The evolutionary convergence of mid-Mesozoic lacewings and Cenozoic butterflies

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Mid-Mesozoic kalligrammatid lacewings (Neuroptera) entered the fossil record 165 million years ago (Ma) and disappeared 45 Ma later. Extant papilionoid butterflies (Lepidoptera) probably originated 80–70 Ma, long after kalligrammatids became extinct. Although poor preservation of kalligrammatid fossils previously prevented their detailed morphological and ecological characterization, we examine new, well-preserved, kalligrammatid fossils from Middle Jurassic and Early Cretaceous sites in northeastern China to unravel a surprising array of similar morphological and ecological features in these two, unrelated clades. We used polarized light and epifluorescence photography, SEM imaging, energy dispersive spectrometry and time-of-flight secondary ion mass spectrometry to examine kalligrammatid fossils and their environment. We mapped the evolution of specific traits onto a kalligrammatid phylogeny and discovered that these extinct lacewings convergently evolved wing eyespots that possibly contained melanin, and wing scales, elongate tubular proboscides, similar feeding styles, and seed–plant associations, similar to butterflies. Long-proboscid kalligrammatid lacewings lived in ecosystems with gymnosperm–insect relationships and likely accessed bennettitalean pollination drops and pollen. This system later was replaced by mid-Cretaceous angiosperms and their insect pollinators.

1. Introduction

Lepidoptera and Neuroptera are members of two basal clades of Holometabola that separated ca 320 million years ago (Ma) during the mid-Carboniferous
Although butterflies (Lepidoptera; Papilionoidea) are perhaps the most iconic group of insect pollinators [3], their earliest definitive fossils occur at the Palaeocene–Eocene boundary, 56 Ma [3]. Molecular studies of various family level ranks [4,5] suggest an earlier, Late Cretaceous origin at ca 80–70 Ma [5,6], considerably after the mid-Cretaceous (125–100 Ma) angiosperm radiation [7]. Butterflies are characterized by a distinctive ensemble of traits, such as diurnal behaviour, tubular (siphonate) mouthparts, wing eyespot patterns and wing scales [3,8,9]. These features appeared at the origin of the clade, allowing butterflies intimate association with more derived angiosperms during the Late Cretaceous and Palaeogene (80–23 Ma), and led to the coevolution and diversification of both groups [5,10]. Was this stereotypical assembly of butterfly features a one-time innovation uniquely associated with angiosperms? Or did the butterfly character-suite evolve in unrelated insect lineages with earlier gymnosperms? Here, we report on a distinctive clade of butterfly-like insects, Kalligrammatidae (Neuroptera), and explore their biological convergence with Papilionoidea.

Kalligrammatidae, or kalligrammatid lacewings (figure 1a–i), are an enigmatic, almost entirely Eurasian [11–13], mid-Mesozoic, holometabolous clade of large, robust-bodied Neuroptera (lacewings). Kalligrammatids had large wingspans, up to ca 160 mm [12], and are among the largest and most conspicuous of mid-Mesozoic insects (electronic supplementary material, table S1). Kalligrammatids were tentatively associated with seed plants [14–16], despite their almost unknown mouthpart and ovipositor structures [16]. Within Neuroptera, the Kalligrammatidae are included within Myrmeleontiformia [17–19], a major clade that encompasses extant antlions, owlflies, silky-winged lacewings (Psychopsidae), and spoon and thread-winged lacewings (Nemopteridae) [20,21]. The Nemopteridae share significant mouthpart and feeding similarities [21,22] with the Kalligrammatidae whereas the Psychopsidae possess similar wing features [16].
All examined kalligrammatid material originated from fine-grained, often carbonaceous lake deposits in one Central Asian and two East Asian localities (figure 2e; electronic supplementary material, tables S2 and S3) [23–25]. The oldest deposit is Daohugou, of the Jiulongshan Formation, Inner Mongolia, from northeastern China. This deposit is radiometrically dated by 87Rb/87Sr at 128.2 Ma low to 121.6 Ma high

in the formation, with most material collected from the Jianshou beds dated at ca 125 Ma [27,31], the date used in this report. Although contentious, Xixian dates are supported by a variety of palaeobiological evidence [27,32], buttressed by pollen studies [33] linked to a distinctive megaflora in the lower part of the unit [34]. Claims of a Late Jurassic age for Xixian fossils represent range extensions of Early Cretaceous lineages downward into the Late Jurassic [31]. The last known kalligrammatid lacewing occurs in the upper Crato Formation of northeastern Brazil, ca 120 Ma [13].

Lake deposits such as the Jiulongshan, Karabastau and Xixian formations typically preserve plants and insects that reveal surface details [23,30,31]. Frequently, resolution of such features extends to colour patterns (figures 1a–d–q and 3e–g, j,k; electronic supplementary material, figure S2), gross (figure 1), to detailed mouthpart structure (electronic supplementary material, figures S1, S4 and S5), micromorphological details of wing and mouthpart scales (figure 3a,b,h,j,l;–p; electronic supplementary material, figures S4 and S5), and reproductive plant features such as pollen (electronic supplementary material, figures S1,l, S5b and S6c–f) and fructifications that

Figure 2. Phylogenetic context of wing spots and eyespots in mid-Mesozoic kalligrammatids, with comparisons to modern lepidopterans (electronic supplementary material, text S3). The best preserved fossil material was used for this analysis. (a) Most parsimonious tree of Kalligrammatidae phylogeny [11] (electronic supplementary material, table S2), with right forewing eyespot/spot condition mapped onto terminal clades and likely wing spot and eyespot origins. Wing eyespot and spot type symbols are at upper-left; crosses are eyespot/spot absences. (b–g) Examples of right forewings with wing eyespots or spots from mid-Mesozoic Kalligrammatidae (b–f), and modern Psychopidae (g). These taxa correspond to a Type 1 eyespot (b), Type 2 eyespot (c), Type 3 eyespot (d), Type 4 eyespot (e) and two Type 5 double spots (f) matched by two spots in modern psychopid (red arrows) in (g). Kalligrammatid wing eyespots and spots are compared to modern Lepidoptera in (h–k), of butterfly species with Type 6 eyespots (h) and multiple Type 5 spots (i); moth lacking wing spots or eyespots (j); and modern owl butterfly eyespot (k), showing pigmentation similar to Type 2 and 3 eyespots (b), indicated by arrow pointing to an ocule series and longitudinal wing vein. Scale bars: solid, 10 mm; striped, 1 mm.
reveal internal structures (electronic supplementary material, figure 6g–i) that extends previous studies [34–37].

2. Material and methods
The electronic supplementary material documents the general methodological approaches and specific experimental procedures used in six subsudies that buttress our account of ultrastructure and morphology of Mesozoic kalligrammatid lacewings. These studies are (i) kalligrammatid mouthpart structure; (ii) an analysis of pigmentation within wing eyespots; (iii) geochemical analyses of opaque plugs trapped within the food canal of a tubular proboscis; (iv, v) two analyses on pollen occurring adjacent mouthpart contact surfaces; and (vi) taxonomic characterization of pollen in sedimentary matrices adjacent kalligrammatid specimens. We also provide
documentation of kalligrammatid mouthpart morphology. The techniques contributing to these six substrates are briefly outlined below; details of instrumentation and equipment that were used, specific imaging procedures and the protocol for geochemical analyses are provided in the electronic supplementary material.

(a) Specimen imaging

Light, epifluorescence and scanning electron microscopy (SEM) were used to closely examine a variety of kalligrammatid features from gross structure to micromorphology. Structures as miniscule and delicate as setae, wing scales, wing eyespot oculae and pollen grains were captured by microscopic imaging techniques, including the backscattering function linked to SEM imaging. Camera lucida drawings were made (electronic supplementary material, figure S1) to establish the most highly resolved scale available, and included shape, size, surface features and inter-element relationships of siphonate mouthpart structure.

(b) Geochemical analyses

The heads, mouthparts, wing scales and eyespots of several specimens were intensively investigated by electron dispersion spectroscopy (EDS) linked to an environmental chamber SEM (electronic supplementary material, figure S2), also time-of-flight secondary ion mass spectrometry (ToF-SIMS; electronic supplementary material, figure S3) [38]. The latter technique produced intriguing results regarding eyespot pigmentation, and several EDS analyses characterized a structureless plug within the proboscis food canal of one specimen (electronic supplementary material, figure S4e–j). Pollen was detected adjacent vestigial but highly setose mandibulate mouthparts of a second specimen (electronic supplementary material, figure S4a–d). Two morphotypes of elongate cuticular scales were imaged from the mouthparts, particularly the maxillary palps, of another specimen using a variety of techniques that included SEM imaging (electronic supplementary material, figure S5). Wing eyespot pigmentation was detected by EDS by enhanced carbon concentrations that were intrinsic to the eyespot centre and absent from other regions such as the eyespot oculae, other body regions and adjacent rock matrix.

(c) Pollen study

Most sedimentary matrices adjacent to the specimens that were acid macerated failed to preserve pollen, attributable to the oxidized condition of the encompassing rock. The matrix of one specimen, however, provided a well-preserved spectrum of pollen in macerated residues that were mounted on microscope slides for characterization. The resulting pollen was consistent not only with the known megaflora described from the same deposit but also provided common and rare entomophilous pollen taxa (electronic supplementary material, figure S6a–f).

3. Results

Recently, a comprehensive phylogenetic analyses of 30 wing (28 of 30), ovipositor and mouthpart characters for 17 kalligrammatid genera and four outgroups resulted in a single best-supported tree [11] (figure 2a). The phylogeny grouped the genera into five distinct clades, three of which are new subfamilies [11] (figure 2a; electronic supplementary material, table S1). The basalmost clade, Sophogrammatinae, represents the plesiomorphic kalligrammatid condition of mandibulate mouthparts and the absence of wing spots, eyespots, and scales. The four derived clades include Kalligrammatinae, consisting of the speciose Kalligramma and four related genera, and Kallihemeronitinae with six genera. Meioneurinae comprises the sole genus Meioneurites [16], which has a sister-group relationship to Oregrammatinae, the latter consisting of three genera, including probably the most derived genus, Oregramma. Higher-level relationships within Kalligrammatidae are: Sophogrammatinae + {Meioneurinae} + {Oregrammatinae} + {Kalligrammatinae} + {Kallihemeronitinae}.

In forewings, kalligrammatid eyespots and spots typically are deployed on the upper surface midway to two-thirds of the proximal-to-distal wing length, centred between two major branches of the radial vein system. Six distinctive types of forewing eyespots or spots occur on most species of the four derived kalligrammatid clades, occurrences previously known from some taxa [11,15], but not others [12]. The basalmost clade has no wing spots or eyespots (figure 2a), as do almost all modern neuropterans (figure 2g) [19]. There are four eyespot types, each consisting of distinctive, differentially pigmented rings surrounding a central pigmented disc with small, whitish, oval-shaped oculae (Types 1–4; figures 11–p and 2h–e,h,k); electronic supplementary material, figure S2). In addition, there are taxa with two simple spots, consisting of a round, dark patch lacking concentric rings (Type 5; figures 1q and 2f). Eyespots of Type 6 were not mapped onto the phylogeny; as wing characters of one Kalligramma sp. were insufficiently preserved for inclusion in phylogenetic analyses. In Type 1 eyespots, a second ring of dark pigmentation occur relative to single ringsed Types 2–4 and 6 (figures 1l and 2b).

Forewing eyespot and spot types (figure 1l–q) were mapped onto our best-supported tree (figure 2a), revealing major patterns. In all outgroup taxa and the basalmost kalligrammatid clade of Sophogrammatinae, eyespots and spots...
were absent. The evolution of spots and eyespots likely originated early within the kalligrammatid clade, in the sister lineage to Sophogrammatinae (figure 2a). The four kalligrammatid clades derived from this lineage exhibit a variety of spot and eyespot patterns and absences. The most complex eyespot type occurs late in three separate lineages, within Oregrammatinae (Type 1; figure 1l; electronic supplementary material, figure S2), Kallihemerobiinae and Kalligrammatinae (figure 2a), suggesting that these eyespots derive from simpler ones, a transition that likely happened multiple times. In addition, multiple simple spots were converted to single eyespots in several lineages. These patterns are similar to convergent changes conventionally proposed for nymphalid butterflies in modern Lepidoptera (figure 2b,i,j) [8,39,40]. Changes include transitions from moth taxa possessing monochromatic wings lacking differential pigmentation (figure 2j), to basal nymphalid taxa with simple repeated spots, such as *Idea lyneus* (figure 2i), to more elaborate and individualized eyespot patterns of *Bicyclus anynana* with multiple colour rings (figure 2b) [8,39]. The deployment of a spot of monochromatic pigment between two major veins in basal Kallihemerobiinae, Kalligrammatinae and Oregrammatinae (figure 2a,f) has convergently re-evolved in modern, distantly related Psychopsideae (figure 2g) and Nemopteridae [19].

Another point of convergence is the possible presence of melanin in wing eyespot centres as indicated by our EDXS carbon (electronic supplementary material, figure S2) and ToF-SIMS (electronic supplementary material, figure S3) sub-studies. SEM examination of the eyespots using EDXS revealed a significant increase in carbon content within black eyespot centres, whereas the central white pupil was completely devoid of carbon. In the ToF-SIMS analysis, the eumelanin presence was indicated by comparison of the spectrum from the dark eyespot pupil with the spectrum of a modern eumelanin standard. Owing to dissimilarities in the intensity of the organic peaks, similar to what has been found in other studies [41,42], the possibility of an alternative carbon source cannot be excluded. Unlike melanin preserved in many animals, where it occurs in rod-shaped specialized cells [43], insects lack such cells and melanin is diffused throughout the cuticle [44]. The relative abundances of carbon and the possible presence of melanin found in differently coloured regions of kalligrammatid eyespots could match the pigment distribution in many nymphalid eyespot patterns [39]. The muted response of carbon-rich material in kalligrammatid eyespots could mimic the nymphalid condition, as scales in an eyespot centre often are devoid of melanin and reflect all light wavelengths, appearing white [45], whereas black scales encircling the eyespot centre contain melanin [46].

Wing scales are another convergent feature occurring in Kalligrammatinae and modern Lepidoptera, although there are differences in detail. The basalmost clade, Sophogrammatinae, lacked wing scales, as do virtually all other modern, major neopteran lineages (figure 3c,d). The four derived kalligrammatid clades bore two types of wing scales. The first type were large scales with a flattened, elongate-spatulate shape socketed on major veins and possessing three to four longitudinal ribs, increasing to six to eight ribs at the distal wider end (figure 3a,b,j,p; electronic supplementary material, figure S5d). The second scale type were small, short scales that were basally broad but tapered, bearing four or fewer longitudinal ribs, and originating from smaller sockets on areas between the major veins (figure 3h,j,l–o; electronic supplementary material, figure S3d). This distribution indicates wing scales originated de novo among early Kalligrammatidae, after separation from Sophogrammatinae (figure 2a). By comparison, in extant Lepidoptera, scales emerge predominantly from membrane surfaces and minor veins, but often are absent on major veins and larger cross-veins.

Mouthparts of kalligrammatid Neoptera and papilionoid Lepidoptera offer another remarkable example of convergent evolution. Kalligrammatid mouthparts evolved from an ancestral mandibulate (chewing) state to a derived long-proboscid (siphoning) state in which maxillary elements were conjoined to form a tube (electronic supplementary material, figure S1). This parallels the evolution of the proboscis in glossect Lepidoptera, which also originated from mandible-bearing ancestors [47]. The kalligrammatid proboscis is present in all clades except basal Sophogrammatinae. Rudimentary, mandible-bearing mouthparts were retained in one long-proboscid specimen of Kallihemerobiinae (electronic supplementary material, figures S1,u and S4), which bore a much-reduced labium and specialized mandibles, likely for pollen handling, indicated by adjacent pollen (electronic supplementary material, figure S1l). Rudimentary mandibles parallel that of the extant Nemopteridae (electronic supplementary material, figure S1u), probable sister-group of Kalligrammatidae [16], that currently have modified mandibulate mouthparts attached to an anterior prolongation of the head capsule for probing and nectar feeding [9,19].

Many extinct and modern insects bear a long proboscis [9,14,36,48], but the proboscides of more derived kalligrammatids bear a special resemblance to those of Lepidoptera [47]. The kalligrammatid proboscis was long (8–20 mm), flexible, lacked styles or other piercing structures, smooth or covered with surface hairs, bracketed by multisegmented maxillary palps, and its terminus typically rounded or truncate, resembling the end of a thick straw (electronic supplementary material, figure S1v,c)—all morphologies paralleling modern Lepidoptera [49]. In addition, kalligrammatid proboscides were longer and more robust, and thus differed from other coexisting, long-proboscid lineages, such as the shorter and more gracile, labellate pads borne by brachycerous flies [35,48], and analogous pseudolabellae of aneuretopsychine scorpionflies [36]. Suction forces were provided by one, perhaps two, sucking pumps located in the frontal head region (electronic supplementary material, figures S1 and S6), mirroring those in Lepidoptera. The considerable mouthpart variation in kalligrammatids, especially of the proboscis, is comparable to modern Nymphalidae and other lepidopterans that probe for nectar and pollen at different floral depths and resistance [5,9,39]. Some kalligrammatid taxa bore thin and gracile proboscides (electronic supplementary material, figure S1r,s), and likely probed into narrow and shallow receptacles for ovular pollination drops and secretions from pollen organs [7,14]. By contrast, the robust and comparatively longer mouthparts of other kalligrammatid taxa (electronic supplementary material, figure S1i,p) were likely suited to probe larger, sturdier reproductive structures of Bennettitales, cycad-like plants contemporaneous with the Kalligrammatidae.

Three sub-studies (electronic supplementary material) explored the dietary range of kalligrammatid lacewings. The first examination targeted an opaque plug trapped within the food canal of a specimens’ proboscis (electronic supplementary material, figure S4e–j), also seen under light microscopy
likely hosts for Kalligrammatidae include cycads (Beania), bennettitaleans (Williamsonia, Weltrichia) and caytonialeans (Caytonia, Caytonianthus). Members of the bennettitaleans and caytonialeans possessed the type of recessed ovules with tubular access that would receive long, probing proboscides of Kalligrammatidae[7,36,50–52]. Some Cheirolepidaceae possessed cone scales partially concealing deep funnels connected to ovules [35]. Early angiosperms from the Yixian Formation are delicate, aquatic, with small, nontubular flowers [34,53], unlikely hosts for Kalligrammatidae. Larger gymnospermous reproductive structures likely accommodated the more robust spectrum of kalligrammatid siphoning proboscides (electronic supplementary material, figure S1 and table S3).

Of all known Mesozoic gymnosperm groups, the bennettitalean family Williamsoniaceae most likely formed a close pollinator mutualism with the Kalligrammatidae. Six lines of evidence point to this inference. First, stoutly constructed and elongate kalligrammatid proboscides match the deeply placed fluids and pollen of bennettitaleans [7,50–52] (electronic supplementary material, figure S6g,h) better than other co-occurring proboscis-bearing taxa [13]. At least two Late Jurassic to Early Cretaceous Eurasian ovulate organs, Williamsonia bryoeae, and W. minima, had deep throats [50,52], and would have accommodated the longer proboscis lengths of kalligrammatid taxa, as would the Jiulongshan specimen (electronic supplementary material, figure S6b). Second, Cycadopteris and other monosulcate pollen (electronic supplementary material, figure S6c) are present in the Jiulongshan [54], Karabastau [29,52] and Yixian [34] biotas, which also preserve diverse Kalligrammatidae [11] and Williamsonioaceae male (Weltrichia) and female (Williamsonia) organs. Both taxa broadly coincide as fossils during a 60 million-year period of the mid-Mesozoic. Third, Weltrichia pollen organs (electronic supplementary material, figure S6g) bore secretory glands [50,51], interpreted as ‘nectaries’ [55], positioned below paired dehiscing pollen sacs along the inner surfaces of clasping bract-like structures [50,51,55]. Analogously, conspecific Williamsonia ovulate organs (electronic supplementary material, figure S6h) produced pollination droplets [35,52]. These nutritional rewards would have been lures for pollinator visits to male and female organs. Fourth, cheirolepidaceans and other conifer pollen occurred adjacent to the head and mouthparts on one kalligrammatid specimen (electronic supplementary material, figure S1h) [35], suggesting seed–plant pollen consumption and a predisposition for pollination [7], as pollen is often a supplemental protein source in modern pollinating insects [9,49]. Fifth, the presence of a curved, saw-like ovipositor (figure 1i–k), homologous and similarly shaped to that of the Dilaridae and used for inserting eggs into deep substrates [56], suggests that females sliced plant tissues for egg deposition and that their larvae consumed internal plant tissues, explaining insect galleries in williamsonioaceae tissues [35] and their expected occurrence in Early Cretaceous amber [38]. Sixth, placement of Weltrichia and Williamsonia organs on separate parts of the same plant or on different conspecific plants [50,51], indicates an outcrossing reproductive strategy. For such functionally dioecious plants, wind may achieve moderate levels of fertilization, but insects are significantly more efficient [7].

4. Discussion and Conclusion

Several accounts [15,16]—some made nearly a century ago [57,58]—have opined on the superficial similarity of poorly preserved kalligrammatid lacewings with modern butterflies. Such analogies, however, were not based on detailed, ultrastructural, micro- and macromorphological, geochemical and palynological evidence. In this study, a broad array of evidence is marshalled to support structural convergence between mid-Mesozoic kalligrammatid lacewings and modern butterflies. This convergence extends to possible melanin presence, simpler spots to complex eyespots, wing scales, long-proboscis siphonate mouthparts, feeding style similarities, and associations with seed plants. These major convergences appeared twice in time and space, presumably under similar selective pressures.

Our data allow for inferences regarding the ecology of insect–predator antagonistic interactions. Similalrities between kalligrammatid eyespots and butterfly eyespots lie in the use of concentric circles of pigmented cells to produce a conspicuous and contrasting display. This pattern was used either for predator intimidation or alternatively predator deflection to the wings away from the core body in extinct kalligrammatids, serving the same functions in butterflies [59,60]. Repeated evolution of eyespots from simpler multiple spots arose during the Middle Jurassic in Kalligrammatidae (figure 2a), closely paralelling Nymphalidae ca 110 Myr later [39]. An ecological explanation for why multiple wing spots were replaced by single wing eyespots in Kalligrammatidae may be the eyespot’s larger and more effective startle or deterrent signal [61]. Eyespots likely were used to dissuade or deflect attacks by predators such as early birds or small theropod dinosaurs [60,61] or mantid insects [59].

Wing scales appeared in Middle Jurassic Kalligrammatidae and Early Palaeogene Lepidoptera. Previously, wing scales were not documented on other fossil or modern neopterans. Our survey of NMNH Neoptera (figure 3c,d) found a single occurrence of scales on the forewings of one genus of extant, unrelated Berothidae [62]. Although these scales have differences in branching and number of ribs compared to those of Kalligrammatidae (figure 3e), they likely are homologous. This indicates that wing-scale presence in the Kalligrammatidae and the absence in almost all other fossil and modern neopterans may be due to changes in deployment of the gene regulatory network within wings, rather than independent origins of scales across Neoptera.

There likely was an association between kalligrammatid lacewings and coexisting gymnosperm seed plants. Diverse evidence support this mid-Mesozoic association, including gymnosperm pollen grains occurring in proximity to the insects; mouthpart morphology designed for probing and fluid feeding; carbon-rich compounds in a kalligrammatid...
proboscis food tube; the contemporaneous existence of compatible gymnosperms bearing secretory tissues and other rewards in reproductive organs and elongate ovulate structures similar in tubular dimensions to probing kalliogrammatid proboscides. This suite of structural features ended with the extinction of Kalligrammatidae and their plant hosts, coincident with the primary ecological expansion of angiosperms during the middle Cretaceous at ca 125–90 Ma [7]. At this time, other functionally similar but anatomically analogous, long-proboscid mouth-parts evolved in unrelated lineages, including Trichoptera (caddisflies) and Hymenoptera (wasps and bees) [9,14], which would have accessed angiosperm nectar [7,9,35].

Although understanding of the ecology in mid-Mesozoic insect clades is sparse [16], our study of Kalligrammatidae now establishes 20 genera and 51 valid species of plant-associated insects (figure 2a; electronic supplementary material, table S1). Kalligrammatidae are the most diverse and third major clade of recently recognized Eurasian, preangiospermous, long-proboscid insects [14], complementing brachypterous flies [35,48,63] and aneuoretopsychine scorpionflies [36]. These multiple origins of long-proboscid insects [14] took place in a Jurassic world dominated by diverse gymnosperms with virtually no modern analogues [14,29,35,64]. Our data also suggest that if angiosperms antedated the mid-Early Cretaceous and were insect pollinated, they most likely harboured associations with mandibulate rather than long-proboscid insects, consistent with early angiosperm floral structure [7,19,35], and antedating the considerably more recent origin of distinctive tubular floral modifications that would accommodate long-proboscid insects [7,14]. Varied fossil data suggest that the mid-Cretaceous demise of many pre-existing gymnosperms led to extinction of their diverse insect associates [14,30,63–65], including Kalligrammatidae, during early angiosperm diversification. Intriguingly, this clade was replaced by ecologically convergent butterflies ca 60 Myr later.

Data accessibility. Data forming the basis of this research and the details of analyses are available in the electronic supplementary material attached to this article.

Author contributions. D.R. and Q.Y. prepared the fossil material. C.C.L. and D.R. designed the research and wrote the paper. Q.Y., Y.-J.W., D.R. provided work on systematics and phylogeny reconstruction. J.A.S.B. and C.C.L. provided wing eyepoint and mouthpart analyses; T.R.R. and Y.G. worked on light microscopy, SEM, EDS and related analyses; A.M. provided expertise on interpretation of eyepoint and scale data. C.I.H. identified pollen and interpreted their context, C.K.S., C.C.L. and Y.G. worked on systematics and mimicry; Y.G. and S.S. conducted the ToF-SIMS analysis; and D.L.D. and C.C.L. provided macrofossil insights.

Competing interests. We declare we have no competing interests.

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