving from high energy at the cave entrance to much lower energy, quieter water deposits at the back of the cave.

6.2.3 Facies changes through time

The nine sedimentary facies each have their own hydrological interpretation, relating to the timing and relative lateral position in the cave of the sedimentation. Facies changes are not restricted to horizontal changes through the deposit, and vertical changes in facies within FBU have also been observed and are illustrated in almost every stratigraphic column (Figures 3.12, 3.14, 3.18, 3.22, 3.24, 3.25 and 3.27)).

The vertical arrangement of sedimentary facies is explained by Walther's Law, which originally states (as translated by Middleton, 1973, p979):

> "The various deposits of the same facies-area are similarly the sum of the rocks of the different facies-areas are formed beside each other in space, through in a cross-section we see them laying on top of each other…it is a basic statement of far-reaching significance that only those facies and facies-areas can be superimposed primarily which can be observed beside each other at the present time" (Walther, 1894).

Walther's Law is interpreted to mean that facies that occur in conformable vertical successions of strata, also occurred in laterally adjacent environments, and that it is shifts in these lateral environments through time which has resulted in the vertical stacking of the facies (Middleton, 1973; Boggs, 2001).

The best example of vertical facies changes is shown in Figure 6.2, where FBU HL consists of a lower flowstone, a gap where no sediments are preserved, a layer of large (up to 15cm) dolomite blocks, which fine upwards into typical Facies A sediments, which in turn fine upwards into a capping of finely layered, muddy Facies C sediments, which are intercalated with the upper binding flowstone. The gap in the sequence was probably filled with Facies C sediments, which have not preserved in this section, but is observed elsewhere within the cave.

The vertical succession of facies shown in Figure 6.2, of finer grained through to coarser grained and back into fine grained sediments, represents different velocities of flow of sediment into the cave. Initially, sedimentation was gradual and gentle, producing the muddy strata of Facies C. Then sediment supply increased, and the prograding fan brought coarser grained dolomite blocks (Facies D) down the slope; some gravity slumping may have aided this process. The fan continued to prograde, but sediment supply dropped off, producing the fining upwards from Facies D into Facies A. Flow regimes then changed again, with finer sediments being deposited under gentler conditions to cap the unit in Facies C (Figure 6.2).

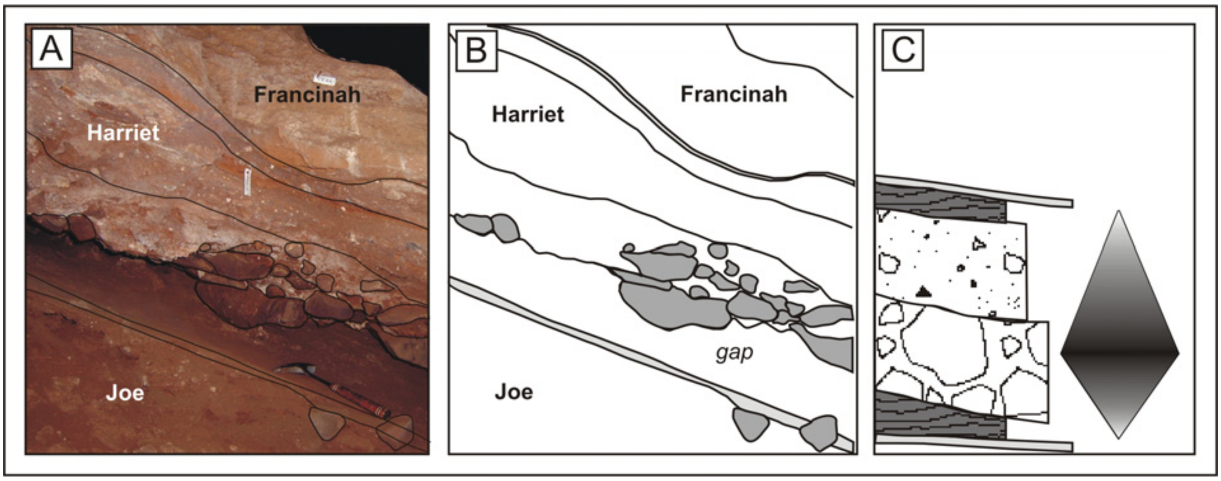

Figure 6.2. Vertical facies changes in FBU HL exposed in WF2, A; photograph of FBU JS, HL and FN, B: line drawing of section as shown in A, C: schematic of FBU HL showing vertical facies changes.

Unlike in a marginal marine or other terrestrial setting, where accommodation space is controlled by tectonics or eustasy and modified by the sedimentary fill, the accommodation space within the Gladysvale Cave during the last 600 kyr was fixed, and has been limited during later stages of sedimentation by the presence of previous fill events. Depositional cycles are, therefore, controlled to an extent by autocyclic changes in sediment supply and the ability of the sediments to fill the available accommodation space (Figure 6.2). Sediment supply itself is controlled by the prevailing climatic regime, with sediment supply decreasing as one moves into a wetter period; meaning that allocyclic controls also control depositional cycles.

The amount of sediment supply and the stage of fan sedimentation will also have played a role in defining facies changes through time. The amount of accommodation space in the cave is fixed, increasing the importance of sediment supply. Initially sediment supply is high, and the fan prodgrades into the cave, bringing in coarse grained sediment and filling in the spaces left by the underlying units (Figure 6.3 A). As sediment supply evens out, there is an equilibrium phase during which the fan aggrades (Figure 6.3 B) and forms the middle part of the package shown in Figure 6.2. As sedimentation supply eases off, the final phase of sedimentation is marked by a retrogradational fan (Figure 6.3 C), bringing finer grained facies over the coarser underlying facies, as seen in Figure 6.2.

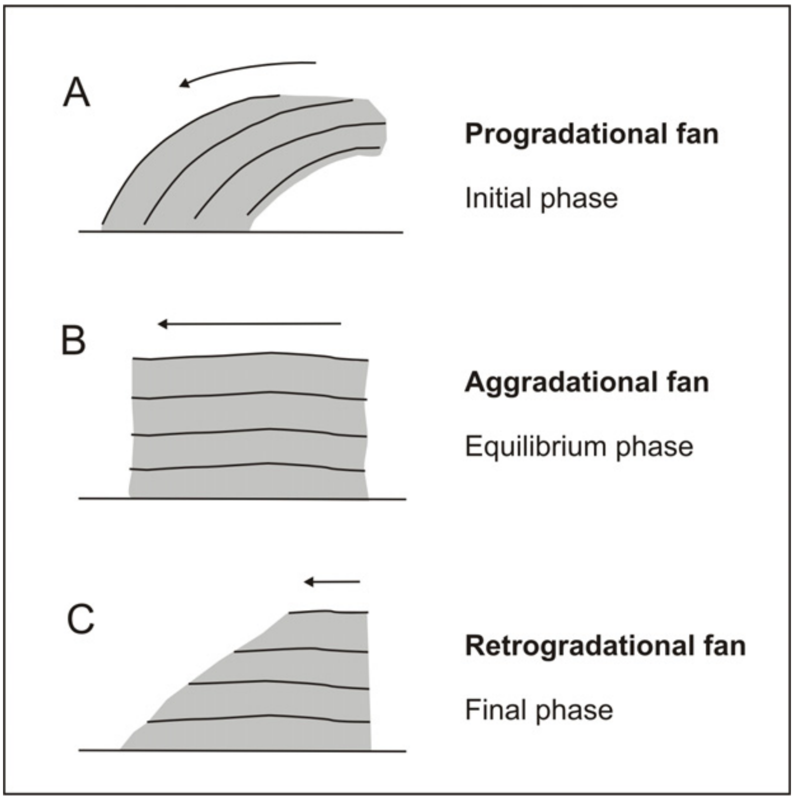

Figure 6.3. Schematic diagram showing the three stages of fan sedimentation, controlled primarily by sedimentation supply.

The flowstone facies binding the vertical succession shown in HL in Figure 6.2 are known to relate to wetter periods in other cave settings (Ayliffe *et al*., 1998) and Moriarty *et al*. (2000) suggest that the intercalated clastic sediments of a FBU relate to drier periods. As neither tectonics nor eustasy are providing allocyclic controls over sedimentation, climate changes are thought to be governing the nature and rate of sedimentation inside the cave.

6.3 Timing of flowstone growth at Gladysvale Cave

Flowstones only grow when a specific set of conditions are met. These are: increased effective precipitation; sufficient humic acid levels in ground water to concentrate Ca; and adequate CO_2 partial pressure to drive degassing of cave waters and the formation of calcium carbonate (Richards & Dorale, 2003; Moriarty *et al*., 2000; Ayliffe *et al*., 1998). These conditions are essentially climatically controlled (Richards & Dorale, 2003; Ayliffe *et al*., 1998), with regional and global climatic regimes being reflected in the presence of speleothems. The presence of the intercalated flowstones at Gladysvale is evidence that these conditions were met on several occasions through time, and that some kind of climatic threshold was crossed to allow for speleothem growth. The U-series dates for the flowstone horizons at Gladysvale can be compared to global records of climatic change to determine the overall climatic regime operative at the time of speleothem growth at Gladysvale.

The Imbrie *et al*. (1984) SPECMAP record (Figure 6.4) is of global sea level change, consisting of glacial and interglacial cycles, which are driven by orbitally forced changes in global climate, from colder and warmer periods respectively. The majority of the flowstones grow during the recovery phase following full global interglacials. It is possible that, as with the Naracoorte Caves (Ayliffe *et al*., 1998), conditions during full interglacials, although warm, were too arid and evaporative to be conducive to speleothem growth. During the recovery period following full interglacials, conditions at Gladysvale must still have been warm, but wetter, with increased effective precipitation allowing for speleothem growth to take place)Figure 6.4).

Four of the ten dated samples did not grow in well defined interglacial recoveries. Sample RP010 (255 ka) grows during the recovery of an interstadial in OIS 8. Conditions following a full glacial must therefore be similar to those following a full interglacial, which makes sense, as the intermediate conditions between the two climatic extremes would be the same. The four youngest dated samples all grew in the period of warming following OIS 2. Samples RP006, RP005 and RP002 are all from different layers of a single flowstone horizon (FN top flowstone), and grew in the rapid warming period following the Last Glacial Maximum (LGM) in OIS 2. RP003 is from the same flowstone, but is separated from the other samples by a break in the flowstone, marked by a bedding plane of detritus and a distinct change in U levels (Table 6.1). RP003 grew in the period of rapid warming following the extreme period of early Holocene cooling, the Younger Dyras. Speleothem growth stopped at Gladysvale Cave after ~7 kyr as the climate continued to warm into the mid-late Holocene. There is limited modern flowstone growing at Gladysvale, but growth is restricted to the warm, wet summer months of December to February.

The plotting of the dated Gladysvale flowstone against the global climate change SPECMAP record demonstrates that during the recovery period following full interglacials, conditions in the Cradle of Humankind World Heritage Site were conducive to speleothem growth. Speleothems also grew during interstadials and during the warming phase of the early to mid Holocene. It has been established that the periods of speleothem growth correspond to warmer periods, but in order to determine what the precipitation levels were like, detail finer than the global sea level change record is needed, and regional records of terrestrial climate change must be examined.

6.3.1 Comparison with the Tswaing Impact Crater precipitation record

The palaeoclimatic record from the Tswaing Impact Crater lake sediments is reviewed in Chapter 1, but in brief, the Tswaing record provides a 200 kyr estimation of rainfall variations in sub tropical southern Africa (Partridge *et al*., 1997). The changes in precipitation are clearly orbitally forced, with a cyclicity of 23 ka, pointing to precessionally controlled variation. The 200 kyr precipitation estimates are shown in Figure 6.5, with the Gladysvale U-series dated flowstone superimposed.

Unfortunately only three episodes of flowstone growth (~8 ka, 10-16 kyr and 42-56 kyr) at Gladysvale fall into the time period covered by the Tswaing record. The ~8 ka and 14-16 ka flowstones correspond to slight increases in precipitation in the overall drier period following the LGM. The 42-56 ka flowstone corresponds nicely to a significant and short lived peak in increased precipitation, where rainfall increased by as much as 200 mm/year. These correlations are supportive evidence that flowstone growth at Gladysvale occurred during warm and wet phases following full interglacial cycles.

6.3.2 Age model of undated flowstones

U-series dates were not obtained for three of the Gladysvale flowstones, as the samples were heavily contaminated with detritus and not well preserved. Samples such as these can be dated via isochrons, but this was beyond the scope of this project. The work of Ayliffe *et al*. (1998) and Moriarty *et al*. (2000) on the Naracoorte Caves in South Australia has shown that episodes of flowstone growth correlate to wetter periods, during which there was increased effective precipitation. The comparison of the Gladysvale U-series dates with the precipitation record from the Tswaing Crater record of Partridge *et al*. (1997) has shown that this is also the case for the Gladysvale flowstones. Beyond the 200 kyr Tswaing record, the Gladysvale flowstones can be compared to the glacial and interglacial SPECMAP record of Imbrie *et al*. (1984), and from this correlation it appears that the flowstones, at Gladysvale, grew during the recovery period following a full interglacial. Therefore, the undated Gladysvale flowstones can be given model ages, as shown in Table 6.1 and Figures 6.4 and 6.5.

The flowstone capping JS is assigned a model age of 122 ± 2 ka, corresponding to the Eemian, or OIS 5e, which is the penultimate interglacial, and is associated with major world-wide flowstone growth (Richards & Dorale, 2003). 122 ka is also a very wet phase at Tswaing (Partridge *et al*., 1997) and increases in the Indian Ocean Sea Surface Temperature (SST) are also documented at 121.2 ka (Bard *et al*., 1997; Bard, 2003), suggesting that this was a warm, wet period, conducive to speleothem growth.

Stratigraphy	Sample	Age (ka)	Comment
FN top flowstone	RP003 RP002 RP005 RP006	7.45* 10.32* 14.385 16.501	U-series age U-series age U-series age U-series age
HL top flowstone	RP007 RP008	42.82* 56.766	U-series age U-series age, Tswaing wet phase
JS top flowstone		**125**	Eemian, Tswaing wet phase, warm Indian Ocean SST
SR top flowstone		**160**	Tswaing wet phase, warm Indian Ocean SST
SR small stalagmite	RP010	255.297	U-series age
PP basal stalagmite	RP001	307.516	U-series age
SR lower flowstone	RP009	393.303	U-series age
LK top flowstone		**470**	IG recovery from OIS 13 (SPECMAP)
MK flowstone		**535**	Interstadial during OIS 14 (SPECMAP)
FBI 2 stalagmite	RP004	571.38	U-series age

Table 6.1. U-series ages, corrected ages* and model ages (bold) for flowstones at Gladysvale Cave.

160 ka is an interstadial during OIS 6, but there is a very wet phase at Tswaing at 160 ka and a significant increase in SST in the Indian Ocean at 158 and 165 ka (Bard *et al*., 1997; Bard, 2003). While 160 ka is only an interstadial and not a major interglacial (such as the ~200 kyr interglacial in OIS 7), the evidence of the local terrestrial precipitation and SST are taken above the global, smoothed SPECMAP record, and an age of 160 ka is therefore modelled for the flowstone capping SR (Table 6.1; Figure 6.5).

The other undated flowstones are stratigraphically below the U-series dated flowstone of 393 ka, and are therefore too old to be compared to the Tswaing or Indian Ocean SST records. A model age of 470 ka is proposed for the flowstone capping LK, as this corresponds to an interglacial recovery period on the SPECMAP record, and the stratigraphically lower flowstone at the base of the sequence is dated at 571 ka, which also corresponds to an interglacial recovery. The flowstone capping MK is assigned a model age of 515 ka, which corresponds to an interstadial during OIS 14 on the SPECMAP record (Table 6.1; Figure 6.5).

6.3.3 Age model for intercalated breccias

The U-series chronology for the flowstones at Gladysvale points to a strong climatic control on the nature of sedimentation in the cave. The breccia units are intercalated with flowstones and are, by definition, flowstone bound; it is therefore possible to generate model ages for the breccias, based on their constraining flowstones. Direct dating of the breccia layers, via Luminescence dating or U-series on the included fossil bone, would be ideal, and would act as a valuable test of the U-series chronology, but this was beyond the scope of this study.

Periods of flowstone growth at Gladysvale correspond to local increases in effective precipitation and globally to periods following full interglacials. The Gladysvale flowstones agree with the cave sedimentation model of Ayliffe *et al*. (1998), and Moriarty *et al*. (2000), that propose that flowstones represent wetter periods. This model goes on to propose that breccias, conversely, correspond to drier periods. In the South African context, these drier periods would appear to be during glacial cycles, as flowstone growth is associated with interglacials. The Tswaing Impact Crater record (Partridge *et al*., 1997) includes periods of reduced rainfall, and these drier periods correspond to global glacial periods on the Imbrie *et al*. (1984) SPECMAP record (Figure 6.4). Thus an age model for the Gladysvale breccias can be generated (Table 6.2; Figure 6.6). During the time periods between flowstone growth there are often several dry phases, and it is not possible at this stage to tie sedimentation to one or another of these episodes, and therefore several model ages are proposed for each breccia layer.

The youngest breccia, unit FN, is given model ages of between 20 and 40 ka. At 45 ka there is a significant dry phase at the Tswaing Impact Crater (Partridge *et al*., 1997) and colder SST are recorded in the Indian Ocean (Bard *et al*., 1997; Bard, 2003). OIS 3 occurs around 40 ka, and is a glacial. The third Heinrich event, H3, takes place at 37 ka. The middle of the LGM, at 20 ka, coincides with OIS 2.

Stratigraphy	Age (ka)	Comment
FN top flowstone	7.45* - 16.501	U-series ages
FN	**20 40**	**Dry phases at Tswaing, OIS 2 & 3, cold Indian Ocean SST**
HL top flowstone	42.82* 56.766	U-series age, Tswaing wet phase
HL	**65 110**	**Dry phases at Tswaing**
JS top flowstone	125^{m}	Eemian, Tswaing wet phase, warm Indian Ocean SSY
JS	**135 150**	**Dry at Tswaing OIS 6**
SR top flowstone	160^{m}	Tswaing wet phase, warm Indian Ocean SST
SR	**180**	**Dry phase at Tswaing, OIS 7, cooler Indian Ocean SST**
SR small stalagmite	255.297	U-series age
JN	**260**	**Glacial during OIS 8 (SPECMAP)**
Porcupine Pit stalagmite	307.516	U-series age
SR lower flowstone	393.303	U-series age
BM	**430**	**Glacial during OIS 12 (SPECMAP)**
LK top flowstone	470^{m}	Inter Glacial recovery from OIS 13 (SPECMAP)
LK	**515**	**Glacial during OIS 14 (SPECMAP)**
MK flowstone	525^{m}	Interstadial during OIS 14 (SPECMAP)
MK	**535**	**Glacial during OIS 14 (SPECMAP)**
FBI 2 stalagmite	571.38	U-series age

Table 6.2. Age model (bold) for intercalated breccias at Gladysvale Cave, including U-series ages of flowstones, corrected U-series ages* and model flowstone ages^{m}.

The next breccia, HL, is given model ages of 65 and 110 ka, which are dry periods in the Tswaing Impact Crater record (Partridge *et al*., 1997). Colluvium, signalling dry conditions, is found in the Voordrag sequence, in KwaZulu-Natal, between 96 and 99 ka (Clarke *et al*., 2003). Unit JS is assigned model ages of 135 and 150 ka, which once again are dry periods within the Tswaing record. Unit SR is given a model age of ~180 ka, which is the second last dry phase recorded at Tswaing.

The units older than this are beyond comparison with the Tswaing record; model ages are therefore assigned on the basis of comparison with global climate changes in the SPECMAP record of Imbrie *et al*. (1984). Unit JN is found only in the Porcupine Pit, and overlies the 307 ka stalagmite and is capped by the 255 ka flowstone and therefore must have an age somewhere between these two U-series ages, and is given a model age of 260 ka, which is the peak glacial period in OIS 8. BM is thus given a model age of 430 ka, which relates to the glacial during OIS 12. LK is assigned an age of 515 ka, which relates to one of the glacials duirng OIS 14. MK is assigned a model age of 535 ka, which corresponds to the other glacial peak during OIS 14 (Table 6.2; Figure 6.6).

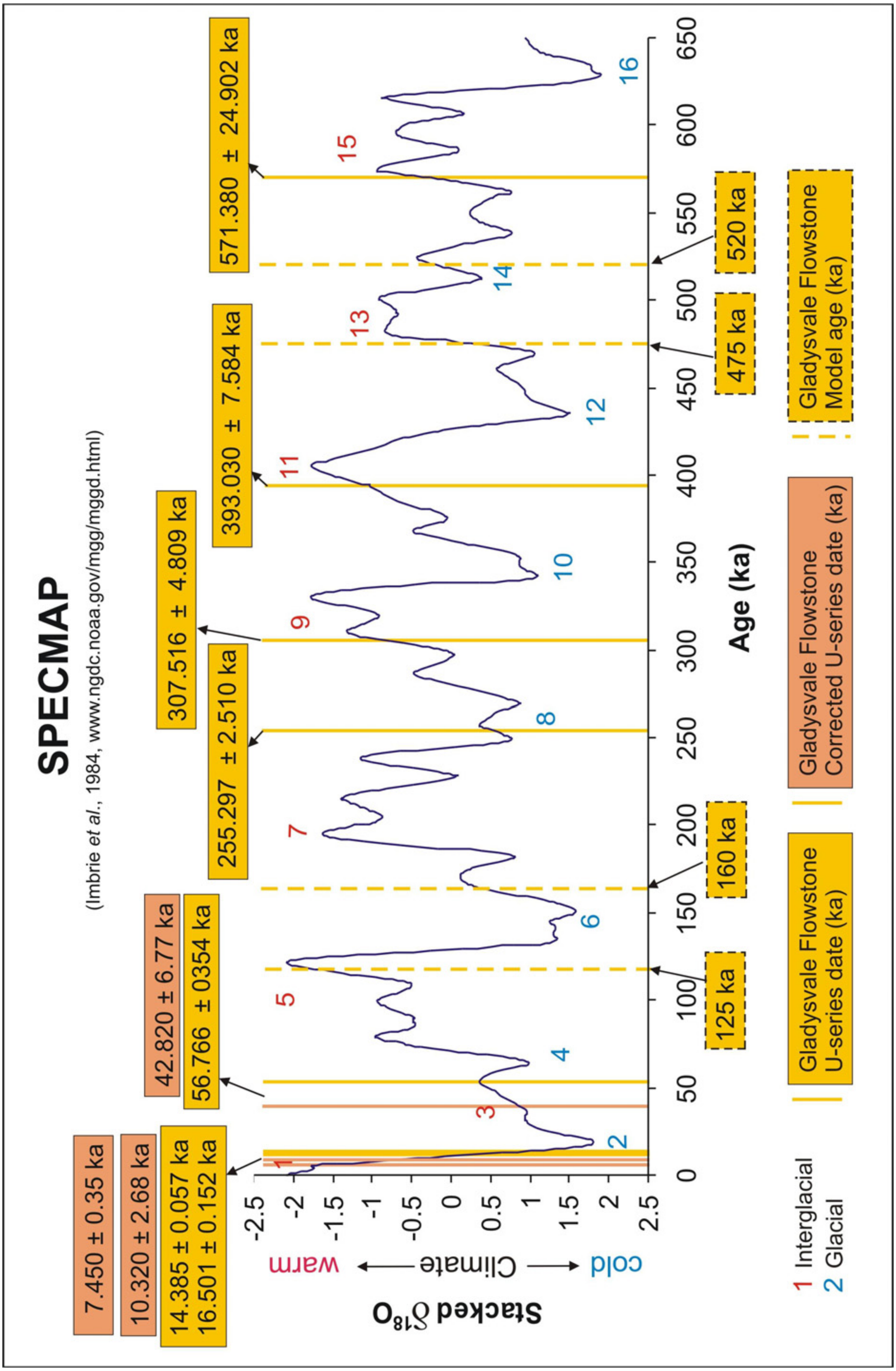

Figure 6.4. Real (yellow), corrected (peach) and model (dashed yellow) U-series dated Gladysvale flowstones plotted against the global climate change SPECMAP record of Imbrie *et al*. (1984).

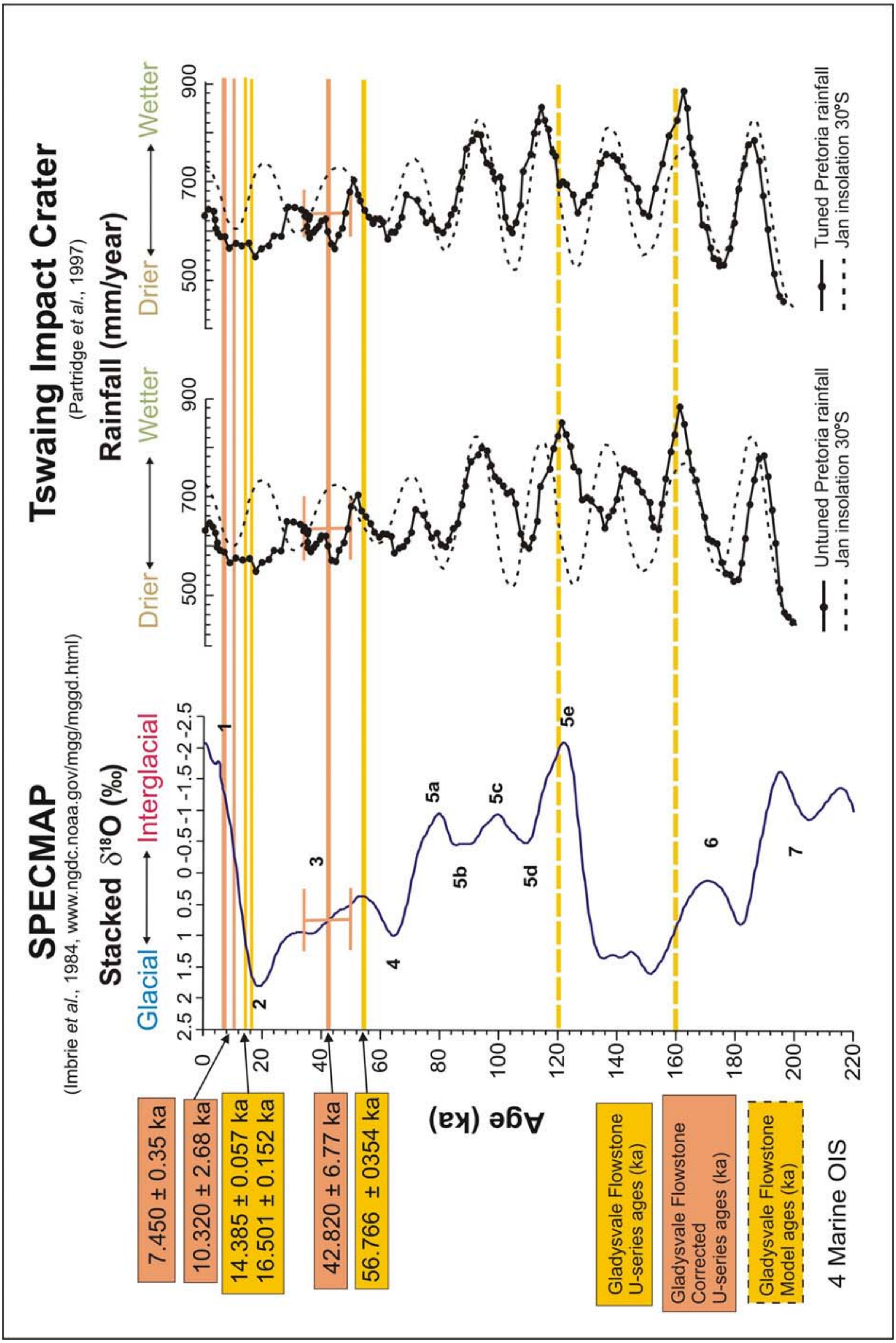

Figure 6.5. Real (yellow), corrected (peach, with errors) and model (dashed yellow) U-series dated Gladysvale flowstones plotted against the Tswaing (Pretoria Saltpan) precipitation record of Partridge *et al*. (1997).

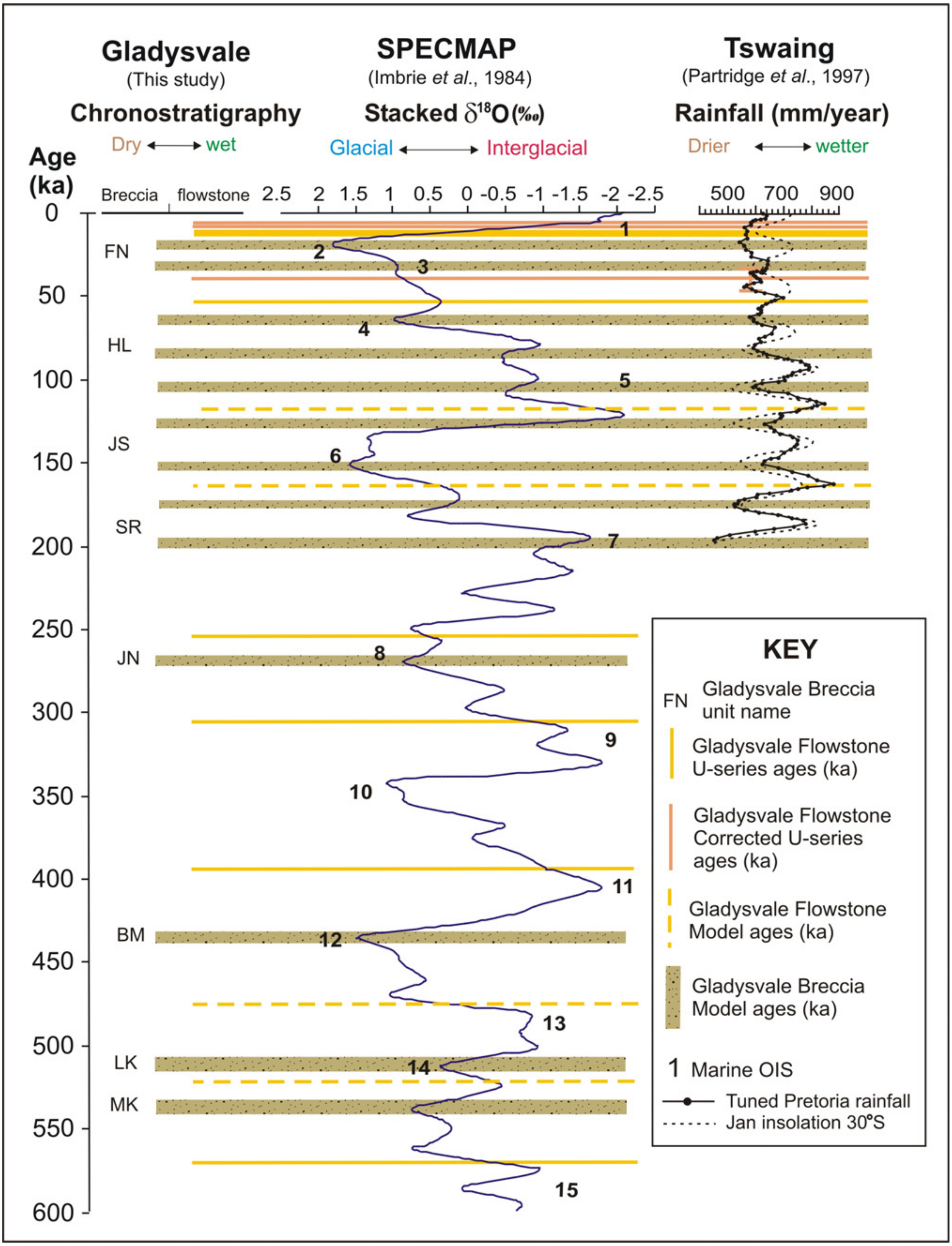

Figure 6.6. Model ages for < 500 ka breccias at Gladysvale (brown, stippled) plotted with U-series and model ages for flowstones, against the global SPECMAP and local Tswaing climate change records.

6.4 Climatic control of sedimentation at Gladysvale

The stable light isotope composition of the flowstones and breccias at Gladysvale can provide insights into the climatic control of the sedimentation in the cave, as these isotopes are palaeoclimatic proxies in themselves. The stable light isotope results and interpretations are summarised in Table 6.3 and Figure 6.7.

Type of sediment	Nature of isotope signal	$\delta^{18}O$ (Ave)	Interpretation	$\delta^{13}C$ (Ave)	Interpretation	Timing of deposition	Palaeoclimate inference
Flowstone	Indirect – cave drip waters from ground water percolated through dolomitic cave roof	-3.8‰	Oxygen signal very similar for flowstone and breccia and is most likely masked by the dolomitic cave roof, and no palaeo-environmental interpretations can be made	-5.9‰	60% C_3 = woodland	Period following interglacials and interstadials	Warm periods of increased effective precipitation, with less seasonal, persistent rain
Breccia	Direct sampling of carbon signature from soil outside the cave. Indirect for oxygen, calcium carbonate cement from cave drip waters	-3.9‰		-3.4‰	50-80% C_4 vegetation outside the cave. Dolomitic roof may be under-estimating C_4 content.	Glacials	Cooler, drier periods, with more seasonal rainfall and a higher frequency of convective storms

Table 6.3. Summary, interpretation and palaeoclimatic inferences of carbon and oxygen data from Gladysvale Cave flowstones and breccias.

Disappointingly, the $\delta^{18}O$ signal of the flowstones and breccias is very flat, with no clear distinction between the different types of sedimentation. The flatness of the signal is most likely from the residence time of the groundwaters above the cave, during which they lose their original signal and inherit the $\delta^{18}O$ signal of the cave roof dolomite. Continuously growing stalagmites, such as T7 and T8 from Makapansgat, have much better $\delta^{18}O$ records than the Gladysvale flowstones, which represent relatively short periods of time during which conditions were conducive to flowstone growth.

The carbon isotopes from the breccias and flowstones tell a much more interesting story, despite the possible dampening effect of the cave roof dolomite. The $\delta^{13}C$ signal is interpreted as representing changes in the vegetation above the cave, from an arid-adapted C_4 grasses signal for the breccias to a to higher rainfall adapted C_3 trees signal for the flowstones (Table 6.3; Figure 6.7).

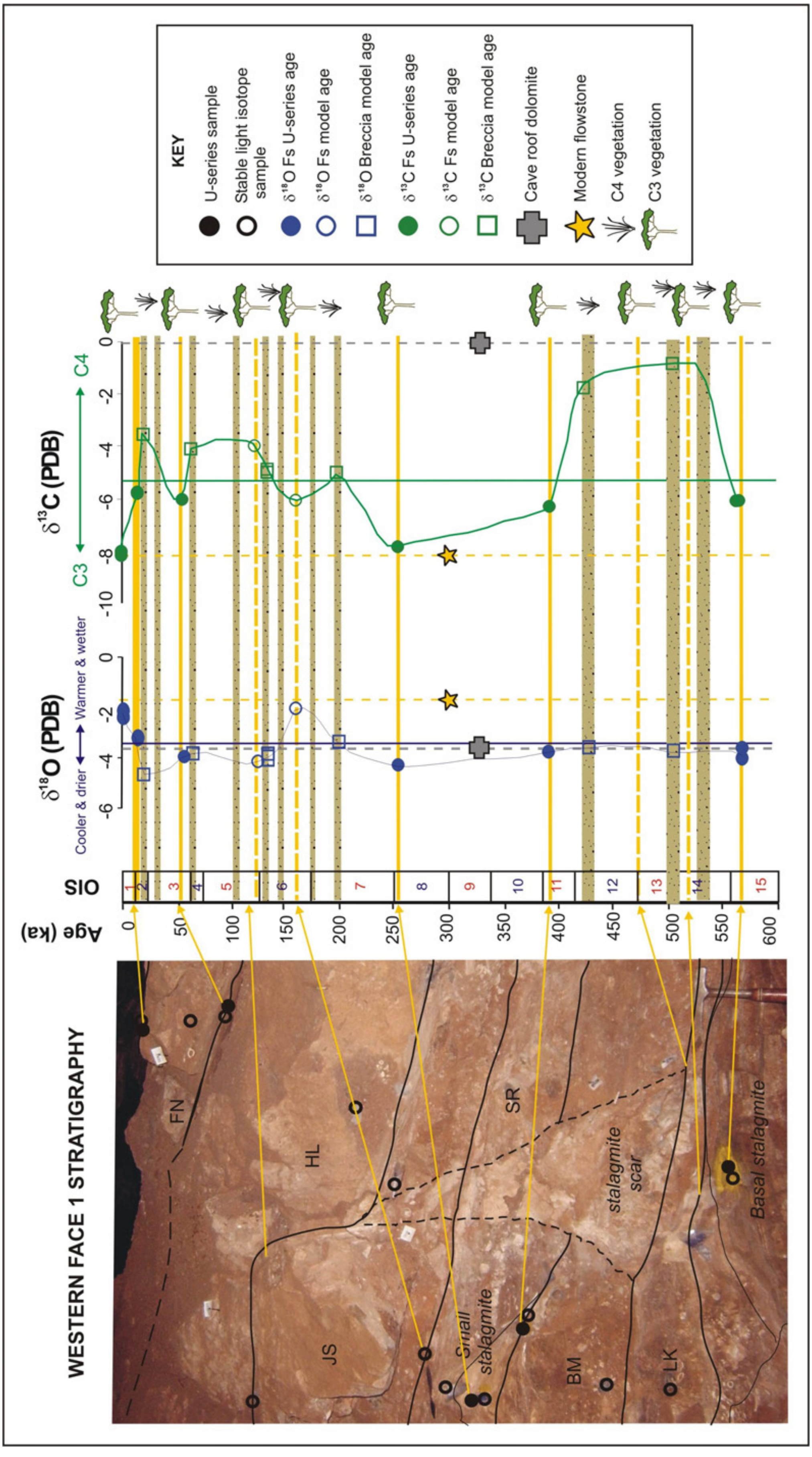

Figure 6.7. Carbon and oxygen isotopes for flowstones and breccias for the Western Face 1 plotted against U-series and model ages. Isotope values for cave roof dolomite and modern flowstone are included, and are arbitrarily plotted in the middle of the diagram.

Based on the $\delta^{18}O$ signal from T8 at Makapansgat, Holmgren *et al*. (2003) argue that changes in climate in the past were controlled by modifications in the atmospheric circulation, which cause differences in the amount and type of precipitation. Wetter periods are characterised by less seasonal, persistent rain and warmer temperatures, which are conducive to C_3 vegetation and are the ideal conditions for flowstone growth. Although the $\delta^{18}O$ signal from the Gladysvale flowstones does not directly support this, the flowstones have been shown to grow during periods of increased precipitation, and the $\delta^{13}C$ signal, suggesting C_3 vegetation and more persistent rainfall, bears this out.

Three independent lines of evidence provide addition palaeoenvironmental information. First, the thin section analysis of the breccias (Chapter 3.3.2) revealed that the breccias consist predominantly of structures known as micropeds (Partridge, pers. comm.) (Figures 3.3, 3.4 and 3.5), which are associated with granular soils (Retallack, 1990), and have been found in other cave sediments (Moriarty *et al*., 2000), suggesting that the breccias consist of remobilised soil horizons from outside the cave. Micropeds and larger granular peds are common in the surface horizons of grassland soils (Retallack, 1990), corroborating the $\delta^{13}C$ signal evidence from the breccias.

Second, the fossil snails found preserved within the breccias, *Trophidophora insularis* (Chapter 3.3.3, Figure 3.8), are found in a variety of habitats from forest to woodland to thorn savannah, where they live in the sheltering microhabitats of the tree trunks and in the leaf litter (Pfeiffer, 1852; Herbert & Kilburn, 2004). The presence of the snails within the breccias is therefore an indicator that, although the vegetation outside the cave was predominantly a grassland, there were some trees on the landscape, as suggested by the 50-80% C_4 vegetation from the carbon isotopes. These trees were most likely concentrated around the cave entrances, where they were protected from fire.

Third, the laser-ablation scans of select Gladysvale flowstones (Chapter 4, 4.3, Figures 4.1 and 4.2) for trace elements Mg, Sr and Ba provide detailed palaeoenvironmental information on a fine scale for individual flowstones. The U-series dates for the Gladysvale flowstones established that flowstone growth occurred in the recovery period following full interglacials, which were periods of increased effective precipitation, as suggested by the Tswaing rainfall record. The LA data suggest that there were subtle fluctuations during these wet times.

Peaks in Sr are interpreted as indicating both periods of increased precipitation (Tesoriero & Pankow, 1996) and faster calcite growth rates (Treble *et al*., 2003). Mg troughs are interpreted as representing periods where the residence times of the groundwater above the cave were shortened, and groundwater was flushed through into the cave (Roberts, 1997; Roberts *et al*., 1998; Hellstrom & McCulloch, 2000). In the Gladysvale samples, Mg troughs correspond with Sr peaks (Figures 4.1 and 4.2), suggesting that these were periods of increased rainfall, during which groundwater residence time above the cave was shortened. The increase in cave drip waters would also have led to an increased calcite growth rate in the speleothems.

Conversely, Mg peaks are interpreted as representing an increased residence time of groundwaters above the cave (Roberts, 1997; Roberts *et al*., 1998; Hellstrom & McCulloch, 2000), and thus slightly drier periods. Ba concentrations in speleothems are temperature related, with higher temperatures producing Ba peaks (Roberts, 1997; Roberts *et al*., 1998). In the Gladysvale samples (Figures 4.1 and 4.2) Ba peaks correspond strongly to Th peaks. Ba is soluble in groundwater, while Th is not (Freeze & Cherry, 1979), indicating that while the Ba enters the cave with the groundwaters, the Th does not. During slightly drier times the cave entrance may have opened slightly, and allowed detrital Th-bearing material to enter the cave. At Gladysvale the Mg peaks also correspond with peaks in Ba and Th concentrations (Figures 4.1 and 4.2), providing further evidence for slightly drier times during otherwise wet phases of flowstone growth.

The U-series dating of the Gladysvale flowstones, discussed in this chapter (section 6.3), indicate that, at least at Gladysvale, flowstone growth took place during interglacials, and, from the comparison with the Tswaing Impact Crater record, that these were periods of increased effective precipitation. According to the climatically controlled cave sedimentation model of Ayliffe *et al*. (1998) and Moriarty *et al*. (2000), the breccia deposits conversely correspond to the drier, more arid periods. At Gladysvale the breccias are intercalated between flowstones, which have been shown to grow during interglacials, meaning that the breccias have to have accumulated during glacial cycles. As illustrated in Table 6.2, the breccias at Gladysvale may also be correlated with periods of aridity from other southern African climate proxy records.

It is therefore proposed that there is a strong climatic control on sedimentation at Gladysvale Cave, with flowstone growth during periods of increased effective precipitation, during which precipitation is more persistent and conditions are conducive to C_3 vegetation. In the summer rainfall area of South Africa, which includes the Cradle of Humankind World Heritage Site, these periods correspond to interglacials. The cave breccias, on the other hand, represent cooler, more arid periods, with less average annual precipitation, but an increased frequency of high altitude storms, which were conducive to the spread of C_4 vegetation.

6.5 Chronostratigraphy and palaeoenvironmental reconstruction for the Pleistocene fill at Gladysvale Cave

The three-dimensional stratigraphy and FBU sedimentology (Chapter 3), the U-series ages (Chapter 4) and stable light isotope data (Chapter 5) have been combined to produce a series of block diagram cartoons reconstructing the conditions inside Gladysvale Cave through time (Figures 6.8 and 6.9).

At 570 ka during the interglacial OIS 15, Gladysvale Cave was closed. The deposition of massive stalagmitic bosses and stalactite chandeliers was underway as conditions were conducive to flowstone growth. One stalagmite produced a U-series age of 571.380 ± 24 902 ka (Figure 6.8 Block A). The stalagmites and corresponding stalactites formed predominantly in the centre and eastern portions of the cave. Globally this was an interglacial period, during which warm and wet conditions prevailed. Based on the isotope data, a 60% C_3 vegetational cover is proposed for the hillslope above the cave.

At around 535 ka conditions changed significantly, with drier conditions experienced in the Gladysvale valley, as a result of a global glacial period during OIS 14. As a result, the C_3 vegetation died back, and the hillslope was eroded, causing Gladysvale Cave to open up, forming a new entrance. Dolomite roof blocks and boulders fell into the cave directly below the new entrance, building up into a wedge-shaped pile of sediment (unit MK), which is found only in the proximal region of the cave. The distribution of MK was also limited by the presence of the large stalagmite bosses in the middle of the cave (Figure 6.8 Block B).

Global climatic conditions shifted into an interstadial period during OIS 14 (~525 ka) and the Gladysvale valley became warmer and wetter, and the cave became closed as dolomite blocks and vegetation blocked the entrance. The increased effective precipitation and closed cave were ideal conditions for speleothem growth, and a flowstone capping over MK and a small stalagmite on the top edge of the sediment pile grew (Figure 6.8 Block C).

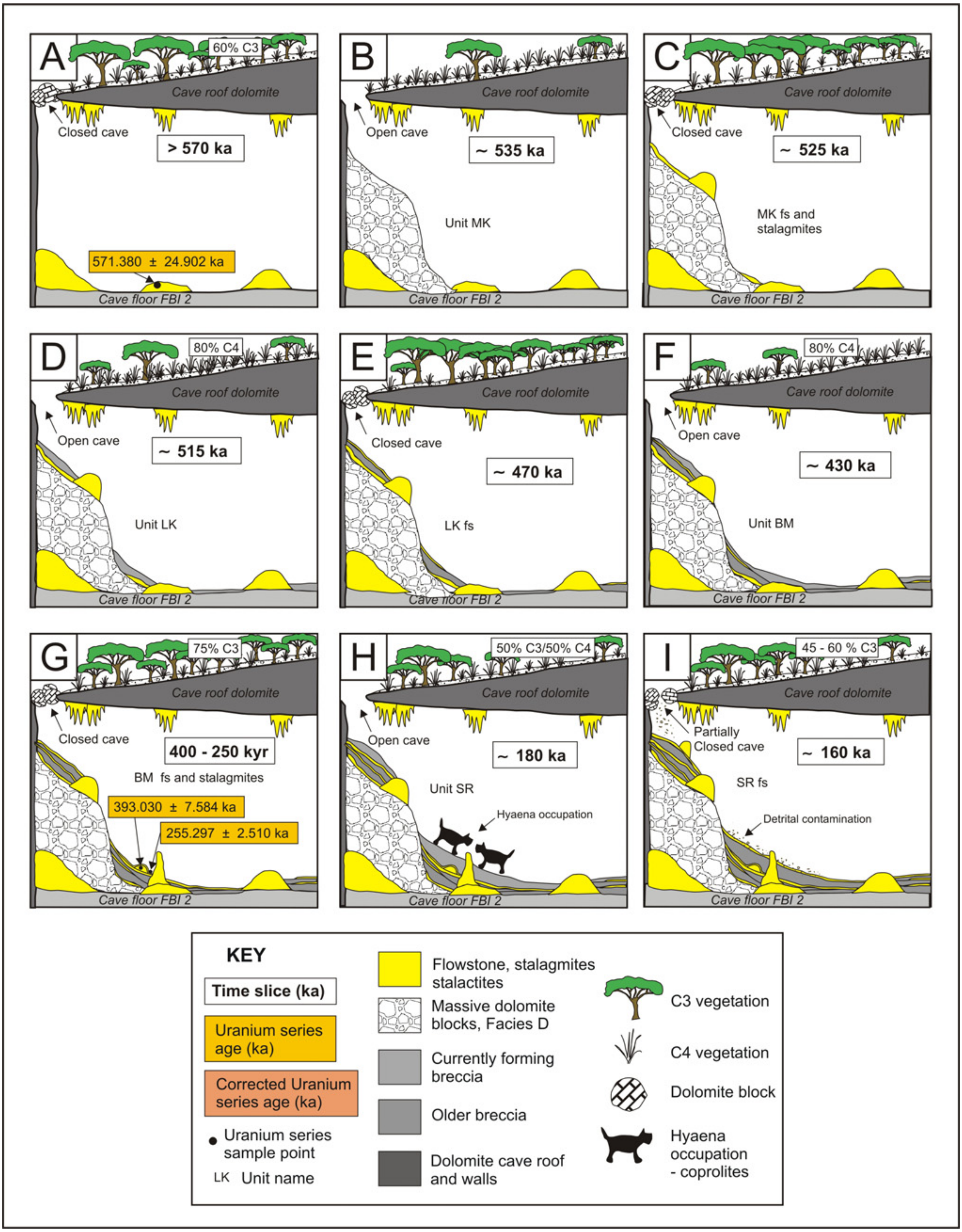

Figure 6.8. Cartoon reconstructions of conditions at Gladysvale Cave from 570-160 kyr. Note sediment slopes are exaggerated, not to scale.

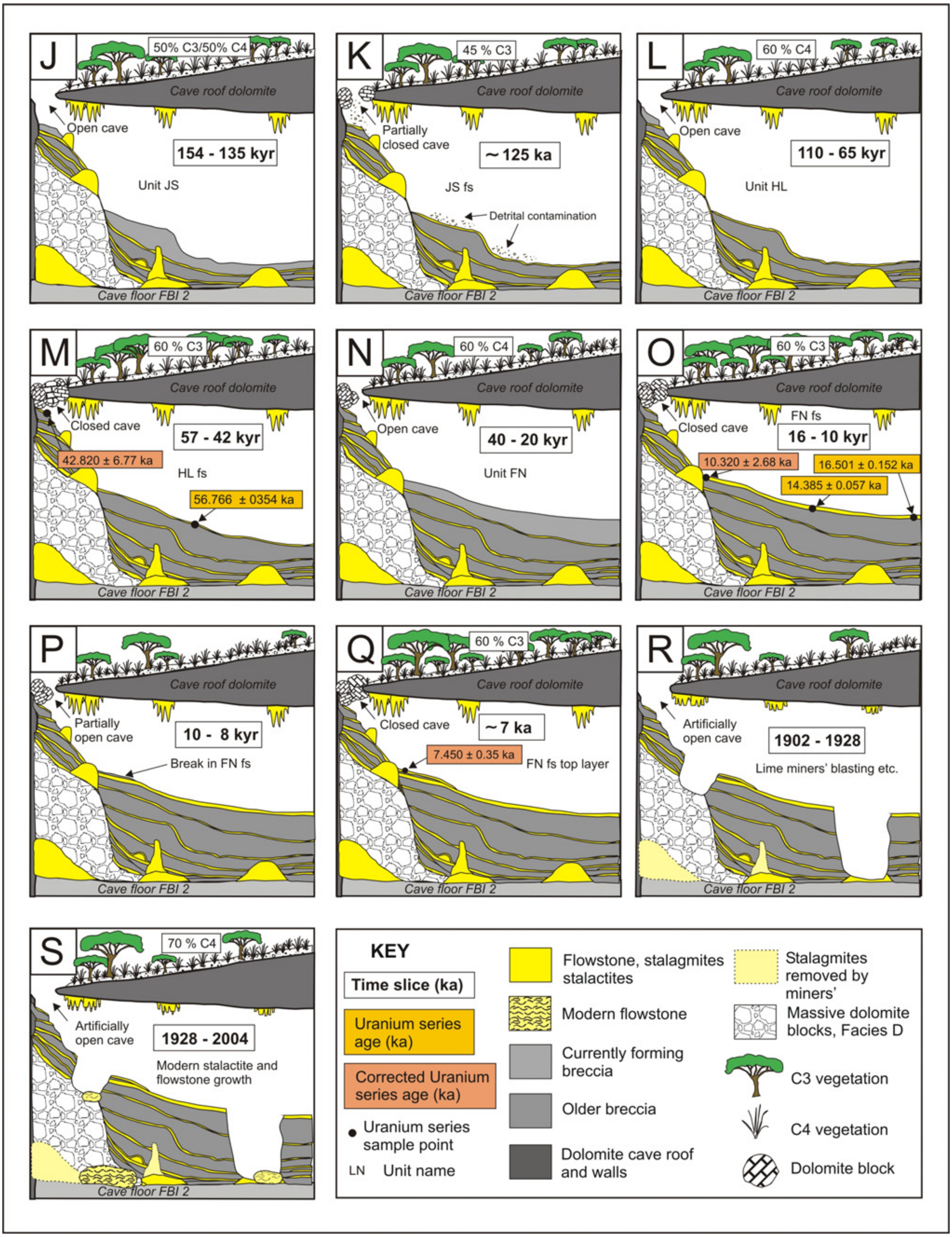

Figure 6.9. Cartoon reconstructions of conditions at Gladysvale Cave from ~150 ka to the present. Note: sediment slope angles are exaggerated, and not to scale.

By ~515 ka global climates shifted back into glacial conditions during OIS 14, and once again hillslope erosion would have opened up Gladysvale cave. The cooler and drier conditions would have favoured C_4 vegetation, and savannah grasslands would have been the dominant vegetation above the cave. According to the model of Holmgren *et al*. (2003), drier periods are characterised by an increased frequency of high altitude convective storms, which would have washed the soil, which was loosely held by the shallow roots of the grass vegetation, into the open cave. The first such clastic sedimentary unit is LK, which formed as a thin layer of sandy sediment overlying unit MK in the proximal region of the cave and overlying FBI 2 (Pickering, 2002) in the rest of the cave. The carbon isotope data for this unit suggest an 80% C_4 vegetational cover growing above the cave (Figure 6.8 Block D).

At ~470 ka warmer and wetter conditions followed the full the interglacial of OIS 13. This led to an increase of C_3 vegetation above the cave, and would have blocked the cave entrance from receiving incoming clastic sediment. Increased effective precipitation and more persistent, less season rainfall (according to the model of Holmgren *et al*., 2003) provided ideal conditions for flowstone growth inside the closed cave and a flowstone cap grew over unit LK (Figure 6.8 Block E).

Global climatic conditions shifted back into a glacial period during OIS 12, opening up the same single entrance to the cave and favouring C_4 plants, which made up 80% of the vegetation above the cave. At ~430 ka the next sedimentary unit, BM, was washed into the cave, probably by flood events following massive, high altitude storms. BM is found throughout the cave, and downlaps into the spaces created by thinning of the underlying LK (Figure 6.8 Block F).

After the deposition of BM, global climates warmed into the interglacial OIS 11, and the cave entrance became blocked off, closing the cave from any further incoming detrital sediment for the next ~150 kyr. During this time a flowstone capping grew over BM, with a small stalagmite developing under a major drip source in the mid-fan region of the cave, which produced a U-series age of 393.030 ± 7.584 ka (Figure 6.8 Block G). The other large stalagmite bosses between the major lobes of the deposit would also have grown during this period. This was followed by a period of no deposition in the cave for ~100 kyr, for the duration of OIS 10. Although this period was a glacial, which would otherwise be associated with clastic sedimentation, this time the cave entrance was *not* opened, as there is no clastic unit corresponding to this period. At ~300 ka the global climate warmed into the interglacial

OIS 9 and the large stalagmitic bosses resumed growth - the upper part of the stalagmite in the Porcupine Pit yielding a U-series age of 307.516 ± 2.510 ka.

Global climate then shifted back into a glacial, OIS 8, and some valley erosion took place and a small second entrance to the cave, further east from the main entrance briefly opened, and the sedimentary unit JN, consisting mainly of collapsed dolomite blocks, was deposited into the Porcupine Pit area of the cave. This unit is restricted to this area of the cave, and was most likely deposited at ~275 ka. This unit is not shown in Figure 6.8 due to its limited lateral extend in the cave.

During OIS 8, there was an interstadial period at ~250 ka, during which conditions were significantly warmer and wetter, and the small entrance, through which unit JN had come, was closed up again; C_3 plants became dominant again, making up 75% of the vegetation above the cave. During this time a flowstone capping grew over everything in the cave, and forms the flowstones above JN in the Porcupine Pit and the small stalagmite growing up from the flowstone already covering BM. This flowstone yielded a U-series age of 255.297 ± 2.510 ka (Figure 6.8 Block G).

This was followed by a depositional hiatus of ~70 kyr, during which neither clastic nor chemical sedimentation took place. At ~180 ka global climates are in the glacial OIS 6, which is reflected by a significant drop in the rainfall record from the Tswaing Impact crater record. During this time the main entrance to the cave opened up again, most likely from valley erosion and from the dying back of the C_3 pants to only 50% of the vegetation above the cave. Clastic sediments were washed into the cave to form the sedimentary unit SR (Figure 6.8 Block H). SR is considerably thicker than the underlying units, and is the first to be found throughout the cave. Hyaenas also occupied the cave at this time, as their coprolites have been found in the sediments of SR. The cave entrance must have been quite large to attract these animals into the cave. In the mid-fan SR consist of Facies E, a powdery, fine grained material, which may have been produced from bat guano, suggesting that bats may have roosting in the cave, as they do today.

Global climatic conditions shifted quite rapidly into a significant interstadial period during OIS 6, during which there was a marked increase in rainfall in the Tswaing Impact crater record. This increase in precipitation favoured C_3 plants and there was a shift to a maximum of 60% C_3 vegetation above the cave. The vegetation blocked off the cave entrance, but only to a limited extent. A flowstone capping grew over SR, with considerable contamination from detrital material entering through the slightly open cave (Figure 6.8 Block I). A small stalagmite also grew up from the flowstone in the proximal region of the deposit.

Globally climatic conditions during OIS 6 became cooler at ~150 ka, and plants above the cave shifted back to 50% C_3/C_4 and the vegetation blocking the cave entrance died back, opening the cave up again. Soil was washed into the open cave and deposited as unit JS between 154 and 135 ka, corresponding to dry phases at the Tswaing Impact crater. JS is the thickest unit deposited so far, and overtops the small stalagmite growing up from the basal stalagmite in the middle of the cave (Figure 6.9 Block J). In the proximal area of the deposit, JS is backed up against the small stalagmite on the flowstone capping underlying SR. JS is then thickest in the mid-fan region of the deposit, and thins rapidly into the more distal regions. In the Porcupine Pit JS is very thick and coarse grained, consisting predominantly of dolomite boulders of Facies D (Figure 3.25). This suggests that a second smaller entrance to the cave also opened during this time, and the resulting dolomite blocks collapsed into this part of the cave.

Between 128 and 125 ka global climates were extremely warm and wet, and this period, OIS 5e, the Eemian, is the last full interglacial before the present. This was a time of global flowstone growth (Richards & Dorale, 2003). In South Africa conditions were slightly wetter, as seen in the Tswaing Impact crater record, but not as wet as expected. The vegetation at Gladysvale shifted to slightly *less* C_3, instead of more as expected. The cave is only partially blocked, and the flowstone layer which grew over JS was heavily contaminated by incoming detrital material and was restricted in lateral extent to areas directly below drip sources (Figure 6.9 Block K).

Following this there are several climatic perturbations during OIS 5, one at 110 ka, (stage 5d) is particularly cold and is seen as a dry phase at Tswaing, as colluvial deposits in the Voordrag sequence between 96 and 99 ka (Clarke *et al*., 2003) and sedimentary fill at Erkroon at 110 ka (Hancox *et al*., 2002b). By ~60 ka there was another global ice age, OIS 4, which is also seen as a slightly drier phase at Tswaing. During one of these two dry phases C_4 vegetation became more dominant at Gladysvale, making up 60% of the plants growing above the cave. The cave entrance opened up again and clastic sediments were washed in to form unit HL (Figure 6.9 Block L). HL occurs sparsely in the proximal region of the middle of the deposit, and downlaps into the space created by the thinning of underlying JS in the mid-fan area of the deposit. HL is very thick and coarse grained in the Porcupine Pit (Figure 3.26), suggesting that the second, smaller cave entrance was open again during this time, and collapse blocks from this smaller entrance were deposited into this part of the cave. At the main entrance to the cave, HL fills the cave almost to the roof, and blocked off this entrance to any further incoming sediment. It is not possible with the current dataset to determine with which of the two dry periods the sediments of HL are associated. The sediments of unit HL could be dated via Luminescence dating, which would solve this problem, however this was beyond the scope of this study.

Global climates then warmed into an interglacial, OIS 3, with wetter conditions recorded at the Tswaing Impact crater at ~52 ka. At Gladysvale C_3 plants were favoured, and made up 60% of the vegetation above the cave. The cave entrance became blocked off and a flowstone capping grew over the clastic unit HL. In the mid-fan region of the deposit this layer is dated to 56.766 ± 0.354 ka. The layer is also dated in the proximal region, but this age of 42.820 ka had to be corrected due to considerable detrital contamination, and has an error of ± 6.77 ka (Figure 6.9 Block M). The flowstone was contaminated more in the proximal than mid-fan region of the deposit, as the proximal flowstone was more vulnerable to detrital contamination, being closest to the cave entrance. Even though this entrance was restricted to major clastic sediment input, some finer material could have entered the cave. Within the error of the younger age, this period of flowstone growth is a long one, and there may well have been a break in flowstone growth at around 50 ka, during the full interglacial.

This episode was followed by the onset of the glacial period, OIS 2. As with OIS 5d and 4, there are two glacial peaks during OIS 2, one at ~40 ka and the second, larger peak centred on 18 ka, which is the Last Glacial Maximum (LGM) and is well recorded in a number of palaeoclimate records throughout southern Africa (e.g. Talma & Vogel, 1992, Partridge, 1993, Holmgren *et al*., 2003, Partridge *et al*., 2004). Once again it is not possible to determine which one of these events is responsible for the youngest sedimentary unit in the cave, FN (Figure 6.9 Block M). Once again only the direct dating of this layer can solve this problem. During the deposition of FN arid adapted C_4 plants were the dominant vegetation above the cave. As already mentioned, the underlying unit (HL) blocked off the main entrance to the cave, and FN is not found in this region of the cave. Instead it appears that FN entered through a narrow slot like entrance that ran across the front wall of the cave, and this would account for the consistent thickness of this unit in the proximal regions of the cave.

Following the LGM global climates began the rapid and intense warming that characterises the Holocene (OIS 1). At Gladysvale the warmer and wetter conditions favoured C_3 vegetation and the cave entrance became blocked off. This was most likely aided by the partial collapse of the cave roof along the front wall of the cave, which created rubble chokes and sealed off the entrance. In the closed cave a thick flowstone capping grew over everything and has a distinctive rippled texture (Figure 6.9 Block O). This flowstone layer yielded ages of 16.501 ± 0.152 ka, 14.385 ± 0.057 ka and a corrected age of 10.320 ± 2.68 ka, from the distal, mid-fan and proximal regions of the cave respectively, suggesting a ~6 kyr episode of flowstone growth.

This period of flowstone growth was briefly interrupted as global climates experience one of the severest and briefest perturbations in Holocene palaeoclimatology – the Younger Dryas. This episode is recorded in a number of South African palaeoclimate records, and is a very hot, dry and evaporative time (Holmgren *et al*, 2003; Scott *et al*., 2003). At Gladysvale the flowstone capping FN stopped growing at this time and a thin (5-10cm) layer of fine grained detrital sediment entered the cave and settled on the flowstone in the proximal regions of the cave (Figure 6.9 Block P).

At about 7 ka global climates recovered and continued the strong warming trend seen in the Holocene. C_3 plants formed the dominant vegetation above Gladysvale Cave and the cave was re-sealed to any incoming sediment. Flowstone growth resumed, but probably only in the proximal regions of the cave, where a U-series age of 7.450 ± 0.35 ka was produced (Figure 6.9 Block Q). There are a few centimetres of flowstone above this dated layer, so flowstone growth continued for some time at Gladysvale after this, but did stop eventually as the climate continued to warm.

Between 1902 and 1928 Gladysvale Cave was mined extensively for the speleothems within the cave, for the production of lime, which was used as a flux in the booming gold industry in nearby Johannesburg (Berger & Tobias, 1994). The miners blasted open the cave and dug significant trenches through the deposit and removed all of the large stalagmitic bosses, and many of the smaller stalagmites, and also broke off the large stalactites (Figure 6.9 Block R). After mining ceased in 1928, small (~4cm), modern stalactites grew down from the stumps of the broken off ones, and patches of modern flowstone developed under major drip points (Figure 6.9 Block S).

6.6 Comparison of Gladysvale with other climatic records

As demonstrated in the previous section, the younger internal deposit at Galdysvale is strongly climactically controlled, with flowstones and breccias accumulating in wetter and drier periods respectively. These types of sedimentation are therefore proxies for the climatic regimes under which they were deposited. The U-series ages of the basal stalagmite and uppermost flowstone provide age brackets for the deposit between 600 and 7 ka, making this the oldest known (although highly punctuated), terrestrial record of climate change in southern Africa. The age range of the deposit at Gladysvale, therefore, extends well beyond all other currently known records of climatic change in Southern Africa, as until now the longest record was the 200 kyr Tswaing Impact Crater rainfall record of Partridge *et al*. (1997). Therefore comparisons of the Gladysvale record with other records of South African climate change records are restricted to the last 200 kyr (Figure 6.10). The period from ~12 to 7 ka is discussed separately in greater detail.

6.6.1 The last 200 kyr

The chronostratigraphic succession of breccias and flowstones generated in this study from Gladysvale Cave for the last ~200 kyr is compared to the global climate change record of ocean volume of Imbrie *et al*. (1984), the record of sea surface temperatures (SST) from the Indian Ocean (Bard *et al*., 1997; Bard., 2003), the Tswaing Impact crater rainfall record of Partridge *et al*. (1997), the record of colluvium and paleosols form the Voordrag sequence of Clarke *et al*. (2003) and the record of periods of dune mobility in the Kalahari of Stokes *et al*. (1999) in Figure 6.9. The Heinrich events of Broecker *et al*. (1992) and Bond *et al*. (1992), H5 – H0, are also included.

Superficially there is remarkable synchronicity between all these very different records (Figure 6.9). Interglacial periods from the SPECMAP record broadly correspond to warmer SSTs in the Indian Ocean, wet phases at Tswaing and rather loosely to periods of paleosol development within the Voordrag sequence. The U-series dated speleothems at Gladysvale also correspond to these wet phases, occurring during interglacials (Figure 6.10). Conversely, glacial periods in the SPECMAP record correspond to lower Indian Ocean SSTs, dry phases at Tswaing, colluvium accumulation at Voordrag, and periods of principal dune mobility in the Kalahari (Figure 6.10).

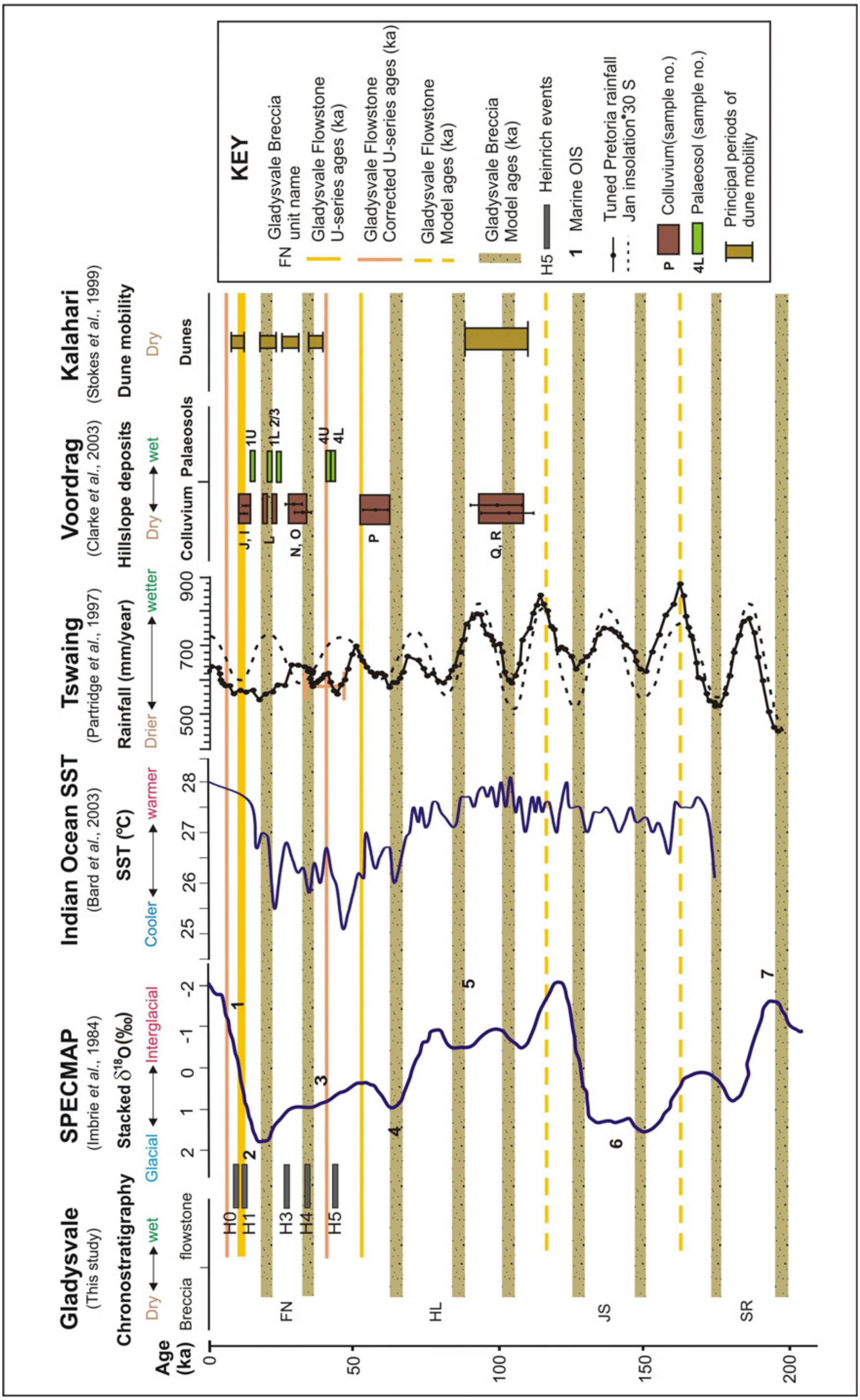

Figure 6.10. Gladysvale chronostratigraphy compared to published records of global and southern African climate change for the last 200 kyr.

There are few other records of this age in southern Africa with which to compare these changes. Marine core records off the west coast, recovered from Walvis Ridge in the SE Atlantic Ocean, record changes in the winter rainfall area of the country (Stuut *et al*., 2002), and comparisons with the summer rainfall area encompassing Tswaing (and Gladysvale) are not immediately apparent (Partridge *et al*., 2004), other than that these records also show strong orbital control. The fluvial sites Erfkroon and Cornelia in the Free State are the only known terrestrial records of climate change at this time, and do provide a sequence of wetter and drier periods represented by episodes of deposition and erosion (Hancox *et al*., 2002b).

OIS 5 is better represented in a number of terrestrial sites across southern Africa. The Tswaing Impact Crater sediments record the fluctuating conditions during OIS 5, with rainfall varying from about the same as today in the Eemian, to 35% higher in OIS 5d (Partridge *et al*., 1997) (Figure 6.10). During the Eemian (OIS 5e), micro-mammalian evidence from Border Cave indicates elevated temperatures and a southward shift of the Miombo woodland boundary of perhaps as much as 3° (Avery, 1992), with rainfall of 1600 mm/year, double that of today. Dating for this site is somewhat contentious, but the presence of the Eemian form the micro-mammalian fauna is indisputable; however, there are problems resolving the timing of the response to this phase with any degree of precision (Partridge *et al*., 2004). The site of Florisbad has a somewhat firmer chronology based on ESR dating of tooth enamel of antelopes occurring in key levels (Grün *et al*., 1996). Eemian deposits are associated with a Middle Stone Age (MSA) lithic tradition and contain moisture-loving taxa, such as hippopotamus and lechwe (Grün *et al*., 1996). However, hyaena coprolites have yielded pollen indicating a significantly more grassy environment than characterises this area today (Partridge & Scott, 2000). Better dating of this site will most likely resolve these issues. At Klasies River Mouth, on the southern Cape coast, there is a MSA occupation layer overlying elevated beach gravels and capped by speleothems dating to just over 100 ka by U-series (Deacon & Lancaster, 1988). The occupation level therefore postdates the peak in high sea level of OIS 5, marked by the presence of the elevated beach gravels. Mollusc shells within this gravel indicate significantly warmer inshore temperatures (Maud, 2000). At Gladysvale, the undated flowstone capping FBU JS is given a model age of ~125 ka to correspond with this wet period (Figure 6.9). Significant detrital contamination of this flowstone suggest that this period was not as wet as expected during the Eemian. At Maandagshoek in Limpopo Province, a colluvium layer yields a luminescence age of 124 ka (Hancox *et al*., 2004), suggesting that, in this area, drier conditions prevailed with sediment accumulation taking place.

The glacial period of OIS 5, following the Eemian, is seen in the colluvial deposits at Voordrag, which are dated to between 99-96 ka via luminescence dating (Clarke *et al*., 2003), indicating increased aridity at this time. This is also the first major period of dune mobility in the Kalahari between 115 and 95 ka (Stokes *et al*., 1997; 1998; 1999; Thomas *et al*., 2000). Periods of dune mobility are interpreted as representing more arid phases, as during more humid phases dunes become better vegetated and less mobile (Stokes *et al*., 1997; 1998;1999; Thomas *et al*., 2000). Cornelia in the Free State has produced a luminescence age of 110 ka for a sedimentary fill event, suggesting an arid period (Hancox *et al*., 2002b). FBU HL at Gladysvale is undated, but most likely accumulated during one of these short-lived arid phases during OIS 5 and OIS 4 (Figure 6.10).

6.6.2 The Last Glacial Maximum

The period directly preceding the Last Glacial Maximum (LGM) is a time during which the strength of precession weakens, from ~60 ka onwards, and other factors begin to control climate changes and responses in southern Africa (Partridge *et al*., 2004). The last wet phase at Tswaing corresponding to precession is at ~50 ka (Partridge *et al*., 1997). This wet phase is also seen in the Voordrag sequence, where paleosols 4L and 4U developed (Clarke *et al*., 2003). At Gladysvale the flowstone capping unit HL is dated to between 56 and 42 ka. The Indian Ocean SST record of Bard *et al* (1997) and Bard. (2003) records two warmer periods at around 55 and 45 ka, suggesting that there were two distinct periods of flowstone growth at Gladysvale at these times, and that this flowstone most likely did not grow continuously (Figure 6.9).

At this time the Tswaing Impact Crater sediments begin to lose their 23 kyr cyclicity (Figure 6.9), and the decrease in the amount of rainfall is seen in the diatom record, which shows an increase in the salinity and alkalinity of the lake, changing it irreversibly from a freshwater system (Partridge *et al*., 1997). This drying phase into the LGM is seen in a number of other records: there are three major, short lived periods of dune mobility in the Kalahari at 46-41 kyr, 36-29 kyr and 26-20 kyr (Stokes *et al*., 1997; 1998; 1999; Thomas *et al*., 2000), which significantly pre-date the massive periods of ice rafting in the North Atlantic (Heinrich events H5, H4, H3 and H1) (Partridge, 2002; Partridge *et al*., 2004). The arid phases at Tswaing also appear to pre-date the Heinrich events (Partridge, 2002; Partridge *et al*., 2004). Increased aridity is also seen in Botswana, as an increase in grassy vegetation after 47 kyr from the stalagmites in the Lobatse Cave (Holmgren *et al*., 1995) and from the pollen signal at Tswaing between 38 and 35 ka (Partridge & Scott, 2000). The breccia unit FN at Gladysvale is given a model age of ~40 ka to correspond with this dry phase (Figure 6.9), during which time grassy vegetation is dominant above the cave. An arid period is also represented in a phase of the sedimentary fills at Cornelia, dated at 24 ka (Hancox *et al*., 2002b).

The LGM itself is well recorded in a number of records across southern Africa. There was a 5-6°C drop in temperature recorded in the Cango Cave stalagmite (Talma & Vogel, 1992) and a decrease in rainfall from 35-70% across the whole country (Partridge *et al*., 1999b). C_4 grasses become dominant in the summer rainfall region at this time, as the reduced CO_2 levels favour C_4 vegetation (Vogel *et al*., 1978). The LGM is recorded in the Indian Ocean SSTs as a significant drop in temperature (Bard *et al*., 1997; Bard, 2003), a dry phase at Tswaing (Partridge *et al*., 1997), and by both colluvium and paleosol development in the Voordrag sequence, suggesting fluctuating conditions during this time. A significant drop in sea level during the LGM is seen along the north coast of KwaZulu-Natal, where a marine regression of -130m caused reworking of older dune material (Sudan *et al*., 2004). The Makapansgat speleothem records drier conditions, lower temperatures and sparser grass cover at about 23-21, 19.5-17.5 and again at 15-13.5 ka, and a subdued cold event at 17.5 ka (Holmgren *et al*., 2003). Maximum cooling is also seen in the Wonderkrater sequence at 17.5 ka, where a 1000m drop in vegetation zones indicates a depression of 5-6°C (Scott, 1982). Further afield, this arid phase is seen in the Antarctic Taylor Dome $\delta^{18}O$ record (Steig *et al*., 2000) and by lowstands in tropical Lake Victoria (Stager *et al*., 2002).

The deglaciation following the LGM is seen in South Africa as rapid warming and associated wetter conditions beginning after 17.5 kyr, which correspond to similar trends in southern Hemisphere polar and tropical ice cores (Thompson *et al*., 1995; Blünier *et al*., 1998; Steig *et al*., 2000). These conditions precede Heinrich event 1 (15-13 ka) and other northern hemisphere records by about 2 kyr. During this period of warming (Partridge, 1993), the flowstone capping Unit FN grew, and is dated between 16.5 and 14.3 ka, with a younger date of 10.3 ± 2.68 ka, which had to be corrected because of serious detrital contamination. These dates suggest that speleothem growth continued at Gladysvale despite the return to slightly colder and drier conditions during the Antarctic Cold Reversal between 15 and 13.5 ka, as seen in ice cores from the Antarctic (Blünier *et al*., 1998).

6.6.3 The Younger Dryas

The Younger Dryas is a global period of aridity, associate with Heinrich event O in the northern Hemisphere (Broeker *et al*., 1992; Bond *et al*., 1993, 1995) and is also seen in the Vostok ice core record (Petit *et al.*, 1999) (Figure 6.10 D). Records of this event from South Africa are compared with the flowstone capping unit FN in the proximal region of Gladysvale Cave in Figure 6.10. The flowstone consists of a number of calcite layers, two of which were dated via U-series and yielded ages of 10.32 ± 2.68 ka at the base and 7.45 ± 0.35 ka at the top (Figure 6.11). Both these dates are corrected for detrital contamination (Table 4.4). These flowstone layers are separated by a distinct layer of fine grained clastic sediment and produced very different $^{234}U/^{234}U$ ratios (Table 4.3).

There is a break in the Makapansgat stalagmite between 12.7 and 10.2 ka, during which conditions were not conducive to speleothem growth in this area (Holmgren *et al*., 2003) (Figure 6.11 C). The Wonderkrater sequence, some 40km away from Makapansgat, shows an interruption in the warming trend centred on 11.3 ka from the pollen-derived temperature index. The high abundance of specific pollen taxa, namely Chenopodiaceae and Amaeanthaceae, suggest that conditions between 10 and 12 ka were strongly evaporative but not necessarily of lower rainfall (Figure 6.11 B). These drier conditions would have caused the cessation of drip waters at Makapansgat and are therefore responsible for the break in the stalagmite. These dry conditions are seen in many other records, including low lake levels in Lake Victoria at 12.5 ka (Stager *et al*., 2002).

Following the Younger Dryas, South African climates show rapid warming and wetting into the southern African Holocene altithermal (Tyson *et al*., 2001), with an increased growth rate seen in the Makapansgat stalagmite (Holmgren *et al*., 2003) and generally warm conditions recorded in the Wonderkrater temperature index between 10 and 6 ka. At ~8.2 ka there is another brief cold event, which is seen as an increase in C_4 grasses at Makapansgat (Holmgren *et al*., 2003), an increase in grass pollen at Wonderkrater (Scott, 1982), as a period of increased dune mobility in the Kalahari (Thomas *et al*., 2000) and as a short but strong dry event in the Kilimanjaro ice core record (Thompson *et al*., 2002).

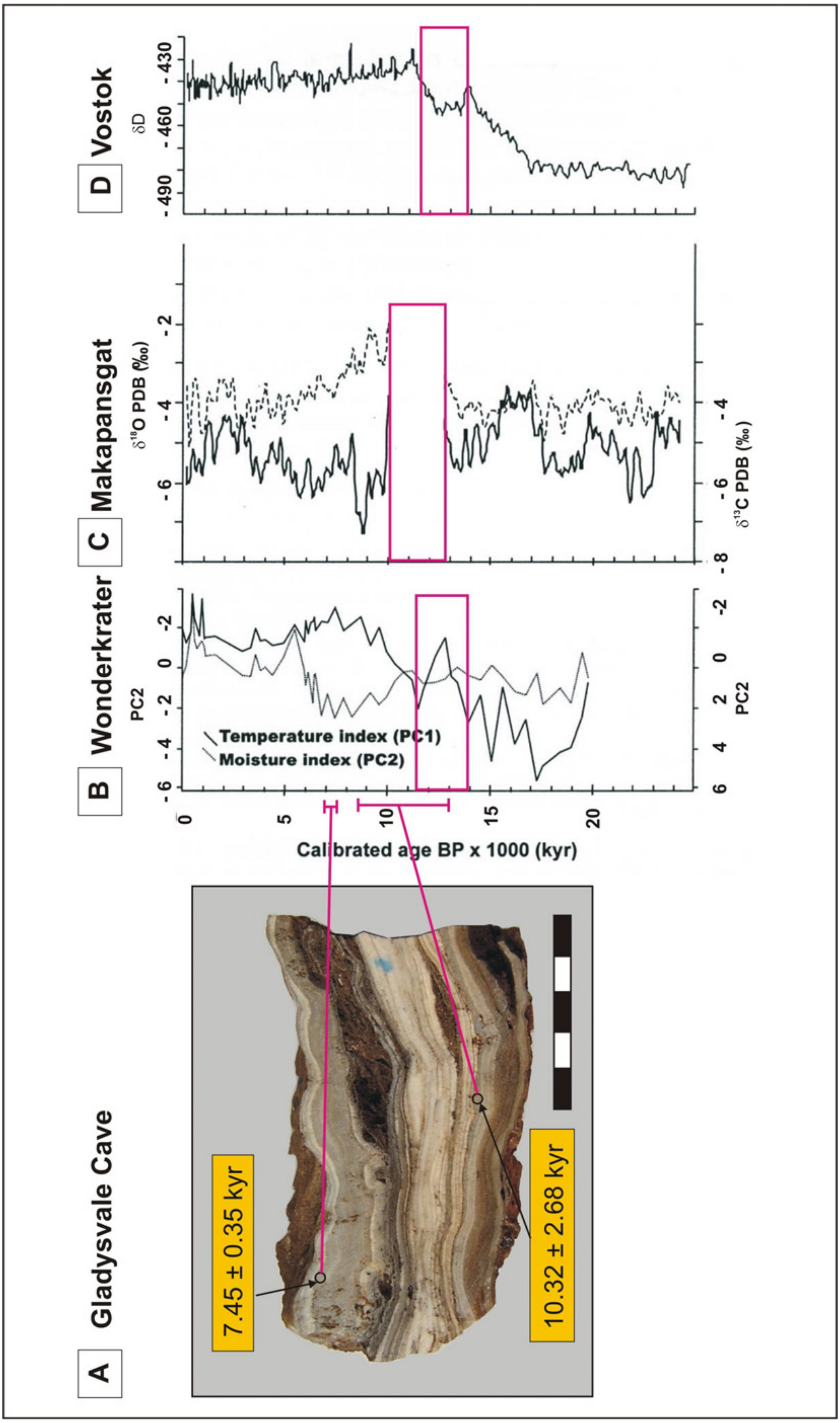

Figure 6.11. Comparison between U-series dated Gladysvale flowstone and the climate change records from Wonderkrater (Scott *et al*., 2003), Makapansgat (Holmgren *et al*., 2003) and the Vostok ice core (Petit *et al*., 1999).

The flowstone capping unit FN most likely records these events. The age for the basal part of the flowstone, at 10.32 ka, postdates the Younger Dryas *sensu stricto*, but within the upper limit of the 2.68 ka error for this age, this flowstone could have grown towards the end of the warm period leading up to the Younger Dryas. The top part of the flowstone, dated to 7.45 ± 0.35 ka, corresponds to the period of warming experienced after the Younger Dryas and seen in the relatively nearby Wonderkrater and Makapansgat records (Figure 6.11). The presence of the fine-grained sediments between the layers indicates a physical break between the two layers of flowstone. The very different $^{234}U/^{234}U$ ratios of the two layers (Table 4.3) suggest that the flowstones were fed by drip waters with slightly different compositions, suggesting a break in time between their deposition. This break may however correspond to the 8.2 kyr event discussed above, as the U-series dates suggest. However, the Makapansgat stalagmite did *not* stop growing during this period, and the Gladysvale flowstones grew through the dry period between 15-13 ka, suggesting that only significant and prolonged periods of aridity would lead to a break in cave speleothem development. Repetition of the U-series ages would better constrain this break and allow for better correlation between deposition at Gladysvale and the Younger Dryas.

6.6.4 Major forcing mechanisms

The synchronous nature of the various climate change records compared to the Gladysvale record in Figure 6.9 points to a strong external, allocyclic control over periods of sedimentation, dune mobility, etc. Partridge *et al*. (2004) argue that the major forcing mechanisms behind climate change in southern Africa for the last ~200 kyr are orbital precession and changes in atmospheric circulation in Antarctica.

The Tswaing record shows that the influence of orbital precession was particularly strong during OIS 6 (Partridge *et al*., 1997). This is due to the fact that when orbital forcing is strong, which it was until ~60 ka, the summer rainfall in the mid latitudes of southern Africa fluctuates as a direct result of changes in the receipts of solar radiation, with a high degree of sensitivity (Partridge *et al*., 2004). The Tswaing crater sediments show a distinct cyclicity of ~23 ka between dry phases, indicating precessional control. Cave sediments at Gladysvale, FBU SR, JS and HL, are assigned model ages based on the presence of dry phases at Tswaing, thus presuming equal orbitally forced precessional control of conditions conducive to clastic sedimentation in the cave. It is most likely that the older deposits in the cave are controlled by similar orbitally forced changes.

After ~60 kyr, precession weakens and changes in ice volume, deep-water formation/thermohaline activity, and atmospheric circulation over and around Antarctica takes over (Partridge *et al*., 2004). These events in Antarctica during this time dominate major responses in terrestrial sequences in southern Africa, especially those governing the timing and distribution of significant intervals of aridity (Partridge *et al*., 2004). These arid intervals predate northern Hemisphere signals, including Heinrich events, by 3-4 kyr, suggesting that these events originate in the southern hemisphere, specifically in Antarctica (Partridge, 2002; Partridge *et al*., 2004). Changes in Antarctica are translated to southern Africa via fluctuations in the heat budget of the western Indian Ocean, which is the source of precipitation for the summer rainfall area of South Africa (Partridge *et al*., 2004).

The climatic changes originating in Antarctica begin with changes in the extent of sea ice, which controls the position of the Antarctic Convergence, which in turn influences the diameter of the circumpolar vortex. The thermal gradient across Antarctica controls the intensity of this vortex. Fluctuations in the amount of sea ice and thermal gradient across Antarctica are driven by changes in solar input from orbital variations (Partridge *et al*., 2004).

An increase in Antarctic sea ice and a steepened thermal gradient across Antarctic causes an increase in the diameter and intensity respectively of the circumpolar vortex. The net result of this is a virtually instantaneous rearrangement of the atmospheric circulation patterns over southern Africa, with a northwards expansion of the mid latitude westerly winds and an associated equatorward displacement of the sub-tropical highs and the enlarging of the zone of Hadley cell subsidence over western South Africa. Coupled with this, the northward movement of the Inter-Tropical Convergence Zone (ITCZ) diminishes the influence of precessional forcing via tropical easterlies, which convey moisture from the western Indian Ocean to inland South Africa (Partridge *et al*., 2004). These changes result in a decrease in the annual rainfall receipts in the summer rainfall area and an increase in the smaller winter rainfall area of South Africa. These dry phases are prolonged and amplified by the slowing or stopping of the thermohaline circulation as the heat transfer from the western Indian Ocean to the south Atlantic, via the Agulhas current, is restricted (Holmgren *et al*., 2003; Partridge *et al*., 2004). The resulting dry phases in the summer rainfall area of South Africa is believed to be the major, allocyclic control on the deposition of breccia units JS, HL and FN at Gladysvale Cave.

During opposite conditions, a decrease in the amount of sea ice and the intensity of the thermal gradient across Antarctica, leads to a contraction of the circumpolar vortex, and the poleward advance of tropical atmospheric circulation, bringing increased rainfall to the summer rainfall region of South Africa (Holmgren *et al*., 2003; Partridge *et al*., 2004). These periods of increased rainfall are recorded at Gladysvale by flowstone growth at 56-42, 16-10 and at 7.45 ka.

6.7 Climatically controlled cyclic model for sedimentation at Gladysvale cave

6.7.1 The Gladysvale Cave model

At Gladysvale Cave, eustasy and tectonics have played no role in sediment supply, thereby leaving climate change as the major allocyclic control on sediment supply, which coupled with vegetational cover and hillslope sediment mobility leads to periods of rapid sediment transfer and formation of the clastic breccia units. The stratigraphic and sedimentological data from these units, the U-series ages for flowstones and stalagmites, and the stable light isotope data are combined to produce a climatically controlled model for the nature and rate of sedimentation at Gladysvale Cave for the last 600 kyr. This model is summarised in Table 6.4.

Palaeoclimatic conditions and sedimentary responses				
Global climate	Interglacial recovery or warm interstadial		Glacial or cool interstadial	
Surface climate	Warm and wet		Cool and dry	
Type of precipitation	Less seasonal, persistent rainfall		More seasonal, increased frequency of high altitude, convective storms	
Dominant vegetation type	C_3 trees and temperate grasses		C_4 grasses	
Cave entrance	Closed	Partially closed	Open	Closed
Clastic input	Nil	Very low, fine grained	High	Nil
Flowstone form	Clean, few inclusions	Detrital contamination, inclusion rich	n/a	n/a
Stratigraphy	Clean flowstones, minor fine grained contamination	Contaminated flowstones	Layered clastic sediments, soil relics	Hiatus surface, no clastic sediments, no flowstone

Table 6.4. A climatically controlled model for the nature and rate of sedimentation at Gladysvale Cave (after a similar table in Moriarty *et al*., 2000)

The model proposed for the control of the nature and rate of sedimentation at Gladysvale Cave is a simple, climatically controlled one, following the models of Ayliffe *et* *al*. (1998) and Moriarty *et al*. (2000) and is built up from a number of different lines of evidence.

First, flowstones can only grow during periods of increased effective precipitation (Richards & Dorale, 2003). Generally flowstones grow during interglacials (see Richards & Dorale, 2003), but in the arid region of South Australia where the Naracoorte caves are, Ayliffe *et al*. (1998) demonstrated that conditions conducive to speleothem growth are met only during *glacials* as during interglacials local conditions are too dry. The U-series ages for the flowstones at Gladysvale indicate that conditions were right for speleothem growth in the period following full interglacials (Figure 6.4). Full interglacial periods were most likely too hot and evaporative for speleothem growth. Comparison with the Tswaing Impact Crater record of Partridge *et al*. (1997) confirms that these are indeed periods of increased rainfall (Figure 6.3).

Warm, wet interglacial periods are further characterised in southern Africa by the type of rainfall. Holmgren *et al*. (2003) argue that the less seasonal, warm, persistent rainfall recorded by Tyson (1986) and Tyson & Preston-Whyte (2000) in historic times can be seen in the 23 kyr record of climate change in the T8 stalagmite from Makapansgat. This type of rain is ideal for flowstone growth, and would also have favoured C_3 vegetation. This provides the first test of the model: that periods of flowstone growth should also be periods of increased C_3 vegetation.

The type of vegetation above the cave can be assessed through carbon isotopes (Talma & Vogel, 1992), and the flowstones from Gladysvale indicate a 50-80% C_3 cover. Trees would also have aided in the blocking off of cave entrances, as even if climatic conditions are optimal, flowstone development in open caves is minimal. The model calls for closed caves during periods of flowstone growth. The nature of the flowstone itself is an indication of how open or closed the cave is, with clean, inclusion-free flowstones indicating a closed cave and heavy detrital contamination in flowstones indicating a slightly open cave. Thin section analysis, laser ablation and $^{230}Th/^{232}Th$ ratios can be used to quantify the level of detrital contamination.

The second aspect of the model is the cave breccias, which in the original Moriarty *et al*. (2000) model are thought to correspond to dry periods. At Gladysvale the breccias occur as units, which are bound top and bottom by flowstones, producing flowstone bounded units

(FBU), upon which the stratigraphy of the deposit is based. The flowstones have been shown, through U-series dating, to correspond to wet, interglacial periods. Consequently the breccias have to correspond to dry, glacial periods, as they occur intercalated between flowstone layers. Direct dating of the breccia layers would test this, but was beyond the scope of this study.

As with interglacials, Holmgren *et al*. (2003) argue that glacial periods in the past (as recorded in the T8 stalagmite from Makapansgat) experienced a specific type of rainfall, originally recorded in historical times by Tyson (1986) and Tyson & Preston-Whyte (2000). During these periods rainfall became more seasonal, and the frequency of high altitude, convective storms increased. These conditions favour C_3 vegetation, whose shallow root systems would have bound the soil less tightly, and been less effective at preventing sediment transfer downslope. Caves could also have been opened up during these drier glacial periods by valley erosion. Following large, convective storms, the soil profile above the cave, lacking the binding provided by trees, would be mobilised and washed into the open caves. This provides the second test of the model: breccias should have relic soil features and the carbon isotope signature of C_4 vegetation.

Thin section analysis of the breccias revealed a prevalence of soil micropeds, suggesting that the matrix of the breccias are indeed re-mobilised soils from outside the cave. Micropeds also form only in soils below grasslands (Retallack, 1990). The carbon isotope signature of the breccias confirm this further, and indicate a 50-70% C_4 cover during periods of breccia accumulation.

In order to receive clastic sediments caves must be open; if a cave is closed clastic sedimentation cannot take place and while climatic conditions outside the cave may be ideal, these will not recorded, creating a hiatus within the deposit.

This model is based on the cyclic nature of different types of cave sedimentation, with breccias and flowstones forming as discrete units at specific times, once climatic thresholds are crossed. This is obviously a simplification, as caves are complex depositional environments and there are bound to be exceptions to this model. However, the model is deliberately kept simple, and could be applied in broad terms to other caves, but each cave needs to be assessed on an individual basis, and deviations from the model explained by local conditions.

An obvious caveat with the model is the cyclic nature of deposition – the model requires that periods of flowstone growth are isolated to specific climatic conditions. This holds for flowstone layers, but there are several examples of long, continuously growing stalagmites – the Cango Cave stalagmite is ~30 kyr (Talma & Vogel, 1992), the T8 stalagmite from Makapansgat is 23 kyr (Holmgren *et al*., 2003) and notably the Devil's Hole calcite is 500 kyr (Coplen *et al*., 1994). There are breaks within the Cango and Makapansgat record (Talma & Vogel, 1992; Holmgren *et al*., 2003), but the Devil's Hole record is continuous for 500 kyr (Coplen *et al*., 1994). Continuously growing stalagmites most likely grew in caves that remained closed, with no clastic material entering the cave to disturb the stalagmite. These features can therefore be accommodated within the model, as if caves remain closed, no clastic material is deposited, while open caves are not conducive to flowstone or stalagmite growth (Table 6.4).

It is possible that the large stalagmite bosses at Gladysvale, which forced the clastic sediments into two lobes, may have grown continuously, or with minor chemical hiatuses during periods of extreme aridity, but these features were removed by the lime miners and while it may be worth investigating the ages of the rubble left behind by the miners, the bulk of this material is destroyed. The presence of the six major flowstone bound clastic units at Galdysvale supports the notion that flowstone growth at Gladysvale was highly episodic, but this is an area of the model that needs further testing, especially at other cave sites where stalagmites and FBU are preserved.

6.7.2 Comparison of the Gladysvale model with published climatically controlled cave sedimentation models

The model generated for the younger cave fill at Gladysvale (Table 6.4) is compared in Table 6.5 to the published climatically controlled cave sedimentation models of Brain (1995) from Swartkrans in the Cradle of Humankind World Heritage Site, and Ayliffe *et al*. (1998) and Moriarty *et al*. (2000) from the Naracoorte Caves in South Australia, both of which are in the southern hemisphere.

Brain (1981, 1993, 1995) provide the best insights into climatically controlled cyclicity in South African hominin bearing caves, arguing that the 'most striking feature is the repeated alternation between periods of sediment accumulation and periods of non-deposition' (Brain, 1995), which he attributes to changes in climate and the extent of ground-covering vegetation.

Brain (1995) argues that during interglacial periods there was little vegetational cover and increased rainfall, making soils prone to erosion, and as a result cave deposition would take place. During the corresponding glacial intervals, vegetational cover was much thicker, resulting in little to no erosion of soil and increased acidity of surface water, which itself was increased, because of low evaporation rates. These acidic, surface waters entering the cave system caused the erosion of the older cave deposits. Brain (1995) does not model the conditions during glacial maxima, nor does he include flowstones in the model, which makes his model somewhat different to the other models (Table 6.5).

Model	**Palaeoclimatic conditions**		
	Glacial (and cool interstadials)	Glacial maxima	Interglacial (and warm interstadials)
Brain 1995	**Erosion** of cave sediments from increased volumes of more acidic water (lower temperatures, therefore reduced evaporation + dense vegetation, therefore acidic water)		**Cave sediment** deposited by storm water entering cave, reduced vegetation cover outside cave
Ayliffe *et al.* 1998	**Speleothem growth**: temperatures and evaporation decreased, therefore increased effective precipitation.	No speleothem growth: relative aridity	**No speleothem growth**: increased temperatures and evaporation, therefore net water deficit
Moriarty *et al.* 2000	**Flowstone growth**: wet phases. Some sediment input if cave entrance is open	Breaks in speleothem growth: dry	**Sedimentary input**, with minor flowstone growth: water deficit, increased input of fauna
This study, Gladysvale Cave	Dry phases, favouring C_3 vegetation, open caves and **clastic sediments** washed in by high altitude storms which increase in frequency during dry phases	Probable clastic sedimentation	Wet phases, with less seasonal, more persistent rain, favouring C_4 vegetation, block cave entrances, **flowstone and stalagmite growth**

Table 6.5. A comparison of the model generated in this study at Gladysvale Cave with other published models of climatically controlled cave sedimentation, Brain (1995), Ayliffe *et al*. (1998) and Moriarty *et al*. (2000).

The cave sedimentation models of Ayliffe *et al*. (1998) and Moriarty *et al*. (2000) do include flowstones. They argue that flowstones are climatically controlled, being associated with periods of increased effective precipitation, punctuated by more arid periods, leading to the opening of caves and the input of clastic sediment, which forms breccias. In the arid setting of South Australia, flowstone growth occurs only during *glacials*, as interglacial conditions are too arid and evaporative for speleothem growth to take place (Ayliffe *et al*., 1998). That is to say that flowstones need periods of increased precipitation to grow, which are not necessarily associated with interglacials; the regional climatic responses to global climate change needs to be taken into account.

The regional climate at Gladysvale, and indeed in most of the northeastern part of South Africa (the summer rainfall area) responds in the opposite way to South Australia to global glacial-interglacial cycles, with interglacials being warm and wet, and glacials being cool and dry (Partridge 1993; Holmgren *et al*., 2003). Thus flowstone growth at Gladysvale occurs during interglacials and breccia accumulation corresponds to dry glacial periods (Table 6.5).

Glacial accumulation of breccias in this model is opposite to what Brain (1995) proposes. However, the conditions Brain (1995) prescribes for interglacial times, namely storm waters washing soils, prone to erosion from reduced vegetation cover, have been shown, via the U-series dating and carbon isotope analysis, to occur during *glacials*. Brain (1995) argues that during glacial periods increased water volumes, from decreased evaporation rates from lower temperatures, caused erosion of cave sediments. For this to occur, caves have to be open. This study suggests that these conditions occur during *interglacials*, not glacials, and would lead to caves being closed and speleothem development taking place. It is possible that erosion may take place if caves are open, but this is not seen in this study at Gladysvale Cave. Thus Brain (1995) describes the correct conditions for breccia deposition, but attributes these to different climatic regimes. Brain (1995) did not have any dates or stable light isotope data to confirm his model, and this study has shown that his conditions for breccia accumulation are 'correct', but occur during opposite climatic conditions (Table 6.5).

6.8 Conclusions

Problems previously experienced in the documentation and understanding of South African hominin bearing cave stratigraphy are well summarised by Partridge (2000), who argues that the cave deposits cannot be well understood because of the limited exposures of the deposits, the complex stratigraphy of the breccias, the high degrees of cementation of the breccias, and the > 500 kyr age of the deposits, that place them beyond the reach of dating techniques such as U-series.

Gladysvale Cave is remarkable among the other caves within the Cradle of Humankind World Heritage Site, as the deposits are well stratified and are well exposed from the activity of the lime miners. The use of a chronostratigraphic approach to the cave sediments, such as that of Moriarty *et al*. (2000), was used to divide sediments into flowstone bounded units, as breccia and flowstone are deposited under different environmental conditions, making them chronostratigraphic units. Within this FBU stratigraphy, a set of sedimentary facies was identified, and changes from proximal to distal, as well as the middle to the edges, of the deposit documented. While the strata at Gladysvale are well stratified, and six major FBU were found throughout the deposit, the deposit is not a simple "layer cake", and has a complex history of cave entrances opening and closing and deposition occurring in different areas of the cave at different times. This said, overall the deposit can be clearly documented and understood through a chronostratigraphic approach.

A number of flowstone horizons and stalagmites from throughout the stratigraphy and from the proximal to distal regions of the cave were dated via ICP-MS U-series dating to further test the chronostratigraphic model of Ayliffe *et al*. (1998) and Moriarty *et al*. (2000). Despite problems with detrital contamination, ten U-series ages were produced, only three of which required correction for excess detrital material. These ages revealed that the deposit is both older and younger than previously thought (Curnoe, 1999; Schmid, 2002), and spans the period from ~570 to ~7 kyr. The Gladysvale flowstones grew during the recovery period following full interglacials, when compared to global climate change records. On the regional scale, the flowstones also correspond to periods of increased rainfall at the Tswaing Impact Crater.

The apparent climatic control of sedimentation at Gladysvale was further investigated through stable light isotopes of carbon and oxygen, on the flowstones and breccia horizons. Oxygen isotopes showed little variation between breccias and flowstones, suggesting that the original, climactically controlled oxygen signal has been lost during the residence time of the groundwaters above the cave and from contact with the cave roof dolomite. Carbon isotopes were interpreted as representing vegetational changes above the cave, with flowstones producing a C_3 signal and breccias a C_4 signal, confirming the climatic control suggested by the U-series and producing a climate change record for the last 570 kyr. Using the climatic framework of Holmgren *et al*. (2003), it is proposed that during the drier times there was an increase in the frequency of high altitude storms, which would have aided in washing the sediments into the caves. During wetter times, according to Holmgren *et al*. (2003), the precipitation would have been softer, more persistent and less seasonal, forming ideal conditions to grow speleothems inside the cave.

The age model generated for the intercalated breccias, together with the tight climatic control over breccia development in the cave, shows that periods of clastic sedimentation in the cave are highly episodic, and that the breccias present a decidedly punctuated record of the events occurring outside the cave. The faunal and hominin remains found within the breccias at Gladysvale and other sites should be viewed within this context, where sedimentation is *not* gradual and continuous, such as in the lake environments of East Africa, particularly where evolutionary rates and changes are being addressed. Brain (1995) eloquently argued the same point, that as the breccias are typically rather brief accumulations, significant evolutionary events are bound to have occurred during unrecorded time.

The dated succession of flowstones and intercalated breccias at Gladysvale provides a climate change record for the last ~600 kyr. Comparisons of the Gladysvale climatic record with other such records for southern Africa are restricted to the last ~200 kyr, as the Gladysvale record is, to date, the oldest climate change record for southern Africa. Dry and wet phases at Gladysvale, represented by breccias and flowstones respectively, show remarkable correspondence with several other marine and terrestrial records of climate changes. The synchronicity of these records suggests that major, allocyclic forcing mechanisms were at play. Up until ~60 kyr, orbitally forced climate change is particularly strong, and preccessional changes in solar output are most likely driving climatic changes and controlling periods of cave sedimentation at Gladysvale. After ~60 kyr, preccesional forces weaken, and atmospheric conditions over the Antarctic become the dominant control over southern African climates. Changes in the position and amplitude of the circumpolar vortex control the amount and type of rainfall, which is turn appears to control cave sedimentation at Gladysvale.

The younger fills at the cave sites within the Cradle of Humankind World Heritage Site are usually neglected as they do not contain early hominin remains. This study has shown the great value of these younger deposits, as they are within the range of presently available radiometric dating techniques, and questions about the timing and control of sedimentation can thus the answered. This study has also shown that there is a wealth of palaeoclimatic information within the younger cave fills, which can contribute hugely to our understanding of past climate changes in southern Africa, where such terrestrial records are rare.

The strong climatic control over the nature and rate of sedimentation at Gladysvale is used to produce a climatically controlled model for sedimentation at this cave, which may apply to other South African caves within the Cradle of Humankind World Heritage Site. The model is simple, with flowstones and breccias corresponding to wet and dry periods respectively. The control over the type of sedimentation is global climatic change, with local conditions, such as the amount and type of rainfall, controlling the rate of both clastic and chemical sedimentation.

The great advantage of a climatically controlled model of cave sedimentation, is that the climatic shifts governing cave sedimentation occur regularly through time and have been documented back to 5 Ma (e.g. Shackleton *et al*., 1990), which is still within the range of even the oldest sites in the Cradle of Humankind World Heritage Site. These climatic changes are global, with different effects in different areas. However, the same wet periods are seen at Galdysvale and the Tswaing Impact crater, which are some 200km apart, so within the small area of the Cradle of Humankind World Heritage Site climatic changes will manifest themselves in regional conditions which will be consistent across this 20x15km area. Thus once the climatic thresholds controlling periods of flowstone growth and breccia accumulation are crossed, the same events should be seen within all the cave sites in the Cradle of Humankind World Heritage Site. A chronostratigraphic assessment of the stratigraphy of these sites, coupled with U-Th and U-Pb dating of speleothems and stable light isotope analysis of speleothems and breccia can be used to test this model at these other sites.