

Supplementary Information for

Pulsed evolution shaped extant angiosperm pollen disparity

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Supplementary Tables

Supplementary Table 1. List of taxa for which pollen grains are pictured in Figure 1, with source of the original image. All images used with permission.

No.	Species	Family	Order	Picture source
1	<i>Nymphaea alba</i>	Nymphaeaceae	Nymphaeales	Lu Lu
2	<i>Schisandra grandiflora</i>	Schisandraceae	Austrobaileyales	Lu Lu
3	<i>Drimys piperita</i>	Winteraceae	Canellales	Lu Lu
4	<i>Peperomia heyneana</i>	Piperaceae	Piperales	Lu Lu
5	<i>Magnolia grandiflora</i>	Magnoliaceae	Magnoliales	Lu Lu
6	<i>Chloranthus japonicus</i>	Chloranthaceae	Chloranthales	Lu Lu
7	<i>Epipremnum sp.</i>	Araceae	Alismatales	Yang Luo
8	<i>Zostera marina</i>	Zosteraceae	Alismatales	Yang Luo
9	<i>Petrosavia sp.</i>	Petrosaviaceae	Petrosaviales	Yang Luo
10	<i>Tulipa illensis</i>	Liliaceae	Liliales	Yang Luo
11	<i>Canna sp.</i>	Cannaceae	Zingiberales	Yang Luo
12	<i>Dendrocalamus sinicus</i>	Poaceae	Poales	Yang Luo
13	<i>Ceratophyllum sp.</i>	Ceratophyllaceae	Ceratophyllales	Alexandra H. Davey
14	<i>Ranzania japonica</i>	Berberidaceae	Ranunculales	Ming-Ying Zhang
15	<i>Thalictrum delavayi</i>	Ranunculaceae	Ranunculales	Ming-Ying Zhang
16	<i>Grevillea baueri</i>	Proteaceae	Proteales	Ming-Ying Zhang
17	<i>Dillenia yunnanensis</i>	Dilleniaceae	Dilleniales	Ying Yu
18	<i>Ribes glaciale</i>	Grossulariaceae	Saxifragales	Ying-Jun Zhang
19	<i>Aphanopetalum resinosum</i>	Aphanopetalaceae	Saxifragales	Ying-Jun Zhang
20	<i>Kallstroemia maxima</i>	Zygophyllaceae	Zygophyllales	Zhi-Bin Tao
21	<i>Acacia concinna</i>	Fabaceae	Fabales	Wei Jiang, Hua-Jie He
22	<i>Nothofagus dombeyi</i>	Nothofagaceae	Fagales	Wei Jiang, Hua-Jie He
23	<i>Cucumis melo</i>	Cucurbitaceae	Cucurbitales	Wei Jiang, Hua-Jie He
24	<i>Podostemum distichum</i>	Podostemaceae	Malpighiales	Zhi-Bin Tao
25	<i>Passiflora incarnata</i>	Passifloraceae	Malpighiales	Zhi-Bin Tao
26	<i>Neurada procumbens</i>	Neuradaceae	Malvales	Ying-Jun Zhang
27	<i>Bombax malabaricum</i>	Malvaceae	Malvales	Ying-Jun Zhang
28	<i>Limnanthes alba</i>	Limnanthaceae	Brassicales	Ying-Jun Zhang
29	<i>Berberidopsis corallina</i>	Berberidopsidaceae	Berberidopsidales	Ying Yu
30	<i>Phanerodiscus diospyroidea</i>	Olacaceae	Santalales	Ying Yu

31	<i>Psittacanthus calyculatus</i>	Loranthaceae	Santalales	Ying Yu
32	<i>Nepenthe smirabilis</i>	Nepenthaceae	Caryophyllales	Ying Yu
33	<i>Mirabilis himalaica</i>	Nyctaginaceae	Caryophyllales	Ying Yu
34	<i>Impatiens delavayi</i>	Balsaminaceae	Ericales	Ying Yu
35	<i>Asclepias angustifolia</i>	Apocynaceae	Gentianales	Li-E Yang
36	<i>Thunbergia alata</i>	Acanthaceae	Lamiales	Li-E Yang
37	<i>Catalpa sp.</i>	Bignoniaceae	Lamiales	Li-E Yang
38	<i>Stylidium perula</i>	Stylidiaceae	Asterales	La Xu
39	<i>Menyanthes trifoliata</i>	Menyanthaceae	Asterales	La Xu
40	<i>Taraxacum eriopodum</i>	Asteraceae	Asterales	La Xu

Supplementary Table 2. Pollen characters and their states as defined in this study.

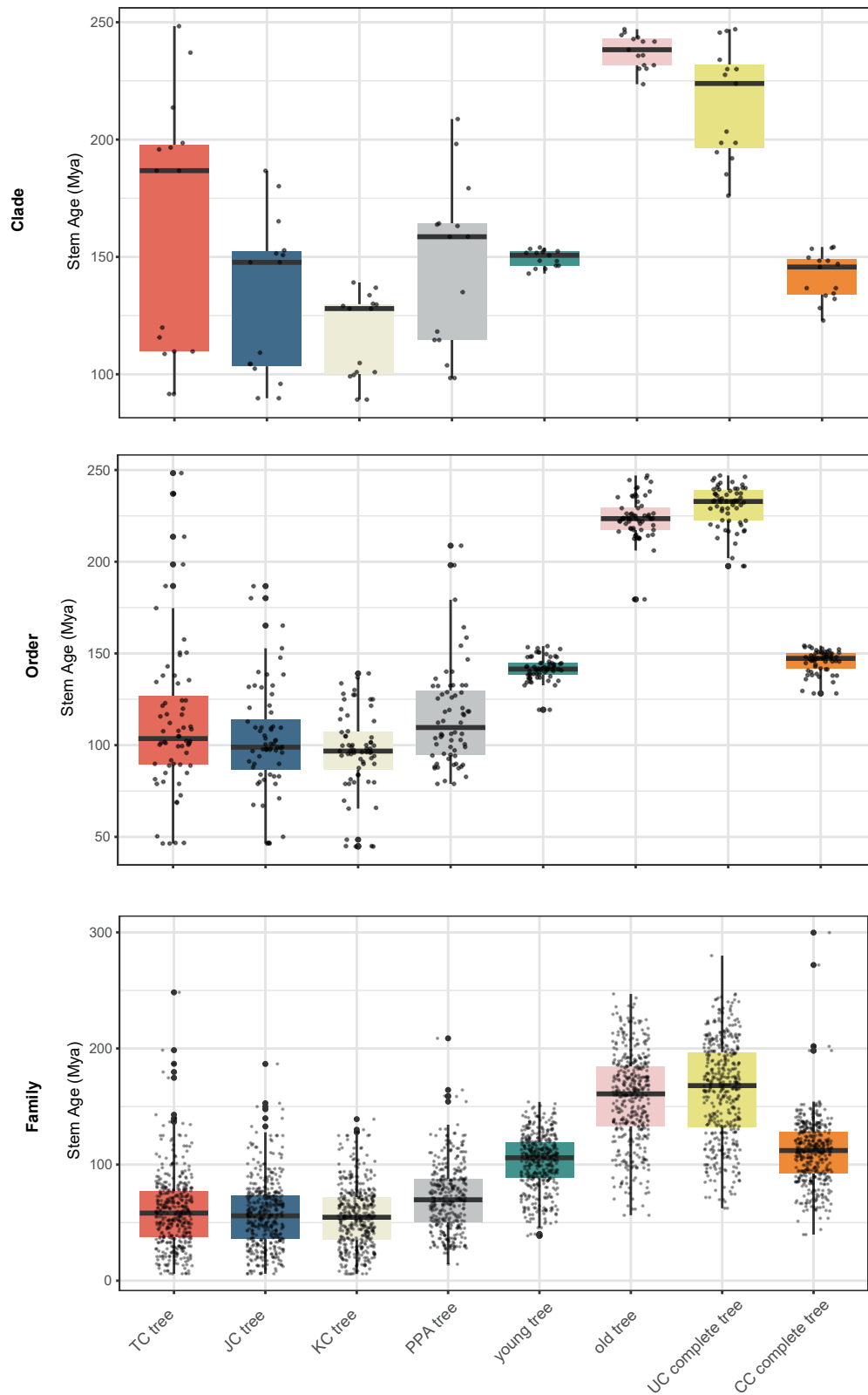
Pollen Characters	Description	Character states
(a) pollen grain shape (shape)		
1 Dispersal unit	The morphological unit in which mature pollen grains are shed—ranging from single grains (monads) to fixed groups (dyads, tetrads, polyads) or larger aggregates like pollinia and massulae.	0 monad, 1 dyad, 2 tetrad, 3 polyad, 4 pollinia
2 Polarity	The presence of distinct poles, inferred from tetrad arrangement, aperture position, or other pollen features.	0 apolar, 1 heteropolar, 2 isopolar (or subisopolar)
3 Symmetry	Arrangement of structural features relative to one or more planes of symmetry, categorized as asymmetrical (no plane), bilateral (one plane), or radial (two or more planes).	0 asymmetrical, 1 bilateral, 2 radial
4 Basic shape	The basic three-dimensional form of a pollen grain, coded as either globose-like (fixiform, with a definite shape) or filiform (nonfixiform, lacking a definite shape).	0 globose-like, 1 filiform
5 Outline in polar view	The outline of a pollen grain seen in polar view.	0 circular & elliptic, 1 lobate; 2 polygonal
6 Macro-ornamentation	Presence of raised ridges on the outer exine forming a distinct pattern.	0 non-lophate; 1 lophate
(b) aperture pattern (aperture)		
7 Size	The length of the longest axis of pollen grain. Size bins are broad to accommodate natural and preparation-related variation.	0 very small (< 10 µm), 1 small (10-24 µm), 2 medium (25-49 µm), 3 large (50-99 µm), 4 very large (100-199 µm), 5 gigantic (>200 µm)
8 Aperture number	The number of delimited openings/thin-walled regions of the exine.	0 zero, 1 one, 2 two, 3 three, 4 more than three
9 Aperture position	The spatial location of apertures on the pollen grain relative to its polar axis and equator.	0 polar: distal, 1 polar: proximal, 2 polar (both distal and proximal), 3 equatorial, 4 global
10 Ectoaperture shape	The shape of the aperture in the outer layer of pollen grain.	0 colpate, 1 porate, 2 zonate, 3 spiral
11 Endoaperture	The presence of an aperture in the inner layer of the pollen grain.	0 absent, 1 present
12 Operculum	A clearly defined part of the ectexine that covers part of the ectoaperture and is completely separated from the surrounding exine.	0 absent, 1 present
13 Annulus	Thickening of the exine surrounding the apertures.	0 absent, 1 present
(c) Exine structure and ornamentation (exine)		
14 Exine	Presence of more than one distinct exine layer.	0 absent, 1 present
15 Tectum	Presence of outer ectexine layer.	0 absent, 1 present

16 Tectum sculpture	The surface pattern of the tectum.	0 imperforate (psilate), 1 perforate/ foveolate, 2 fossulate, 3 areolate, 4 striate, 5 rugulate, 6 reticulate, 7 cupulate, 8 crotonoid, 9 retipilate
17 Supratectal element	Presence of elements on the surface of the tectum.	0 absent, 1 present
18 Infratectum	Presence of the layer of the exine situated between the nexine and the tectum.	0 absent, 1 present
19 Infratectum structure	The form of infratectum	0 granular, 1 intermediate (between granulate and columellate) 2 columellate, 3 alveolate
20 Foot layer	Presence of inner ectexine layer.	0 absent, 1 present

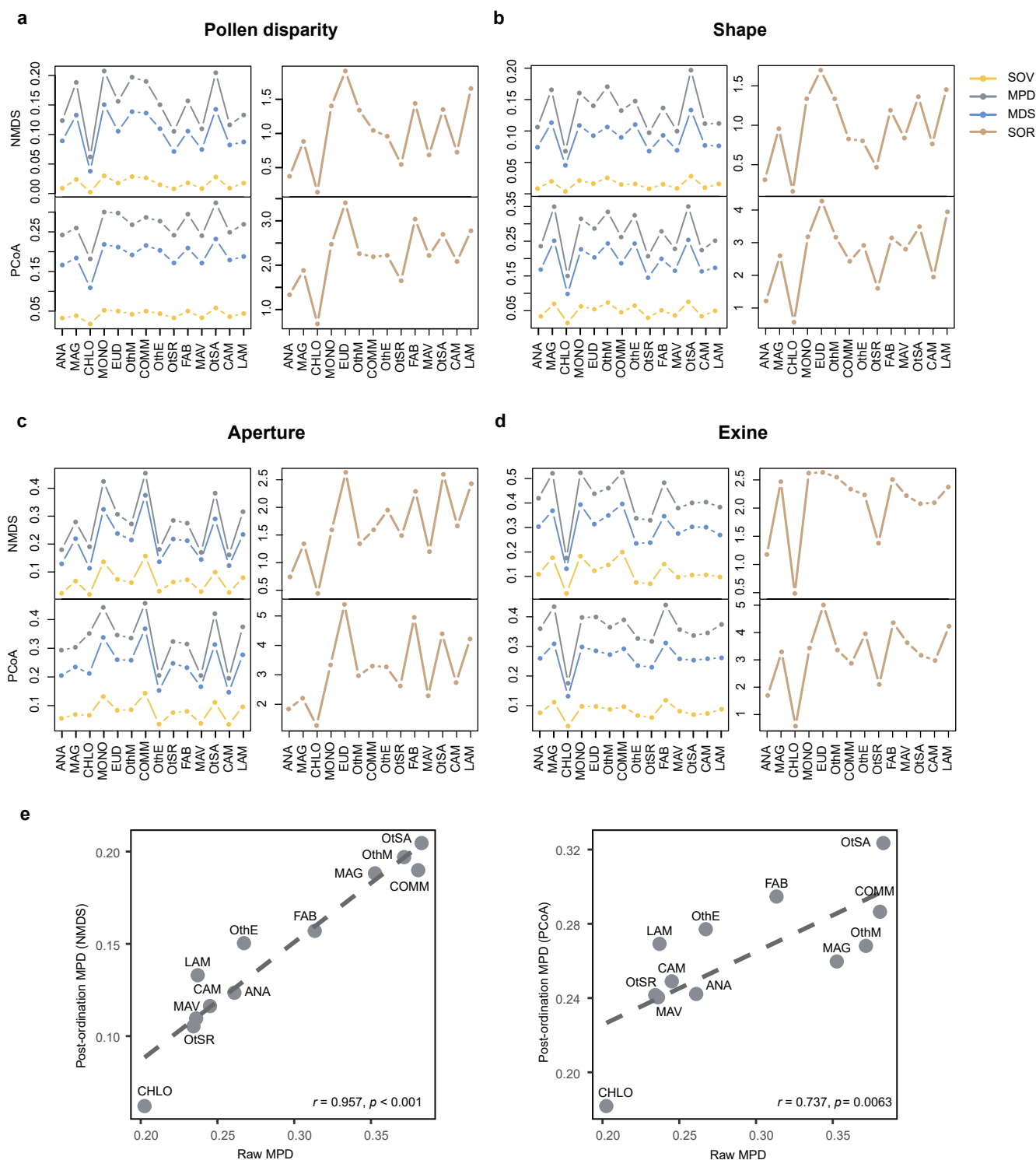
Supplementary Table 3. Fastest-evolving branches during two stages of angiosperm pollen diversification. This table lists the fifteen branches with the highest estimated rates of discrete morphological evolution in two diversification stages—Stage 1 (before 95 Ma) and Stage 2 (70–40 Ma)—based on rate estimates for overall pollen traits and for aperture traits.

Overall pollen morphology		Branch names	
Rank	Stage 1	Stage 2	
1	N-fixing clade	Ericaceae (Ericales)	
2	superasterids	Santanales	
3	Saxifragaceae+Crassulaceae clade (Saxifragales)	Orchidoideae+Epidendroideae (Orchidaceae, Asparagales)	
4	Laurales+Magnoliales	<i>Corispermum</i> + <i>Suaeda</i> + <i>Salicornia</i> + <i>Bassia</i> + <i>Salsola</i> (Amaranthaceae, Caryophyllales)	
5	Myrtales	<i>Cassiope</i> - <i>Gaultheria</i> clade (Ericaceae, Ericales)	
6	superrosids	Euphorbiaceae (Malpighiales)	
7	Ceratophyllales + eudicots	<i>Erica</i> + <i>Rhododendron</i> + <i>Diplarche</i> (Ericaceae, Ericales)	
8	woody Saxifragales	Phyllanthaceae (Malpighiales)	
9	Laurales with Calycanthaceae excluded	Cardiopteridaceae (Aquifoliales)	
10	eudicots	Trigoniaceae (Malpighiales)	
11	asterids	Lamiales	
12	Huaceae (Oxalidales)	Alismataceae (Alismatales)	
13	Crossosomatales	<i>Aldrovanda</i> + <i>Dionaea</i> (Droseraceae)	
14	<i>Saruma</i> (Aristolochiaceae)	Apiaceae (Apiales)	
15	<i>Nymphaea</i> + <i>Euryale</i> (Nymphaeaceae)	Cymodoceaceae-Zostaceae clade (Alismatales)	
Aperture		Branch names	
Rank	Stage 1	Stage 2	
1	superrosids	Orchidoideae+Epidendroideae (Orchidaceae, Asparagales)	
2	woody Saxifragales	Tecophilaeaceae+Ixoliiriaceae (Asparagales)	
3	asterids	Alismataceae (Alismatales)	
4	eudicots	<i>Chloranthus</i> + <i>Sarcandra</i> (Chloranthaceae, Chloranthales)	
5	Cornales	Trigoniaceae (Malpighiales)	
6	Tofieldiaceae (Alismatales)	Aquifoliaceae (Aquifoliales)	
7	Schisandraceae (Austrobaileyales)	<i>Aldrovanda</i> + <i>Dionaea</i> (Droseraceae, Caryophyllales)	
8	Calycanthaceae (Laurales)	<i>Lobelia</i> (Campanulaceae, Asterales)	
9	Nymphaeaceae with Nuphar excluded (Nymphaeales)	<i>Tofieldia</i> (Tofieldiaceae, Alismatales)	
10	Huaceae (Oxalidales)	<i>Pilea</i> (Tofieldiaceae)	
11	Celastrales	<i>Zippelia</i> (Piperaceae, Piperales)	
12	Laurales	Hypericum (Hypericaceae, Malpighiales)	
13	Trimeniaceae (Austrobaileyales)	Annonaceae with <i>Anaxagorea</i> excluded (Magnoliales)	
14	Hydatellaceae (Nymphaeales)	Theaceae-Diapensiaceae clade (Ericales)	
15	Burmanniaceae (Dioscoreales)	Amaranthus (Amaranthaceae, Caryophyllales)	

Supplementary Figures

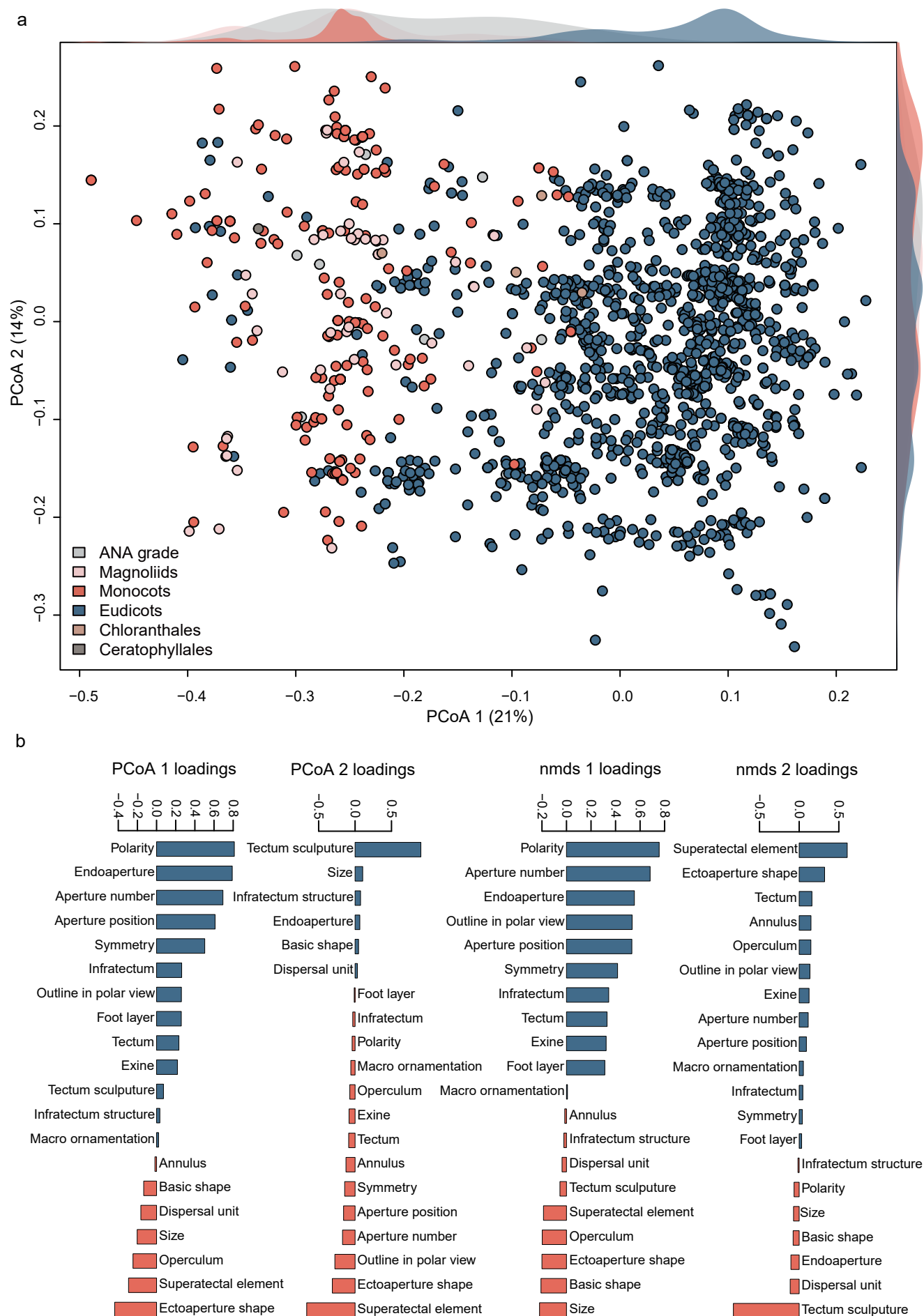


Supplementary Figure 1. Comparison of stem age estimates across alternative time-calibrated phylogenies. Boxplots summarize the distribution of stem ages (in million years) for major angiosperm clades, orders, and families across eight dated trees. These include the TC, JC and KC trees inferred in this study; the PPA tree of Li et al. ¹; the “young” and “old” trees of Zuntini et al. ², and the UC-complete and CC-complete trees of Ramírez-Barahona et al. ³. Boxplots show the median, interquartile range, and 1.5×IQR whiskers; outliers are shown as points. Source data are provided as a Source Data file.

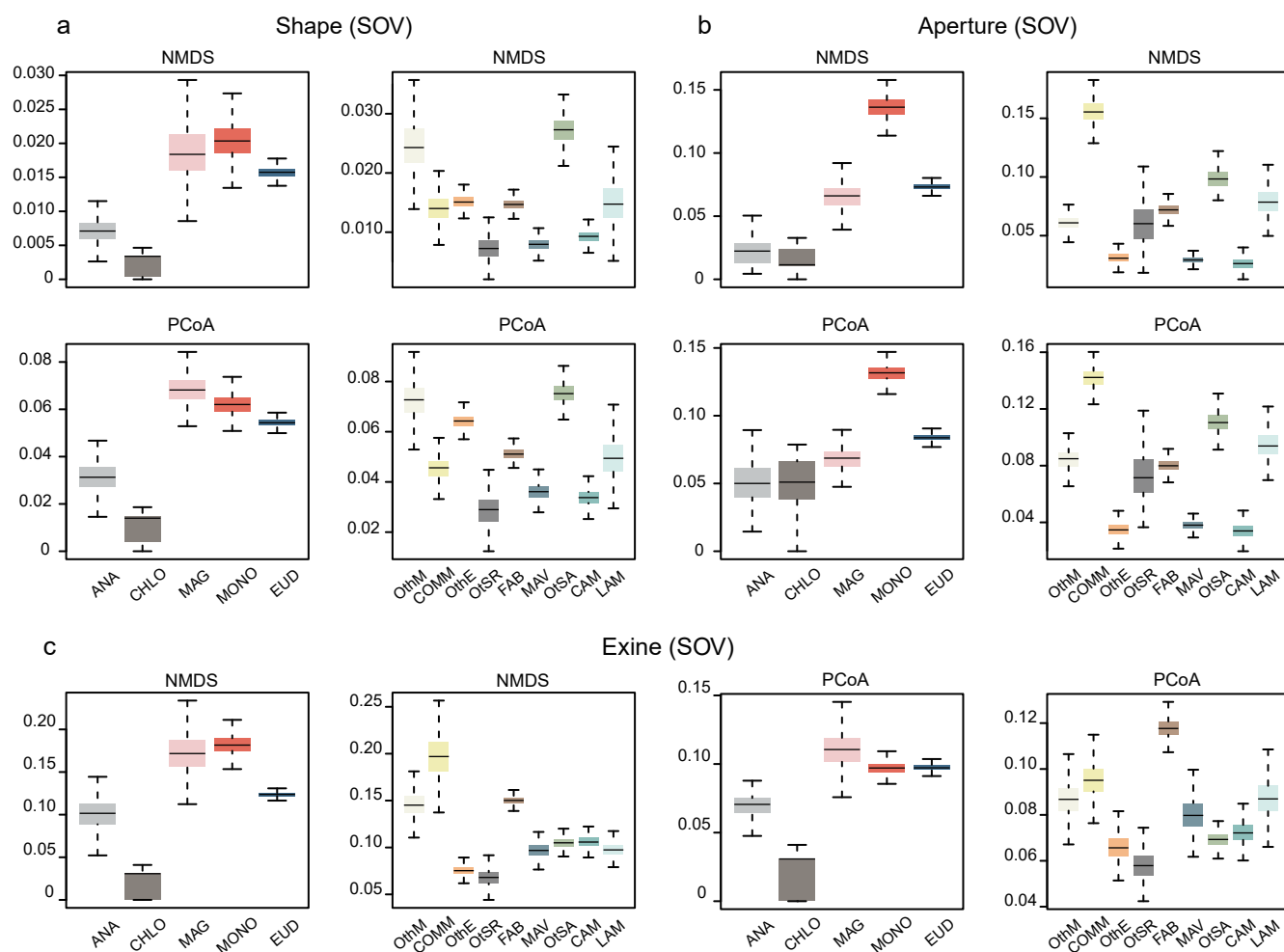


Supplementary Figure 2. Size-related disparity across fourteen angiosperm groups.

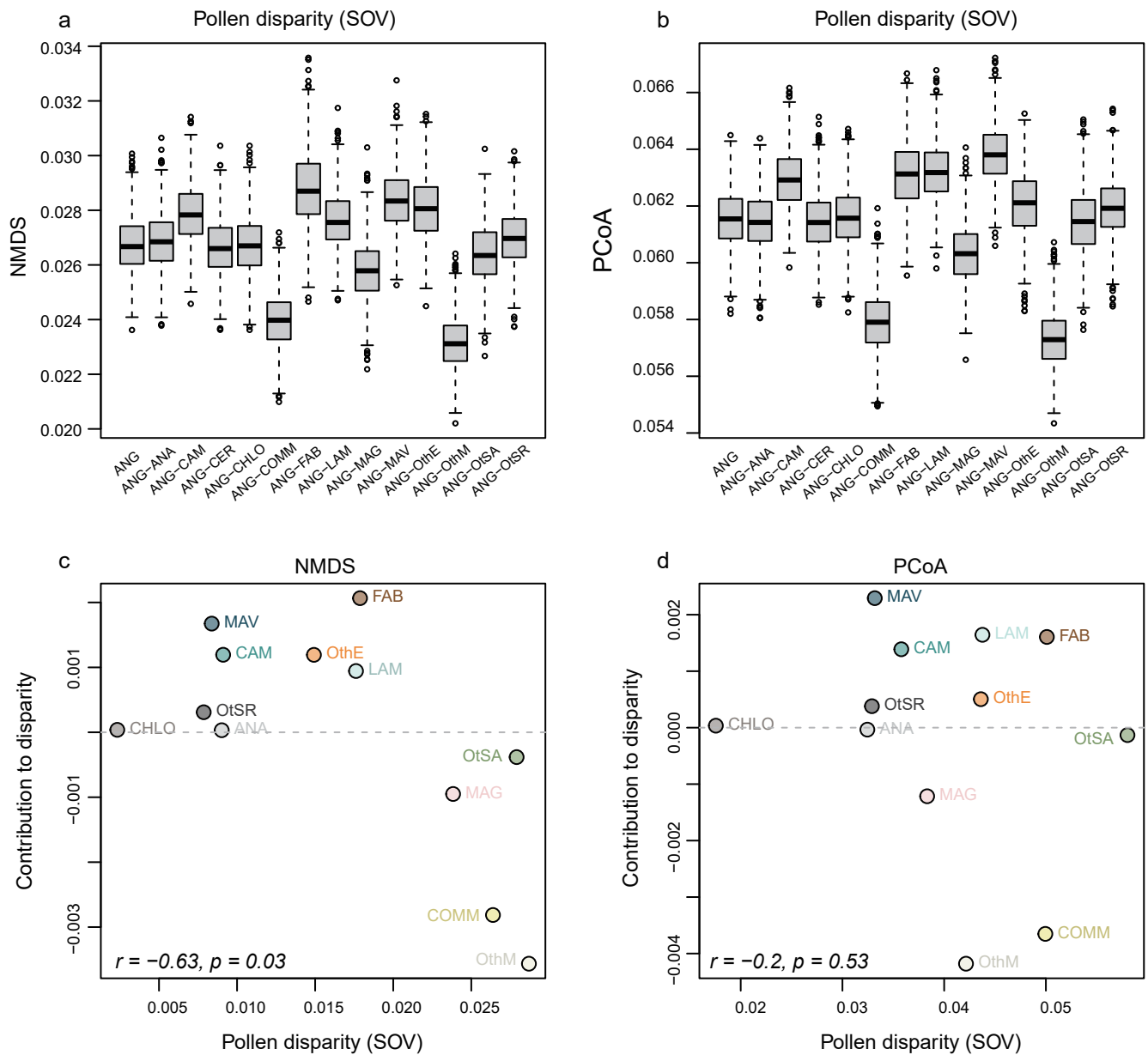
Disparity was quantified using four metrics—Sum of Variances (SOV), Mean Pairwise Distance (MPD), Mean Distance to Centroid (MDC), and Sum of Ranges (SOR)—calculated from NMDS and PCoA ordinations for (a) pollen disparity, (b) shape traits, (c) aperture traits, and (d) exine traits. Values shown for each lineage reflect observed disparity scores, not statistical summaries across replicates. (e) Correlations between MPD values obtained from the raw distance matrix and those derived from NMDS and PCoA ordinated spaces. Each point represents one of the fourteen angiosperm groups. Dashed lines indicate linear regressions. ANA, ANA grade; CHLO, Chloranthales; MAG, magnoliids; MONO, monocots; EUD, eudicots; COMM, commelinids; CAM, campanulids; FAB, fabids; LAM, lamiids; MAG, magnoliids; MAV, malvids; OthE, other eudicots; OthM, other monocots; OtSA, other superasterids; OtSR, other superrosids. Source data are provided as a Source Data file.



Supplementary Figure 3. Angiosperm pollen morphospace. (a) PCoA morphospace occupied by angiosperm pollen, showing the position of 1,880 angiosperm genera along the first two axes. Colours denote major angiosperm lineages. (b) Factor loadings for the first two axes of PCoA and NMDS, illustrating the contribution of each discrete pollen character to the ordination structure. Loadings are shown for all 20 pollen characters (see Supplementary Table 2 for definitions). Source data are provided as a Source Data file.

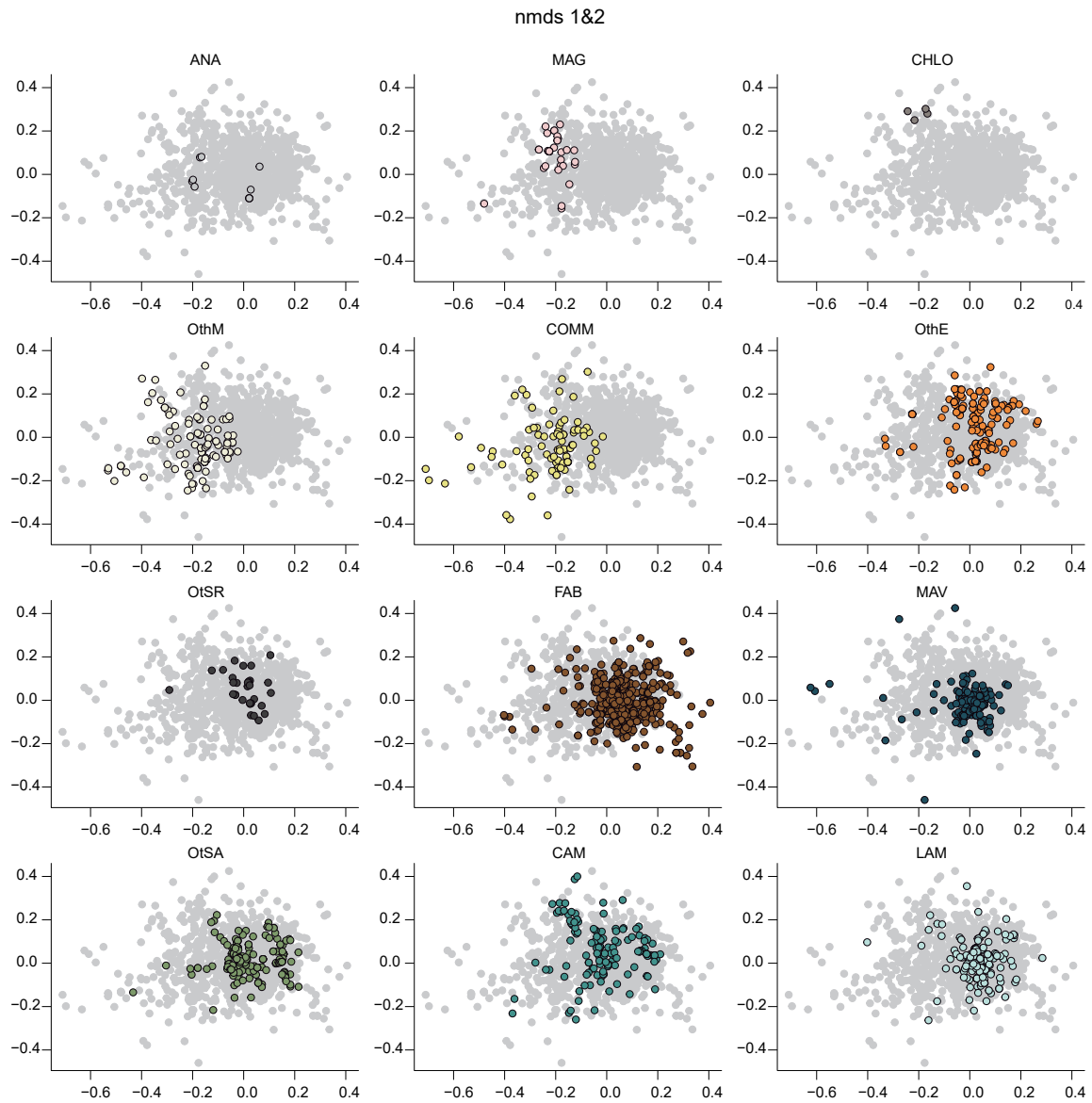


Supplementary Figure 4. Disparity of three pollen character subsets across fourteen angiosperm groups. Shown are the sum of variances (SOV) for the shape (a), aperture (b), and exine (c) character subsets, each estimated from 1,000 bootstrap replicates using NMDS- and PCoA-derived ordination scores. Boxplots show the median, interquartile range, and 1.5×IQR whiskers; outliers are omitted. Original sample sizes for each group were: ANA (n = 12), CHLO (n = 4), MAG (n = 12), MONO (n = 215), EUD (n = 1601); OthM (n = 114), COMM (n = 101), OthE (n = 193), OtSR (n = 30), FAB (n = 687), MAV (n = 173), OtSA (n = 195), CAM (n = 142), LAM (n = 181). ANA, ANA grade; CHLO, Chloranthales; MAG, magnoliids; MONO, monocots; EUD, eudicots; COMM, commelinids; CAM, campanulids; FAB, fabids; LAM, lamiids; MAV, malvids; OthE, other eudicots; OthM, other monocots; OtSA, other superasterids; OtSR, other superrosids. Source data are provided as a Source Data file.

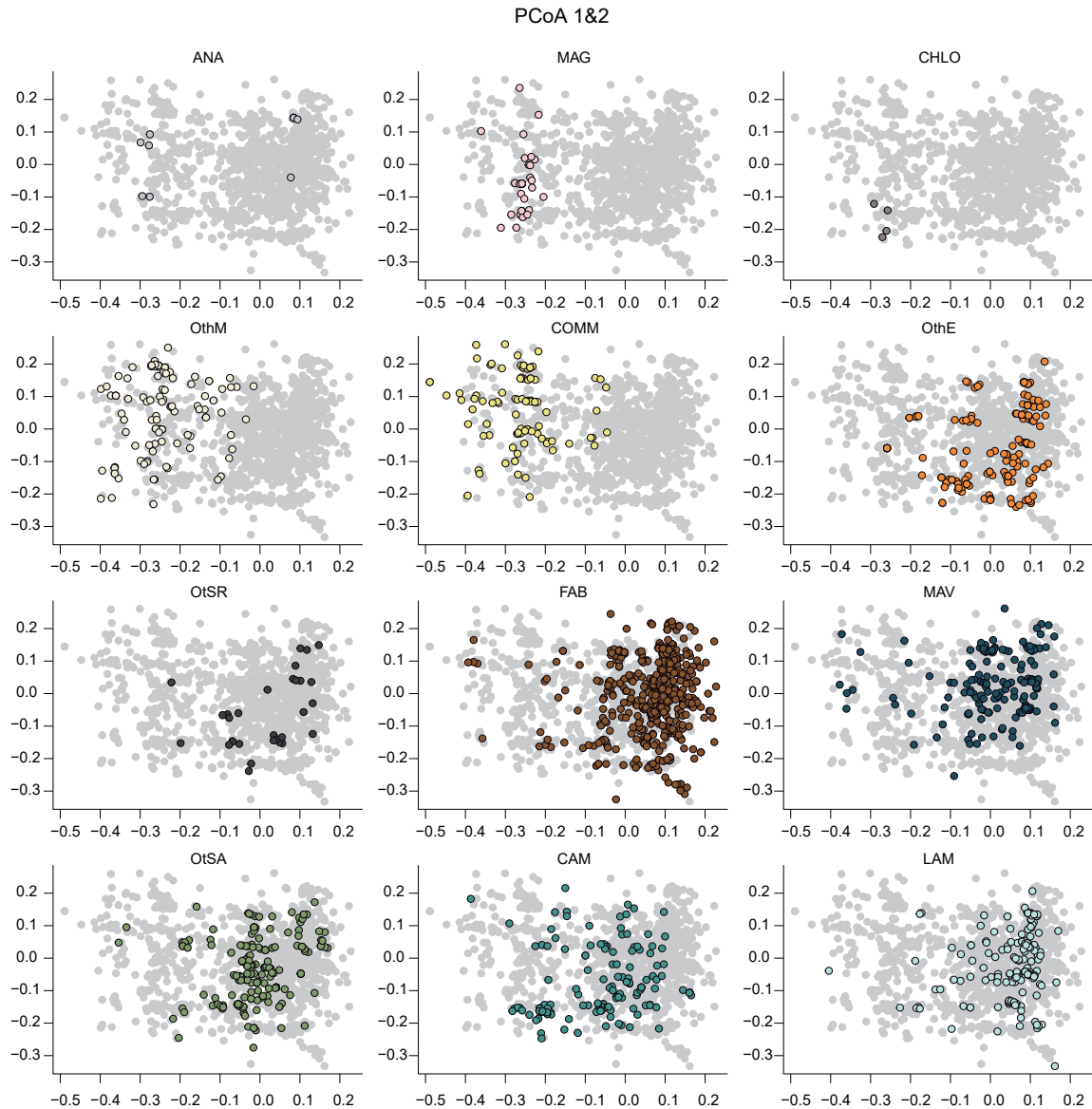


Supplementary Figure 5. Contribution of angiosperm subgroups to overall pollen disparity.

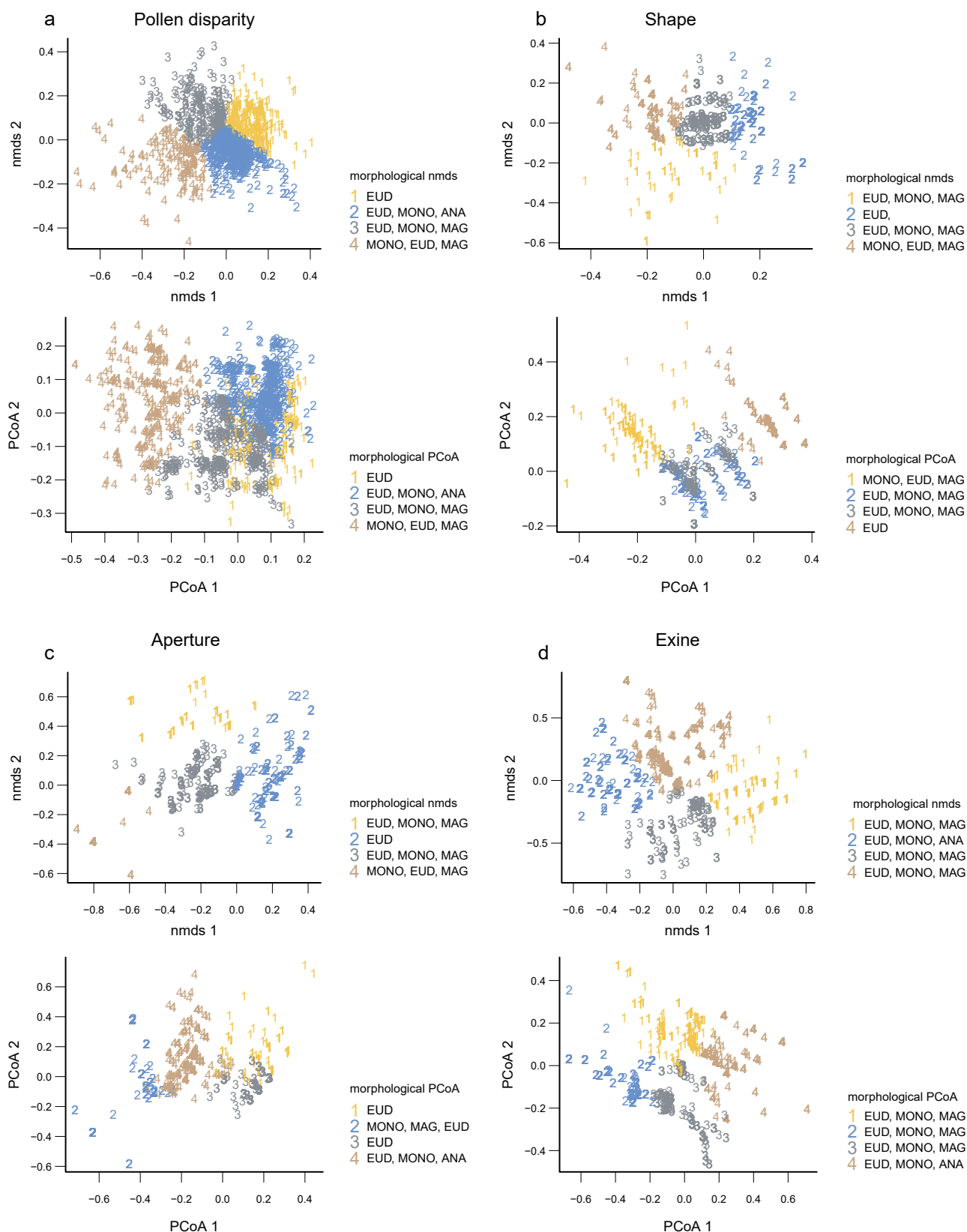
(a-b) Disparity (sum of variances, SOV) of fourteen angiosperm groups estimated from 1,000 bootstrap replicates using NMDS (a) and PCoA (b) ordinations. Boxplots show the median, interquartile range, and $1.5 \times \text{IQR}$ whiskers; outliers are shown as points. Note that dashes connecting ANG (Angiosperms) and the subgroup name represent the removal of the latter from the former from the total ordination matrix. (c-d) Relationship between the observed disparity of each subgroup and its contribution to total angiosperm disparity under NMDS (c) and PCoA (d). Contribution values were computed using a subgroup-omission framework, where the effect of excluding a subgroup reflects its proportional contribution to overall pollen variance. Pearson's correlation coefficient (r) and p values are shown for each ordination method. ANA, ANA grade; CHLO, Chloranthales; MAG, magnoliids; MONO, monocots; EUD, eudicots; COMM, commelinids; CAM, campanulids; FAB, fabids; LAM, lamiids; MAV, malvids; OthE, other eudicots; OthM, other monocots; OtSA, other superasterids; OtSR, other superrosids. Source data are provided as a Source Data file.



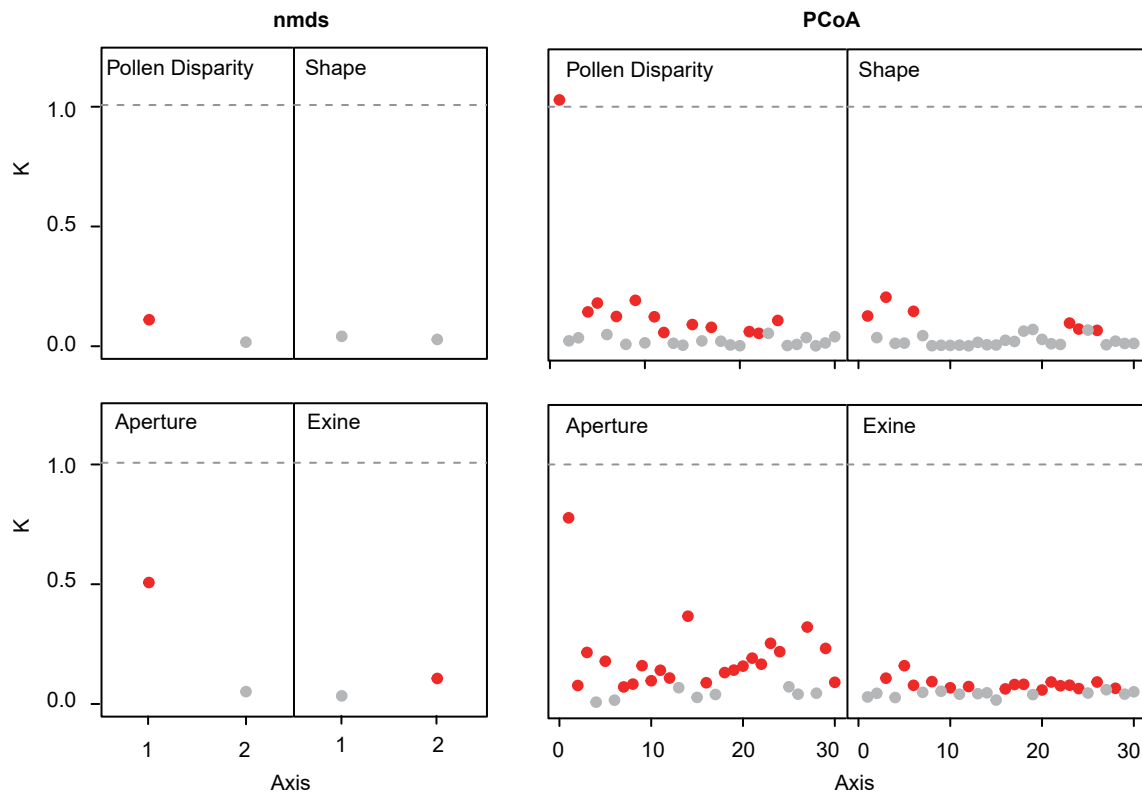
Supplementary Figure 6. Pollen morphospace occupation of twelve major angiosperm subgroups based on the two NMDS axes. Grey points represent the full angiosperm pollen dataset, and coloured points highlight the taxa belonging to each focal subgroup. ANA, ANA grade; CHLO, Chloranthales; MAG, magnoliids; COMM, commelinids; CAM, campanulids; FAB, fabids; LAM, lamiids; MAV, malvids; OthE, other eudicots; OthM, other monocots; OtsA, other superasterids; OtsR, other superrosids. Source data are provided as a Source Data file.



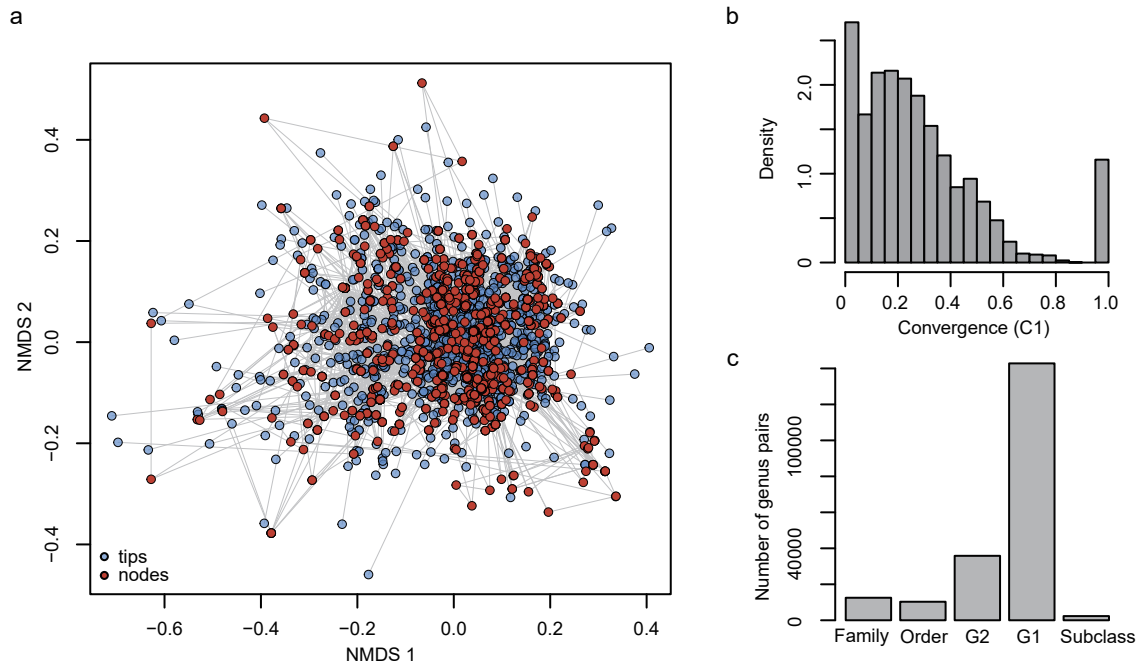
Supplementary Figure 7. Pollen morphospace occupation of twelve major angiosperm subgroups based on the first two PCoA axes. Grey points represent the full angiosperm pollen dataset, and coloured points highlight the taxa belonging to each focal subgroup. ANA, ANA grade; CHLO, Chloranthales; MAG, magnoliids; COMM, commelinids; CAM, campanulids; FAB, fabids; LAM, lamiids; MAV, malvids; OthE, other eudicots; OthM, other monocots; OtSA, other superasterids; OtSR, other superrosids. Source data are provided as a Source Data file.



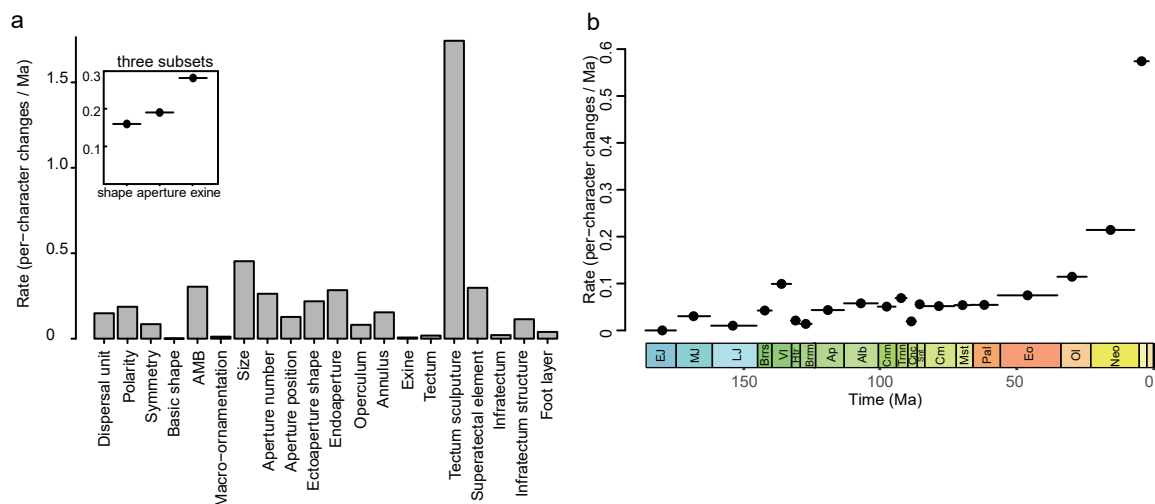
Supplementary Figure 8. K-means clustering of angiosperm pollen morphospaces derived from four morphological dimensions. Morphospaces are shown for the first two NMDS and PCoA axes constructed from four morphological dimensions: (a) pollen disparity, (b) shape, (c) aperture, and (d) exine. K-means clusters are superimposed on each morphospace, and for each cluster the angiosperm groups most frequently represented within that cluster are listed. ANA, ANA grade; CHLO, Chloranthales; MAG, magnoliids; MONO, monocots; EUD, eudicots.



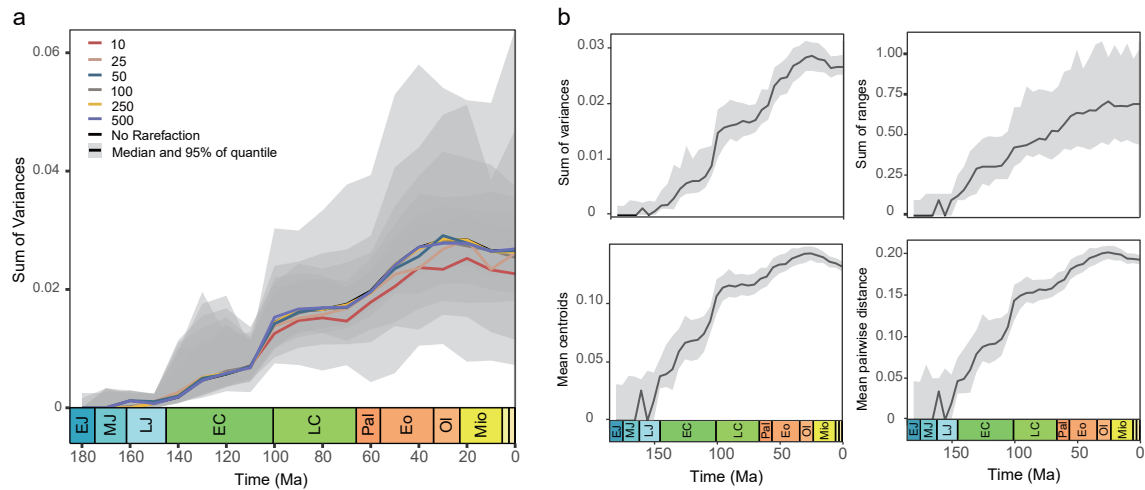
Supplementary Figure 9. Phylogenetic signal in pollen morphospace axes quantified using Blomberg's K. Phylogenetic signal was evaluated for the two NMDS axes and the first 30 PCoA axes across four datasets: overall pollen disparity, shape, aperture, and exine (panels arranged as shown). Each point represents Blomberg's K value for a given ordination axis, with red dots indicating statistically significant phylogenetic signal ($P < 0.05$). The dashed line at $K = 1$ marks the expectation under a Brownian-motion model of trait evolution.



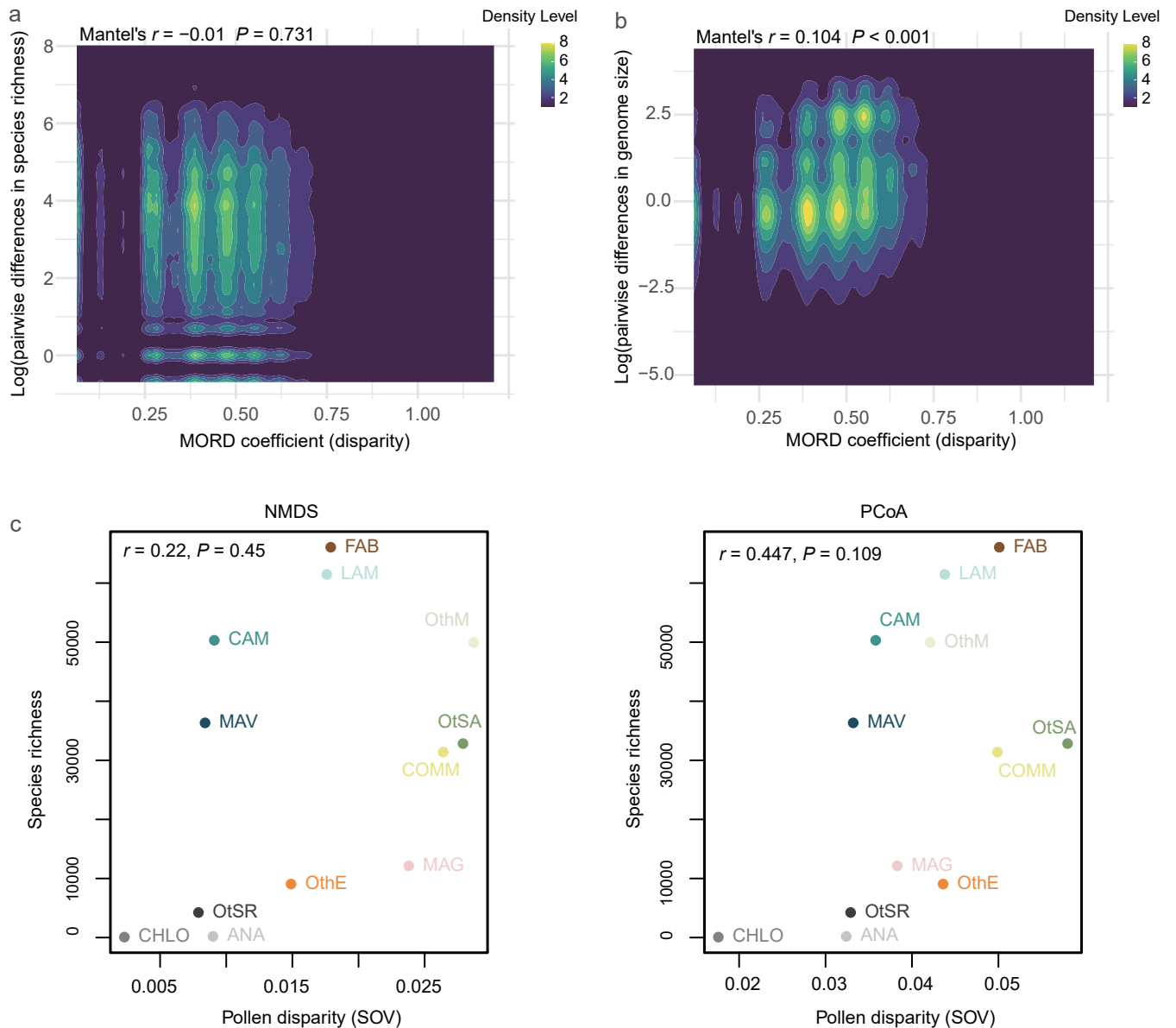
Supplementary Figure 10. Patterns of angiosperm pollen morphospace. (a) NMDS phylomorphospace showing tip values (blue circles), internal-node estimates (red circles), and connecting branches (grey lines). (b) Frequency distribution of C1 convergence values calculated for all 3,530,641 genus pairs using the MORD distance metric. (c) Taxonomic ranks at which highly convergent genus pairs ($C1 \geq 0.90$) are classified, summarised across Family, Order, Subclass, and two informal groupings (G1 and G2; see Methods for definitions). C1 quantifies the proportion of ancestral morphological divergence that has been reduced through subsequent evolution between two lineages.



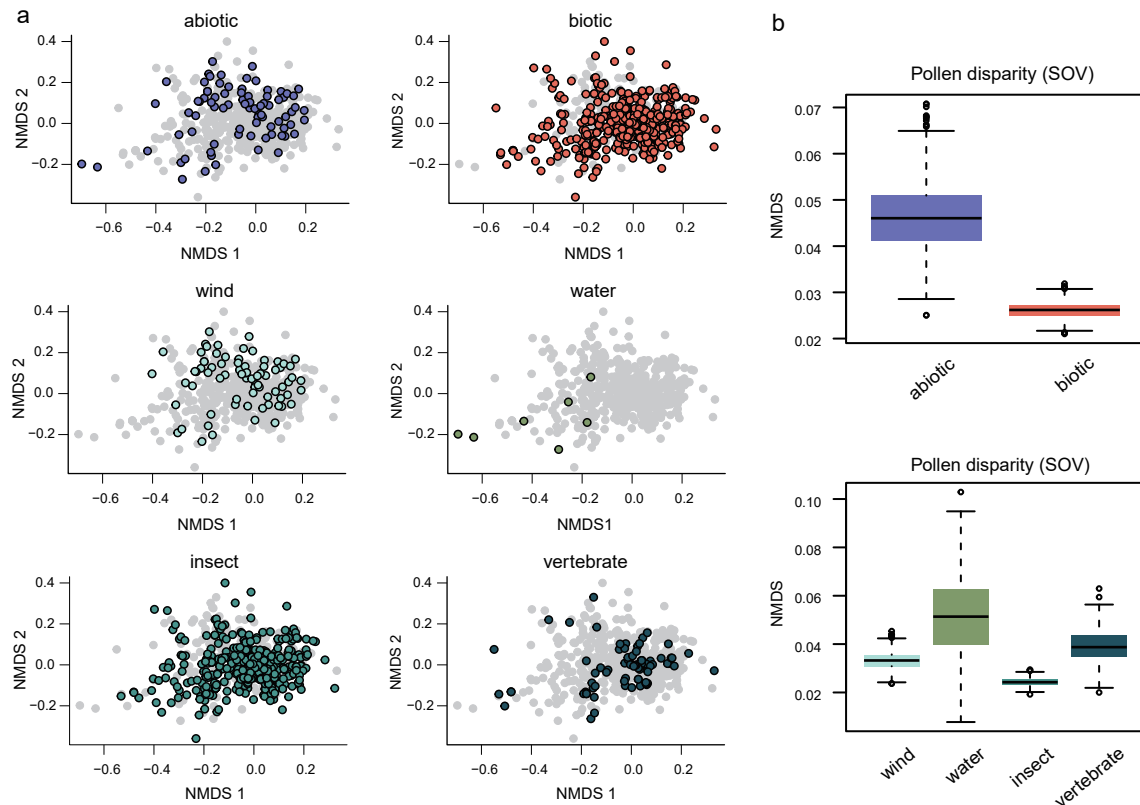
Supplementary Figure 11. Comparison of rates of pollen morphological evolution. (a) Estimated rates of character evolution (λ ; per-character changes per million years) for each of the 20 discrete pollen traits and for the three character subsets (shape, aperture, and exine). Bar heights represent maximum-likelihood rate estimates derived from likelihood-ratio tests. (b) Temporal variation in mean evolutionary rates across 20 time bins spanning the Jurassic to the present. Points indicate the mean rate per bin. EJ, Early Jurassic; MJ, Middle Jurassic; LJ, Late Jurassic; Brrs, Berriasian; VI, Valanginian; Htr, Hauterivian; Brrm, Barremian; Ap, Aptian; Alb, Albian; Cnm, Cenomanian; Trnn, Turonian; Cnc, Coniacian; Snt, Santonian; Cm, Campanian; Mst, Maastrichtian; Pal, Paleocene; Eo, Eocene; Ol, Oligocene; Neo, Neogene. Source data are provided as a Source Data file.



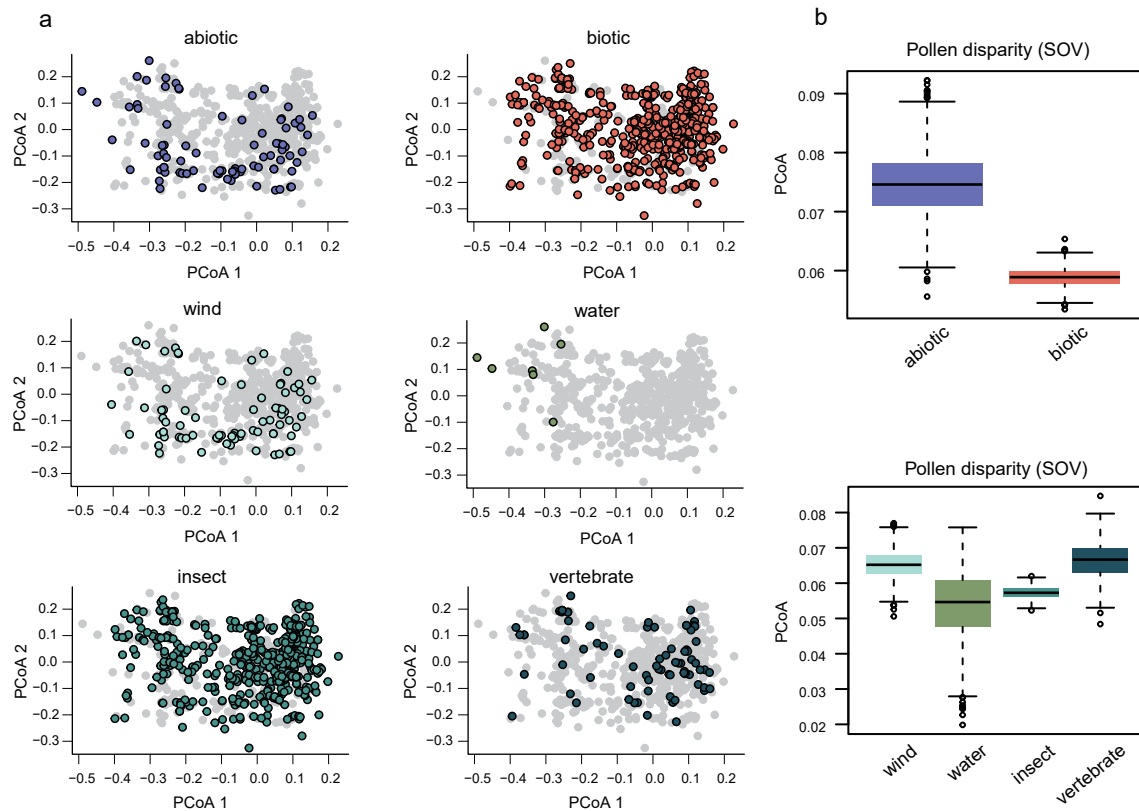
Supplementary Figure 12. Angiosperm Pollen Disparity Through Time. (a) Disparity Through Time (DTT) under different rarefaction levels ($n = 10$ – 500) and without rarefaction. Curves show the median disparity (sum of variances) and shaded regions representing the 5% and 95% percentiles across 100 bootstrap replicates per time bin. (b) DTT for four disparity metrics—sum of variances, sum of ranges, mean distance to centroid, and mean pairwise distance. Except for sum of ranges, which was calculated using rarefaction ($n = 100$), all other indices were computed from the full dataset without rarefaction. EJ, MJ and LJ stand for Early, Mid- and Late Jurassic; EC and LC for Early and Late Cretaceous; Pal, Eo and Ol for three Epochs of Paleogene, i.e., Paleocene, Eocene and Oligocene; Mio stands for Miocene, respectively. Source data are provided as a Source Data file.



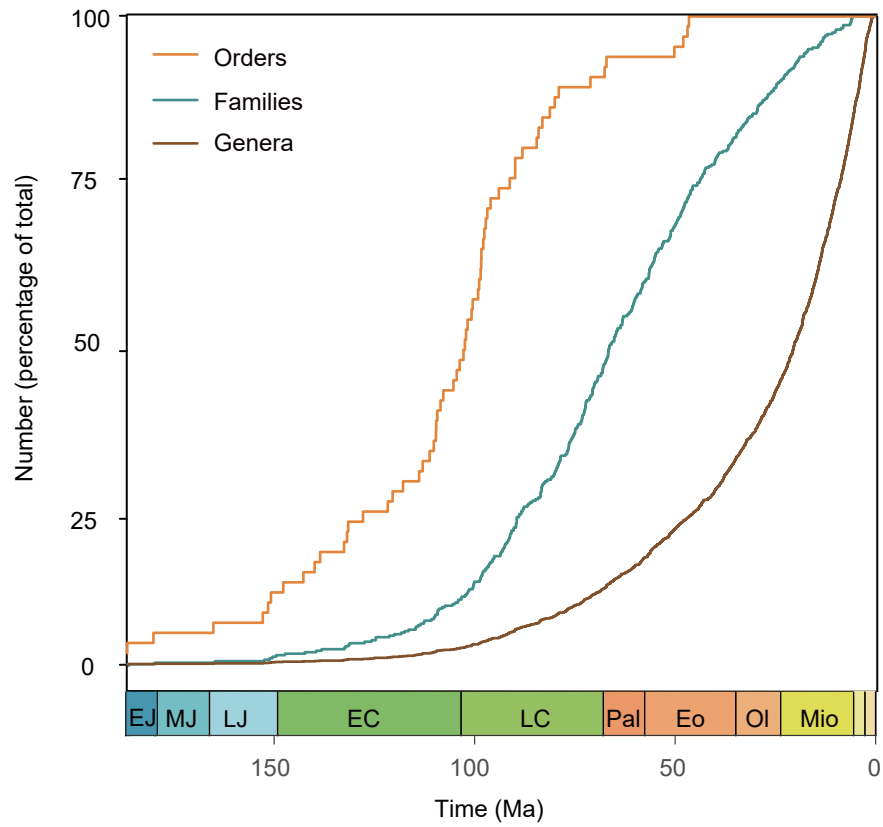
Supplementary Figure 13. Correlation of pollen disparity and other factors. (a) Relationship between pollen morphological dissimilarity (MORD distance) and pairwise differences in species richness among genera. (b) Relationship between pollen morphological dissimilarity (MORD distance) and pairwise differences in genome size among genera. (c) Correlations between within-group pollen disparity (sum of variances, SOV) and species richness across 12 angiosperm groups, based on both NMDS- and PCoA-derived ordinations. Correlation coefficients (r) are shown in each panel. ANA, ANA grade; CHLO, Chloranthales; MAG, magnoliids; MONO, monocots; EUD, eudicots; COMM, commelinids; CAM, campanulids; FAB, fabids; LAM, lamiids; MAV, malvids; OthE, other eudicots; OthM, other monocots; OtSA, other superasterids; OtSR, other superrosids. Source data are provided as a Source Data file.



Supplementary Figure 14. Pollen morphospace occupation and disparity across pollination types based on NMDS ordination. (a) NMDS morphospaces for angiosperms grouped by broad pollination mode (abiotic: $n = 84$; biotic: $n = 624$) and by specific pollination v mode (wind: $n = 77$; water: $n = 5$; insect: $n = 548$; vertebrate: $n = 29$). Points represent genera, and background grey points indicate all angiosperms for reference. (b) NMDS-based pollen disparity (sum of variances, SOV) based on 1,000 bootstrap replicates for each pollination category. Boxplots show the median, interquartile range, and $1.5 \times \text{IQR}$ whiskers; outliers are shown as points. Source data are provided as a Source Data file.



Supplementary Figure 15. Pollen morphospace occupation and disparity across pollination types based on PCoA ordination. (a) NMDS morphospaces for angiosperms grouped by broad pollination mode (abiotic: $n = 84$; biotic: $n = 624$) and by specific pollination mode (wind: $n = 77$; water: $n = 5$; insect: $n = 548$; vertebrate: $n = 29$). Points represent genera, and background grey points indicate all angiosperms for reference. (b) PCoA-based pollen disparity (sum of variances, SOV) based on 1,000 bootstrap replicates for each pollination category. Boxplots show the median, interquartile range, and $1.5 \times \text{IQR}$ whiskers; outliers are shown as points. Source data are provided as a Source Data file.



Supplementary Figure 16. Cumulative proportion of genera, families and orders that have originated through time. EJ, MJ and LJ stand for Early, Mid- and Late Jurassic; EC and LC for Early and Late Cretaceous; Pal, Eo and Ol for three Epochs of Paleogene, i.e., Paleocene, Eocene and Oligocene; Mio stands for Miocene, respectively.

Supplementary References

1. Li H.-T., *et al.* Origin of angiosperms and the puzzle of the Jurassic gap. *Nat Plants* **5**, 461-470 (2019).
2. Zuntini A. R., *et al.* Phylogenomics and the rise of the angiosperms. *Nature* **629**, 843-850 (2024).
3. Ramírez-Barahona S., Sauquet H., Magallón S. The delayed and geographically heterogeneous diversification of flowering plant families. *Nat Ecol Evol* **4**, 1232-1238 (2020).