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CRETACEOUS FOSSILS FROM THE ORAPA DIAMOND MINE

by

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ABSTRACT

The Orapa kimberlite pipe, situated in north-central Botswana, is well-known for its rich reserves of diamonds. It is indeed one of the largest and richest diamond mines in the world. The kimberlite magma transporting the diamonds from the upper mantle erupted through a sequence of Karoo-aged rocks before the deposition of the Kalahari Sands. This eruption has been radiometrically dated at early Late Cretaceous (Cenomanian-Coniacian). When volcanism ceased, a succession of epiclastic crater lake sediments was deposited above the kimberlite plug. Analysis of these sediments, which mostly comprise the results of mudflows and debris flows and finer sediments during quiescent times, suggests that most of the sediments within the crater were deposited rapidly as mass flows, and were therefore mobilised soon after the volcanic eruption. Buried within the fine-grained sediments is a unique assemblage of fossils including flowering plants and many whole-bodied insects. The fossils are commonly exquisitely preserved in extremely fine-grained mudstone. Interpretation of the sedimentary facies and fossils is that the mid-Cretaceous climate of central Botswana was temperate, seasonal and wet, and the area surrounding the crater was forested. The fossils represent the recovery of the biota of the area after the violent eruptions of Orapa and other nearby kimberlite fissures and pipes. The fossils have contributed considerably to our understanding of mid-Cretaceous insects and flowering plants and suggest intimate relationships between the two at an early stage in the radiation of flowering plants. It seems that southern Gondwana (including southern Africa) was a centre of diversification for both insects and angiosperms in the mid-Cretaceous.

KEYWORDS: Fossil angiosperms, Fossil insects, Fossil spider, Lagerstätten, Orapa.

INTRODUCTION

Unusually rich and well-preserved fossil assemblages have contributed considerably to our knowledge of the history of life (Whittington & Conway Morris 1985). Indeed, Sepkoski (1981) found that 20% of the clades he used in his factor analysis of Phanerozoic marine diversity were known exclusively from three such Palaeozoic localities (Hunsrückschiefer, Burgess Shale and Mazon Creek). The classic Eocene beds from Germany gave a name for these exceptional fossil localities – they are called fossil *Lagerstätten*. The information that outstanding fossil assemblages yield provides us not only with details of extinct animals and plants, and thus an indication of differing levels of diversity in the past, but, more importantly, they produce insights into palaeoecological and evolutionary relationships – since entire communities are often preserved. Such details are often lacking or incomplete in more scattered fossil assemblages. The contribution that these fossil *Lagerstätten* have made is, therefore, as remarkable as their preservation (Rayner 1993).

These exceptional *Lagerstätten* localities have almost all been found in the Northern Hemisphere, where most palaeontological activity is centred. Recently, however, some fossiliferous sediments, which lay claim to this status, have been discovered in Southern Africa. These sediments form the infill of a volcanic crater and have been exposed by diamond mining operations. The mining activities have centred on a

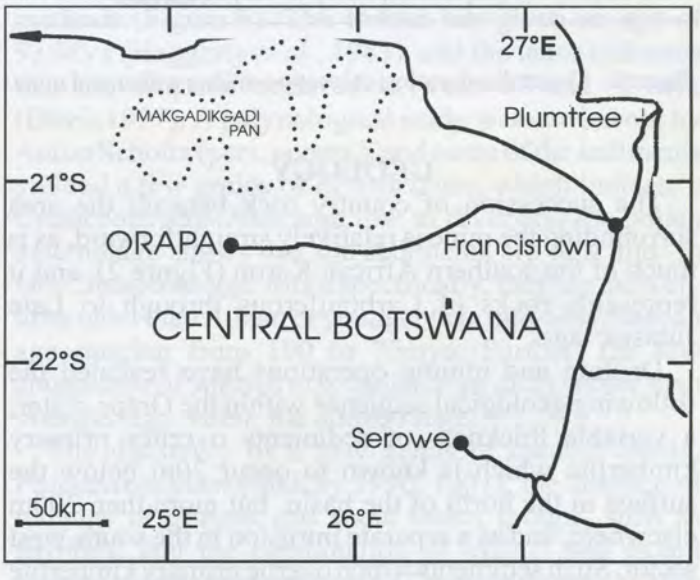


Figure 1. Map showing the locality of Orapa diamond mine.

diatreme of a large diamondiferous kimberlite pipe, located c.220 km west of Francistown in North-Central Botswana (Figure 1). The Director of the National Museum of Botswana, Alec Campbell, invited members of the BPI Palaeontology to visit the diamond mine in 1983. Professor Raath, then director of the BPI, handed the invitation on to Drs Maguire and Rayner. Subsequent excursions have produced many thousands of fossil specimens.

Kimberlites are fairly common in this part of Botswana, Orapa being the largest of a swarm of 29 kimberlite diatremes in the area. Indeed, its lobed appearance at the surface suggests it may be composite, consisting of two or even three individual kimberlite pipes (Figure 3). Recent examination by one of us (RJR) of cores taken from the central area of the mine confirms that the diatreme divides with depth.

The area surrounding the mine is extremely flat, with only a few low hills and ridges, and an average surface elevation of 960m above sea-level. The Makgadikgadi pans lie to the north, and the area is mapped as part of the Kalahari Desert. The climate today is arid to semi-arid, with an average rainfall of approximately 500mm per year. This figure is typically variable, and the rains fall almost exclusively in the summer months. The dominant vegetation is mopane bush (*Colophospermum mopane*).

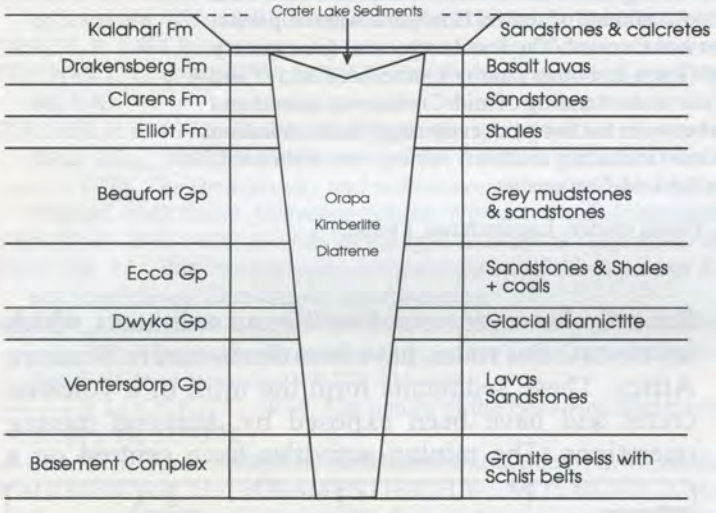


Figure 2. Generalised geological section of Orapa diamond mine.

GEOLOGY

The succession of country rock beneath the area surrounding the mine is relatively straightforward, as is much of the southern African Karoo (Figure 2), and it represents rocks of Carboniferous through to Late Jurassic age.

Drilling and mining operations have revealed the following geological sequence within the Orapa crater: a variable thickness of sediments overlies primary kimberlite which is known to occur 30m below the surface in the north of the basin, but more than 200m elsewhere, and as a separate intrusion in the south-west sector. Such sediments which overlie primary kimberlite from which they were derived are termed epiclastic

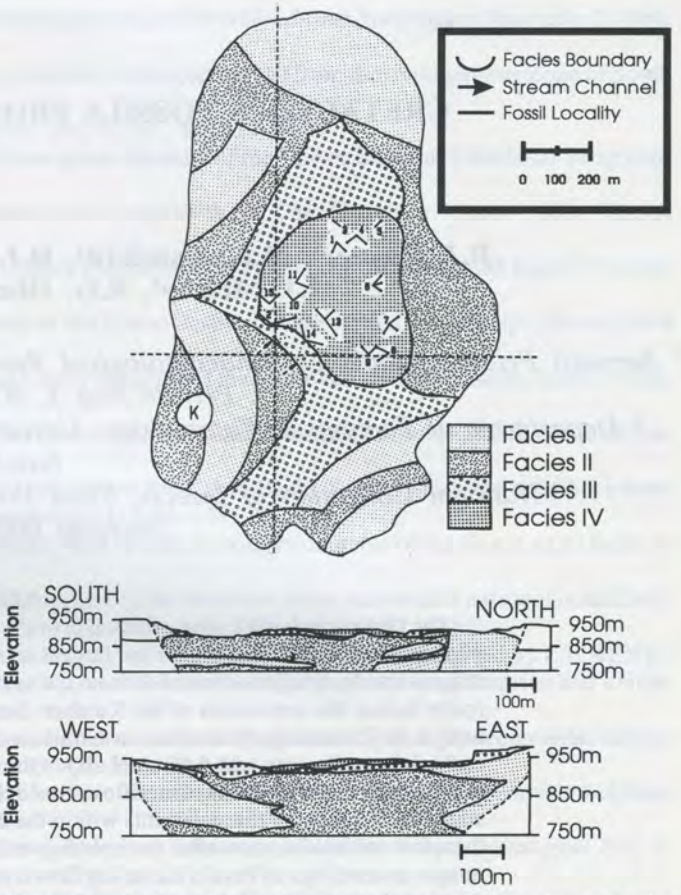


Figure 3: Facies plan and cross sections of Orapa diamond mine. The lobed outline of the crater sediments suggests that they are underlain by up to three kimberlite pipes.

kimberlite (Hawthorne 1975). An important characteristic of the petrology of kimberlite, which in this case assisted fossil preservation, is its great susceptibility to chemical and mechanical weathering and alteration. The fine-grained nature of the Orapa kimberlite matrix is particularly unstable, and would have rapidly supplied large quantities of clay-sized particles during decomposition. Further, the instability of the crater wall slopes and the subsidence as the diatreme cooled, de-gassed and contracted has produced a complex mixture of different facies. The sediments have been classified on the basis of grain size, depositional dip, nature of the matrix, sedimentary structures and genesis into four facies (Figure 3) (Rayner *et al.* 1991).

Facies I – Volcanogenic and Talus Slope Deposits

These are coarse sediments containing clasts of country rock up to 10m across. Their dips are generally greater than 20° and they are poorly sorted. At least some of these are pyroclastics (detrital volcanic material explosively ejected from the kimberlite vent). They form the outer and basal crater facies, and were formed as the diatreme grew, or just after.

Facies II Debris Flow Deposits

These have well-defined flow boundaries, and shallower dips (5-15°), and they are situated closer to the centre of the crater, and are often interbedded with finer material. Flow boundaries consist of layers of shale and

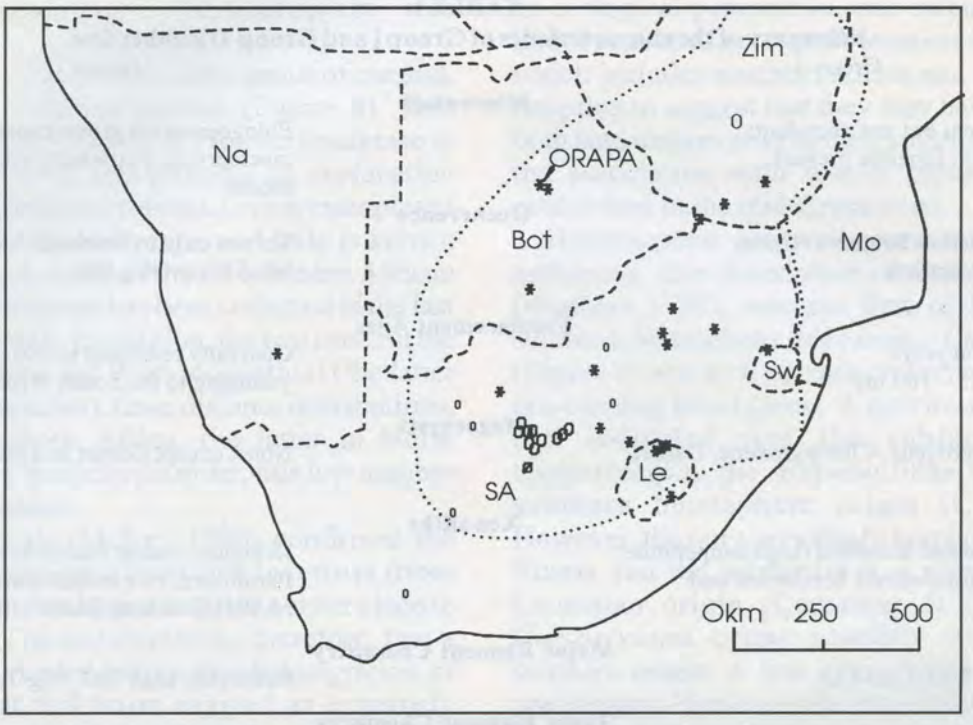


Figure 4: Localities of the Southern African Group I (*) and Group II (o) kimberlites that have been reliably dated (dates in Figure 5). Bot = Botswana; Mo = Mozambique; Na = Namibia; SA = South Africa; Sw = Swaziland; Zim = Zimbabwe. The extent of the Transvaal Craton is shown by a dotted line.

sandstone, which may be destroyed by the loading of boulders from overlying flows.

Facies III Granular Mass Flows (Mudflows)

These are finer-grained than either I or II, and are interbedded with the finest grained sediments close to the centre of the crater. They vary in thickness from over a metre to less than a centimetre, but are poorly sorted. They are persistent over many metres and dip at around 5°.

Facies IV Fine-Grained Sediments

These are the fossiliferous sediments. They occupy an oval area, 500m x 750m, to the east of the crater centre. They are well-bedded, fine mudstones, interbedded with the mud and debris flows, and vary in colour from grey-green, red, brown, to cream.

AGE OF THE SEDIMENTS AND FOSSILS

The conclusion from the nature of Facies I, II and III (Figure 3) is that they were deposited in a very short time. Indeed the deposition of the pyroclastics would have been part of the kimberlite emplacement process. Further, mud and debris flows are deposited instantaneously, commonly taking only minutes from initiation to completion (Beaty 1970; Smith 1986). These sediments comprise most of the sedimentary infill, and indicate that much of the crater was filled very rapidly. The halo of diamond-bearing soils and gravels (initially tuff and air-fall agglomerates of the ash cone) surrounding the crater indicates that, not only were the crater walls washed outwards as well as into the crater, but between 50m and 100m of sediments have been removed by erosion (Rayner *et al.* 1991). The original crater may, therefore, have had a depth of 300m. The fine-grained fossiliferous beds are interpreted as turbidites. Each lamination represents either an individual rain storm, or several pulses within a single storm event. This tends to reinforce the suggestion of rapid infill.

A number of kimberlite pipes in southern Africa, including Orapa, have been dated radiometrically (Figures 4, 5). The pipes can be divided into two groups, mainly on the basis of mineralogy and isotope and major element chemistry (Table 1).

The indication is that the two groups have different origins. Indeed, Orapa is a group I kimberlite and almost all of these range in age from 85-110 million years ago (Figure 5).

The Orapa kimberlite has been dated by both the low-contamination hydrothermal U/Pb, and the fission track methods (Figure 6). The former has given an age of 93 Mya (Haggerty *et al.*, 1983), and the latter indicates that the eruption occurred between 87 and 92 mya (Davis 1977). A palynological study was carried out by Anton Scholtz (pers. comm.), and some of the sediments yielded a few grains of *Ephedripites*, which indicate a Cretaceous age. Although low in diversity, the pollen assemblage shows that the sediments are of a mid- to late Cretaceous age. More specifically, they are unlikely to be older than Albian or younger than mid-Senonian, an age ranging from 100 to 75mya. Further, the low abundance of species may indicate an older rather than younger age within the above range.

The discovery of a new genus of carabid beetle, *Palaeoaxinidium* (McKay 1990, 1991), the absence of remains of grasses and some insect groups, such as termites, and the combination of extinct and extant genera, are all consistent with a Cretaceous age for both the eruption and the subsequent deposition of the

TABLE 1.
Summary of the characteristics of Group I and Group II kimberlites.

Group I	Group II
Mineralogy	
Phlogopite present but not abundant; Perovskite Zircon Ilmenite present	Phlogopite-rich groundmass ± phlogopite macrocrysts, Perovskite-poor; Zircon Ilmenite absent
Occurrence	
Widely distributed in Southern Africa; Known on most cratons	Known only in Southern Africa, generally in NE-SW trending belt
Emplacement Ages	
1 600 - 50 million years; Most between 85 - 100 my	Generally restricted to 200-110 million years, younging to the South West
Megacrysts	
Olivine, Orthopyroxene, Clinopyroxene, Garnet, Ilmenite, Zircon	None, except Garnet in a few occurrences
Xenoliths	
Eclogites, coarse and deformed (high temperature) Peridotites, metasomatized Peridotites and MARIDS	Eclogites, coarse Peridotites, rare deformed Peridotites, rare metasomatized Peridotites, MARIDS lacking Rutile ± Ilmenite
Major Element Chemistry	
Relatively high TiO_2 CaO CO_2	Relatively high SiO_2 MgO K_2O Al_2O_3
Trace Element Chemistry	
Relatively high V Nb U P/Ce OIB	Relatively high Rb Ba Pb LREE/HREE, low P/Ce
Isotopic Compositions	
$^{206}Pb/^{204}Pb_o$ = 18.3-20.0 $^{87}Sr/^{86}Sr_o$ = 0.703-0.705 $^{87}Sr/^{86}$ $^{143}Nd/^{144}Nd_o$ = 0.51268-0.51276 $\delta^{13}C$ = -6.4 ± 0.8 ‰$_\delta$	$^{206}Pb/^{204}Pb_o$ = 17.2-17.7 Sr_o = 0.7075-0.710 $^{143}Nd/^{144}Nd_o$ = 0.51206-0.51227 ^{13}C = -7.2 ± 0.3 ‰

sediments. This leads us to conclude that the Orapa fossiliferous sediments (which were deposited immediately after eruption) are Cenomanian (c.95 Mya) in age.

PALAEONTOLOGY

The fossils are compressed along bedding planes, and commonly organic matter is preserved. This type of preservation is commonly referred to as coalified compression (*sensu* Schopf 1975). Specimens collected in the upper parts of the succession, however, are mere compressions, the organic matter having been removed by oxidising groundwaters. Many insect structures, particularly the wings, and some plant fragments are highly reflective to light. This posed a problem in microscopy, particularly when taking photographs or when producing *camera lucida* drawings. A method using polarised light was developed which not only removed glare, but also enhanced the natural contrast of the specimens (Rayner 1992).

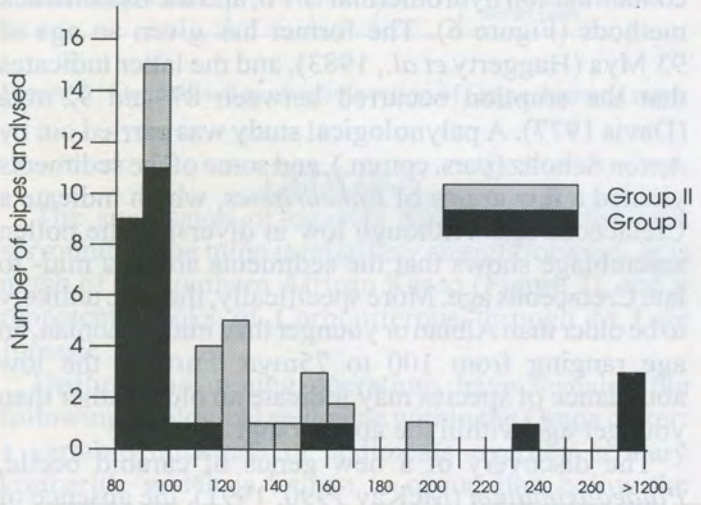


Figure 5: Histogram showing the ages of the Southern Africa Group I and Group II kimberlites (data from Anglo American internal report).

Fossil fauna

The fauna is overwhelmingly dominated by insects, with a few spiders. Most of the insects are beetles (Coleoptera) (Figure 7). This is in keeping with today's pattern of insect diversity and shows that the

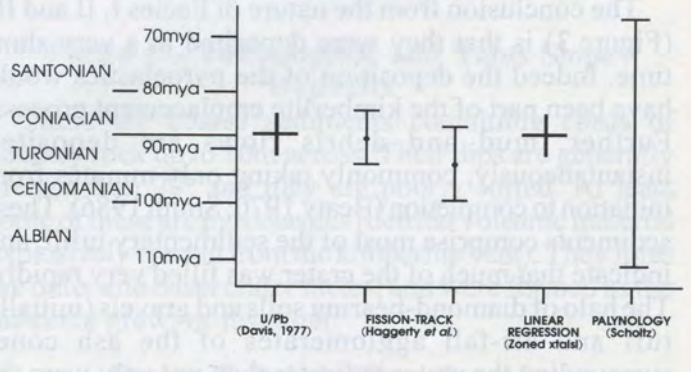


Figure 6: Summary of the age determinations for both the kimberlite and crater lake sediments of Orapa diamond mine. U/Pb data from Davis (1977), fission track and linear regression of zoned crystals from Haggerty *et al.* (1983) and palynology from Scholtz (pers. comm.).

overwhelming abundance of Coleoptera was established early.

McKay (1990, 1991) erected a new genus of carabid, or ground beetle, *Palaeoaxinidium* (Figure 8). This places the origin of the sub-family Promecognathinae in or before the Cretaceous and provides an explanation for a teasing biogeographic problem. Living examples of this sub-family are extremely rare, and little is known about their biology. Indeed, of the six southern African species, only one specimen has been collected in the last 25 years (McKay 1990). In addition, the two tribes in the sub family, Axinidiini and Promecognathini (the latter contains only two species), have disjunct distributions, the former in southern Africa, the latter in North America. For such a species-rich order, this low number of species is anomalous.

A cladistic analysis (McKay 1990) confirmed the division of the Promecognathinae into two sister tribes (Basilewesky 1958), but both constitute a sister clade to *Palaeoaxinidium*. The assumption is, therefore, that a common ancestor existed before the disintegration of Gondwana and that this taxon enjoyed an extremely wide distribution, taking in both southern Africa and North America. The distribution suggests that climatic zones typical of today were much broader in pre-Cretaceous times, and the promecognathines were spread from the Cretaceous equator to 35° S. After the separation of Gondwana, two sister tribes were established and were restricted to similar climates to those in which they are found today. The extremely low numbers of species in an otherwise species-abundant clade is presumably related to their flightless nature making them somewhat susceptible to environmental degradation.

A member of the Staphylinidae, not formally described but figured, is of considerable interest because of curious structures attached to its abdomen (Rayner & Waters 1991). These structures are small and approximately spherical, and generally consistent in both size and general morphology with pollen or spores. The highly mobile, predatory beetle may have lain in wait on primitive angiosperms or ferns for its prey – and may thereby have inadvertently carried pollen from plant to plant or inflorescence to inflorescence and acted as a pollinator. In addition, a scarab (family Scarabeidae) has been described (McKay & Rayner 1986). The presence of a possible dung beetle in the absence of other fossil evidence for its large herbivore benefactors invites the suggestion that they were associated with large dinosaur herbivores in the mid-Cretaceous (cf. Chin 1995).

A new genus and species of weevil (Curculionoidea), *Orapaeus cretaceus* (Kuschel *et al.* 1994), was placed in the tribe Eurhynchini of the family Brentidae. Several other weevils have also been described, but not named. There are only 30 living species in the tribe Eurhynchini. These occur in the eastern, wetter parts of Australia, from Tasmania to northern Queensland and in New Guinea. They seem to be absent from the drier western parts of Australia and Africa. A Gondwanan distribution is, therefore, established with the Orapa material. From an ecological perspective, one extant species burrows into the stems of a protea. Proteaceae have a distribution which includes southern Africa and Australia and it is tempting to suggest that they may have been present on both land masses prior to their splitting and, further, that the association with weevil parasites was already established in the mid-Cretaceous.

Hymenoptera are well-represented in the Orapa sediments. The description of a new species of wasp (Brothers 1992), was the first of its kind from the southern hemisphere Mesozoic. *Curiosivespa orapa* (Figure 9) was well enough preserved to be placed in a pre-existing fossil genus. A previous cladistic analysis had indicated that the subfamily containing *Curiosivespa*, the Euparagiinae, probably had a southern hemisphere origin (Carpenter 1981). However, the only previously known fossils were from Russia and the subfamily was regarded as having a Laurasian origin (Carpenter & Rasnitsyn 1990). *Curiosivespa orapa* possibly re-establishes that southern origin. A few other well-preserved parasitic and stinging Hymenoptera (including a putative ant) are currently being studied.

A large number of Diptera have been discovered in the sediments (Waters 1990). Most Diptera are classified partly on the details of their wing venation, and this is often preserved in exquisite detail in the Orapa material, allowing reliable comparisons with modern representatives. The predatory *Pseudoacarterus orapaensis* (Figure 10) put the origin of the subfamily Hybotinae back to at least the early Mesozic, and extended the evolution of the family Hybotidae back at least 40 million years (Waters 1989a).

Several specimens of a species of *Bibio* were found (Figures 11 & 12). All of them had identical wing venation, but more unusually they also possess evidence of wing spots, or stigmata (Rayner 1987). Such pigmentation is extremely rare in the fossil record (see also the spider, Figure 16). Bibionids are phytophagous insects and indicate the presence of substantial vegetation nearby. The living members are called March Flies, for they commonly swarm in the northern hemisphere spring. The presence of several of them on the same bedding plane indicates a similar behaviour in the mid-Cretaceous, and suggests a seasonal climate.

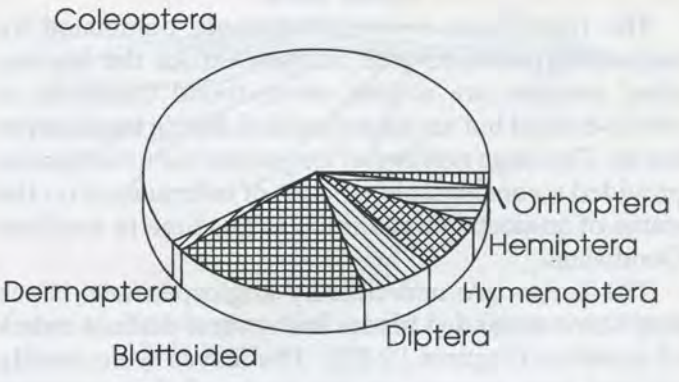


Figure 7. Summary of the relative abundance of the identified insect remains from Orapa mine.

A dance fly, *Empis (s.s.) orapaensis* Waters, was described from a single male specimen (Waters 1989b) (Figure 13). This dipteran was placed in a modern subgenus, the representatives of which have a particularly interesting and elaborate courtship display. The male, which is exclusively predatory, captures an item of prey (many species coat it in a silken "balloon") and during their courtship "dance", offers it uneaten to the female prior to copulation. This "nuptial gift" is the only animal protein she receives and is essential for her ovarian cycle. At all other times, she feeds at flowers.

A crane-fly (Tipulidae) exhibited remarkable morphological stasis (Figure 14). Indeed, it was placed with ease in an extant cosmopolitan genus, *Helius*, and its feeding apparatus strongly suggests that it was a pollinator (Rayner & Waters 1991).

There are other indications of the close association between early flowering plants and insects at Orapa. An extremely rare find of a single wing of a fossil aphid (Figure 15), the first from Africa, resulted in a tentative assignment of the specimen to the genus *Siphonophoroides* in the family Drepanosphidae (Rayner & Waters 1989). This representative of a group that exclusively parasitises angiosperms today suggests that the association between aphids and their angiosperm hosts developed early.

The fauna also contains large numbers of cockroaches. The Blattoidea is an ancient group and its presence at Orapa is somewhat predictable. Some of the fossil cockroaches are large and powerful animals, and yet there are no signs of disturbance in the very fine-grained sediment. It seems from this and other evidence that the waters may have been poisonous or inhospitable, and the insects therefore died soon after landing in the mud. Additional finds of interest were an orthopteran hind leg and a cricket (McKay & Rayner 1986).

The non-insect elements of the fauna included spiders. One well-preserved, almost complete specimen was placed in the superfamily Lycosoidea (Figure 16). Spider compressions are particularly rare in the fossil record, and this is the first to be described from Africa (Rayner & Dippenaar-Schoeman 1995). Such is the quality of preservation that pigmentation is even preserved on the legs (Figure 17).

Fossil flora

The fossil flora is overwhelmingly dominated by angiosperm remains (see below). Unlike the insects, plant remains are almost never found complete or whole-bodied but are disarticulated during transport or burial. The large number of fragments has nevertheless provided a considerable amount of information on the status of angiosperm evolution at this time in southern Gondwana.

The leaves are undoubtedly angiospermous, since they show expanded blades and several distinct orders of venation (Figures 19-23). The leaves were readily divided into groups on the basis of this venation (Bamford 1991). This ranged from simple-pinnate, and pinnate-compound (Figure 18) through to more complex forms where three or more primary veins originate at one point (Figures 20, 22 & 23), and in some specimens these primary veins branch dichotomously (Figure 21). Most of the leaves were deciduous, indicating seasonality.

The flora is unique. There is nothing with which to compare it in the southern hemisphere, and the plants are unlike anything that has been described from the Northern Hemisphere. A total of 29 leaf types has been described and given formal generic and specific names (Bamford 1991). Only one of them, based on two specimens, could be placed in an existing fossil genus. This is the North American *Sapindopsis* Fontaine, a deeply lobed type. The Orapa leaf (Figure 18) is much smaller, however, and is arguably distinct generically. The leaves show similarities in levels of organisation and complexity to northern hemisphere material from the Aptian-Albian (Hickey & Wolfe 1975; Hickey & Doyle 1977).

A complex fruit from a compound inflorescence has been described (Bamford 1991) (Figure 24). In addition, three new genera and species of flowers, together with another six unnamed forms; 13 genera and 14 species of seeds and fruits; and five ferns were also described. The morphology of the flowers indicates both wind (Figures 27 & 28) and insect (Figures 26 & 29) pollination. The closed corolla tube at the base of the flower in Figure 26 indicates insect pollination and further suggests faithful pollination. However, some of the flowers show a higher level of organisation than their northern hemisphere counterparts (Friis & Crepet 1987). The tubular flower (Figure 26), for example, is considerably earlier than such structures from the north. Lower plants were also represented and several delicate ferns were found. These were presumably growing close to the lake shore.

Plant fossils were noticeably a lot less common and less diverse than the fauna. This presumably reflects the greater mobility of the flying insects which blundered into the fine-grained muds associated with the shallow crater lake. Plants were, however, more common at the top of the exposed succession than in the lower parts. We have interpreted this as possibly indicating that the volcanic explosion, or series of explosions, was so violent that it cleared vegetation for a considerable distance from the crater. The lower parts of the sedimentary succession were deposited too rapidly to permit complete colonisation by vegetation, which was only achieved later.

As the leaves cannot be compared directly with any other fossilized flora, their morphology and size characteristics are considered. The leaves are mostly small (microphyllous size class of Webb 1959). This would indicate a cool temperate or wet montane climate, the latter being unrealistic. The percentage of entire-margined leaves (45%) indicates a warm temperate and moist climate. The data are conflicting but the overriding feature of the leaves is their diversity. The flora is a successional one and inhabited the unstable inner cone slopes surrounding the crater lake and would therefore be an unreliable climatic indicator.

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Figure 8. *Palaeoaxinidium* (McKay 1991). Scale bar 1mm.

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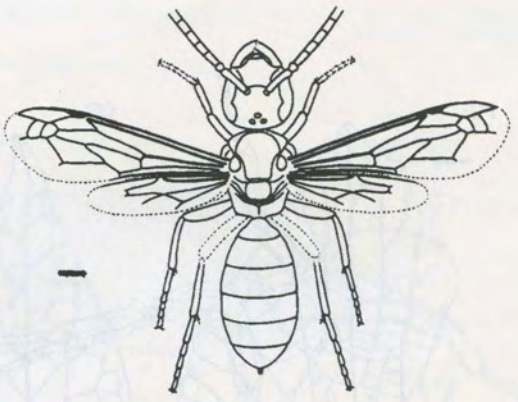


Figure 9. *Curiosivespa orapa* (Brothers 1992). Scale bar 1mm.

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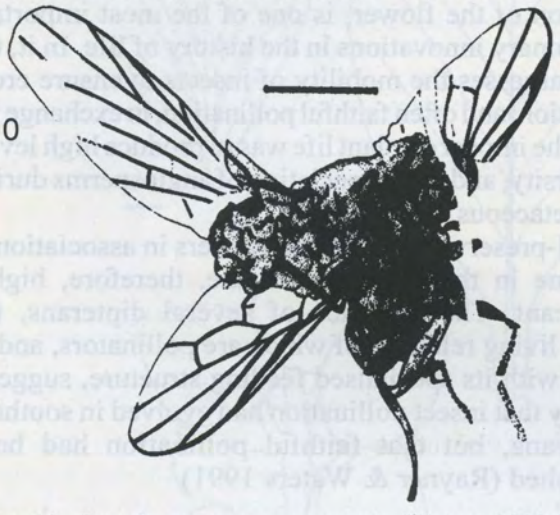
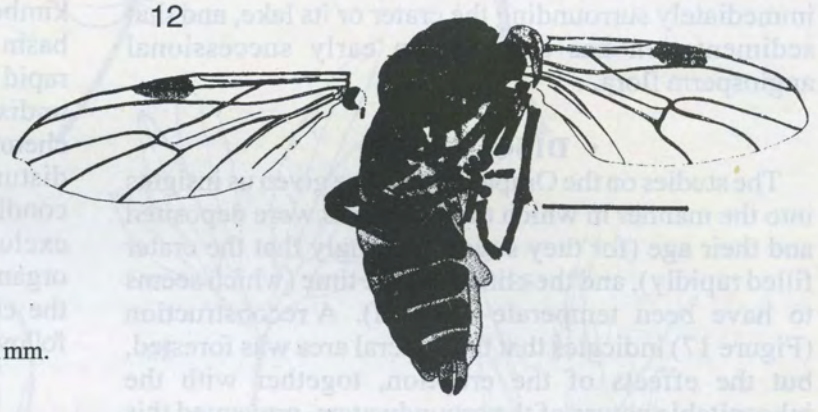


Figure 10. *Pseudoacarterus orapaensis* (Waters 1989a). Scale bar 1mm.

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Figures 11 & 12. *Bibio* (Rayner 1987). Scale bar 1mm.

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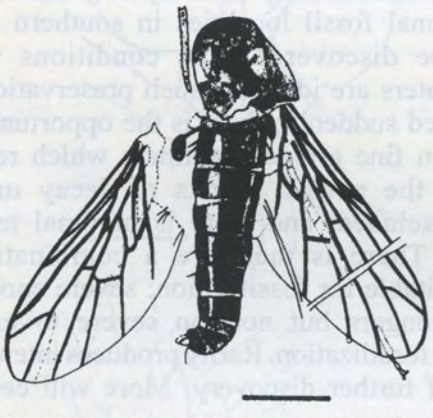


Figure 13. *Empis orapaensis* (Waters 1989b). Scale bar 1mm.

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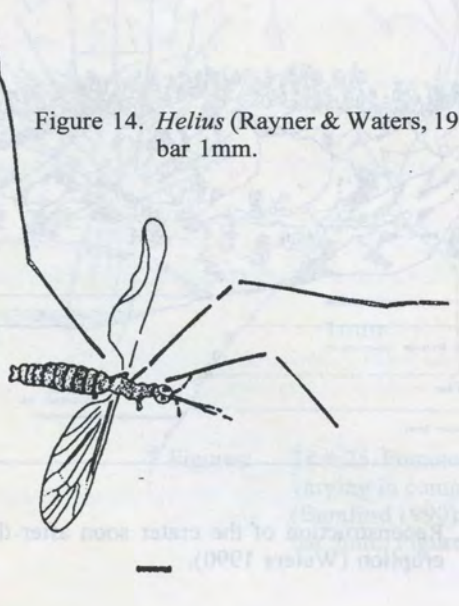


Figure 14. *Helius* (Rayner & Waters, 1990). Scale bar 1mm.

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Figure 15. *Siphonophoroides*? *orapaensis* (Rayner & Waters 1989). Scale bar 1mm.

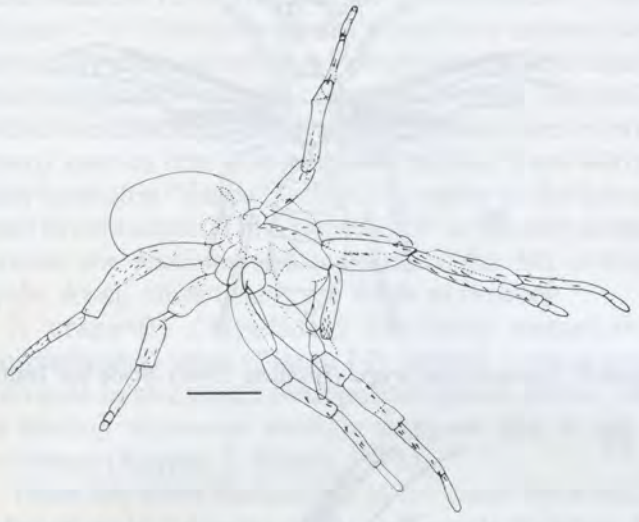


Figure 16. Spider from the family Lycosoidea (Rayner & Dippenaar-Schoeman 1995). Scale bar 10mm.

In addition, there is a notable absence of gymnosperm macrofossils in the flora (Figure 30). Today there are very few Southern African indigenous gymnosperms. However, pollen belonging to Araucariaceae and Cupressaceae and *Ephedripites* has been found in the sediments. These were wind pollinated, but are represented by very few grains. We suggest that, since these sediments represent the lower parts of the sedimentary succession, and since gymnosperms tend to be slow growing, this is further confirmation that the vegetation did not have time to fully colonise the areas immediately surrounding the crater or its lake, and that sedimentation has sampled an early successional angiosperm flora.

DISCUSSION

The studies on the Orapa fossils have given us insights into the manner in which the sediments were deposited and their age (for they suggest strongly that the crater filled rapidly), and the climate at the time (which seems to have been temperate-seasonal). A reconstruction (Figure 17) indicates that the general area was forested, but the effects of the eruption, together with the inhospitable nature of the groundwaters, prevented this vegetation being re-established in the crater soon enough for sedimentation to record it fully.

The morphological stasis shown by some of the described specimens (the carabid, empid and bibionids) is of particular interest. The fact that their closest living relatives are only found in the southern Cape today, which is approximately the latitude of Orapa when the fossils were buried, suggests that there has been some environmental influence. These insects seem to have persisted in their preferred habitat and, as Africa moved north, they remained at approximately the same latitude. Such habitat tracking has been described for Pleistocene beetles, which moved in response to periods of glaciation (Coope 1978, 1979). The unique nature of the angiosperms bears testimony to the highly derived nature of the extant members of the group.

Most importantly, however, the fossils give us a glimpse of ecological relationships between the spiders, insects and plants. Predator-prey relationships were as complex as any in the animal kingdom today. However, few ecological relationships can be more significant than that between plants and insects. The parasitic weevils and aphids and the phytophagous flies emphasise the close association between plant and insect which often characterises the fossil record. In addition, the mutual exploitation which characterises the relationship between plants and animals, and which climaxed in the evolution of the flower, is one of the most important evolutionary innovations in the history of life. In it, the plant harnesses the mobility of insects to ensure cross pollination, and often faithful pollination, in exchange for food. The impact on plant life was to produce high levels of diversity, and rapid speciation of angiosperms during the Cretaceous.

Well-preserved insects and flowers in association at this time in the fossil record are, therefore, highly significant. The presence of several dipterans, the closest living relatives of which are pollinators, and of *Helius* with its specialised feeding structure, suggests not only that insect pollination had evolved in southern Gondwana, but that faithful pollination had been established (Rayner & Waters 1991).

CONCLUSION

The Orapa diamond mine is surely only one of many such exceptional fossil localities in southern Africa waiting to be discovered. The conditions within kimberlite craters are ideal for such preservation: the basin is created suddenly; there is the opportunity for rapid burial in fine grained sediment which remains undisturbed; the normal agents of decay may be chemically excluded; and there is minimal tectonic disturbance. There is therefore a combination of conditions suitable for fossilisation: severe enough to exclude scavengers but not too severe to exclude organisms for fossilization. Rarity produces interest and the chance of further discovery. More will certainly follow.

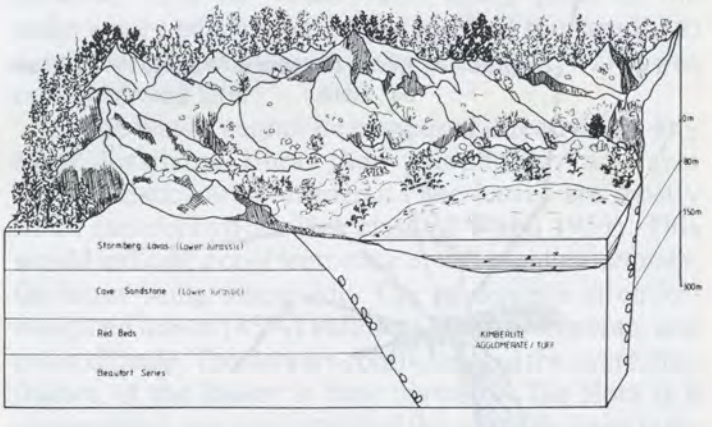
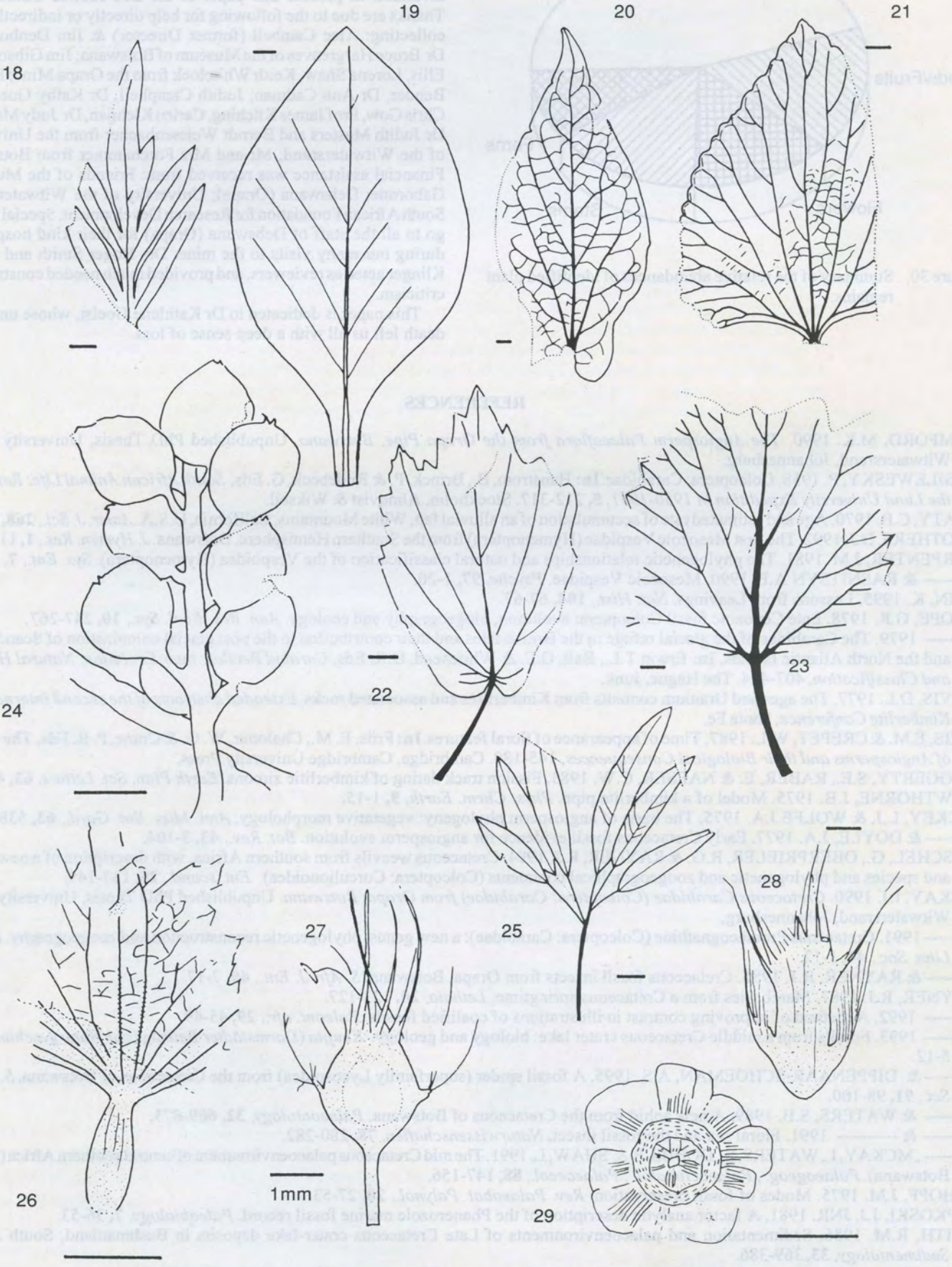


Figure 17. Reconstruction of the crater soon after the volcanic eruption (Waters 1990).



Figures: 18 & 25. Pinnate compound leaf (Bamford 1990); scale bar 5mm. Figures 19-23. Angiosperm leaves varying in complexity and venation (Bamford 1990); scale bar 5mm. Figure 24. Compound fruit (Bamford 1990); scale bar 5mm. Figures 26 & 29. Insect pollinated flowers (Bamford 1990); scale bar 5mm. Figures 27 & 28. Wind pollinated flower (Bamford 1990); scale bar 1mm.

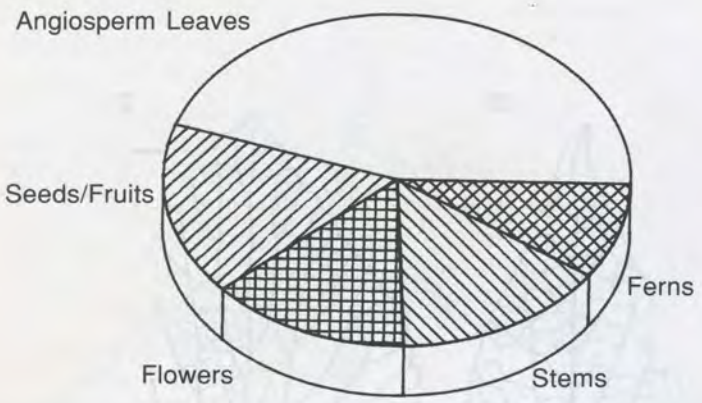


Figure 30. Summary of the relative abundances of identified plant remains.

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