

Wenchao Shu, Jinnan Tong, Jianxin Yu, Jason Hilton, Michael J. Benton, Xiao Shi, José B. Diez, Paul B. Wignall, Daoliang Chu, Li Tian, Zhixing Yi, and Yongdong Mao, 2022, Permian–Middle Triassic floral succession in North China and implications for the great transition of continental ecosystems: GSA Bulletin, <https://doi.org/10.1130/B36316.1>.

Supplemental Material

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S1. STUDY SECTIONS IN NORTH CHINA

Liulin section

The Liulin section is situated in Liulin county, Shanxi province. The Permian to Triassic succession comprises the Upper Shihhotse, Sunjiagou, Liujiagou and Heshanggou formations. The upper part of the Upper Shihhotse Formation consists of green thick-bedded sandstone interbedded with varicolored (dark-red, purple, gray, green and yellow) mudstones and siltstones. The gray mudstone of the Upper Shihhotse Formation yield plants fossils (Fig. S1B). At the section the Sunjiagou Formation is subdivided into three parts. The lower part is dominated by green strata: thin-bedded sandstones, a conglomerate bed and mudstones, and occasional some red beds of siltstones intercalated. Plant fossils associated with conchostracans (Fig. 9H–J) (Fig. S2) are found in the grayish green mudstone beds and coalified woods in the conglomerate beds (Fig. S1E). The middle part consists of red siltstone, a green thick sandstone bed and some poorly developed caliche nodules. The upper part is dominated by red siltstone interbedded with thin sandstone and one more-or-less continuous thin, caliche conglomeratic bed. At this section, two fossil plant assemblages are identified, one in the uppermost Upper Shihhotse Formation and the other in the lower part of the Sunjiagou Formation.

Peijiashan section

The Peijiashan section is in Jiaocheng county, Shanxi Province. The upper part of the Sunjiagou Formation is dominated by red mudstone and very fine sandstone, and occasionally freshwater limestone lenses at the top. The Liujiagou Formation is dominated by red sandstones with some green sandstones in the middle part and interbedded with red mudstones. Plant fossils are found in sandstones in the middle–upper part (Fig. S1H).

Dayulin section

The Dayulin section locates at the Dayulin village, Yiyang county, Henan Province and outcrops an excellent Permian to Triassic terrestrial successions. The uppermost part of the Upper Shihhotse Formation is dominated by well-developed grayish white quartz sandstones, called the ‘Pingdingshan Sandstone Member’ in region. The Sunjiagou Formation can also be subdivided into three parts. The lower part is dominated by grayish green sandstones interbedded with grayish green mudstones bearing rich plant fossils associated with conchostracans (Figs. S1F, 9K) (Fig. S2), sometimes with thin red beds at the top. The middle part begins with a calcareous nodule bed, dominated by red siltstones with occasional lightly grayish green sandstones and pebbly sandstones. The upper part is marked by the rhythmic beds composed of thin calcareous sandstones and thin red mudstones (Fig. S1F). The overlying is the Liujiagou Formation comprising of red sandstones. The Heshanggou Formation mostly comprises of red siltstones with rich calcareous nodules and is interbedded with thin red sandstones, occasionally with some grayish green sandstones in the middle–upper part, the latter bearing plant fossils.

Shichuanhe section

The Shichuanhe section in Tongchuan city, Shaanxi province is also a well-exposed terrestrial Permian–Triassic succession but with some marine flooding beds (Figs. S1A, D). The upper part of the Upper Shihhotse Formation is dominated by thick, greyish green and yellow sandstones interbedded with green or red mud-siltstones. Some plant fossils and one tetrapod tooth were found in the green siltstones (Figs. S1C, 9A–D). The Sunjiagou Formation comprises of red mudstone and siltstones with calcareous nodules in the lower part, and some marine beds containing marine bivalves, lingulids, microconchids, conchostracans, insects and sporomorphs

in the middle part (Fig. 9E–F, L–N) (Chu et al., 2019) (Fig. S2) and red mudstones interbedded with red thin-bedded sandstones in the upper part. The Liujiagou Formation is dominated by red sandstones with some simple trace fossils such as *Skolithos* and *Palaeophycus* (Guo et al., 2019). The Heshanggou Formation is dominated by red mud-siltstones interbedded with red sandstones, abundant calcareous nodules and rich trace fossils, including limuloid trackways (Fig. 4; Shu et al., 2018). The lowermost part of the Heshanggou Formation yield *in-situ* plant fossils in red siltstones and very fine sandstones (Fig. S1I).

Zishiya section

The Zishiya section at the Zishiya village, Linyou county, Shaanxi province is another section bearing two marine horizons. Here, the Qishan Formation (term always used in this region) is equivalent to the Liujiagou Formation. The uppermost Upper Shihhotse Formation is dominated by gray-green or yellow sandstones. The lower part of the Sunjiagou Formation (Fig. S1G) is characterized by gray or black-gray mudstones with rich plant fossils associated with some marine bivalves (Fig. 9O–Q), conchostracans and rich sporomorphs (Fig. S2). The middle part is dominated by red silty mudstone, sometimes with common calcareous nodules. The upper part comprises of sandstones and mud-siltstones forming rhythmic beds. The overlying is the Qishan Formation (a local name for the Liujiagou Formation) comprises of dark-gray mudstones with marine bivalves (Fig. 9S–T), ophiuroids (Fig. 9G), conchostracans (Fig. 9R) and sporomorphs.

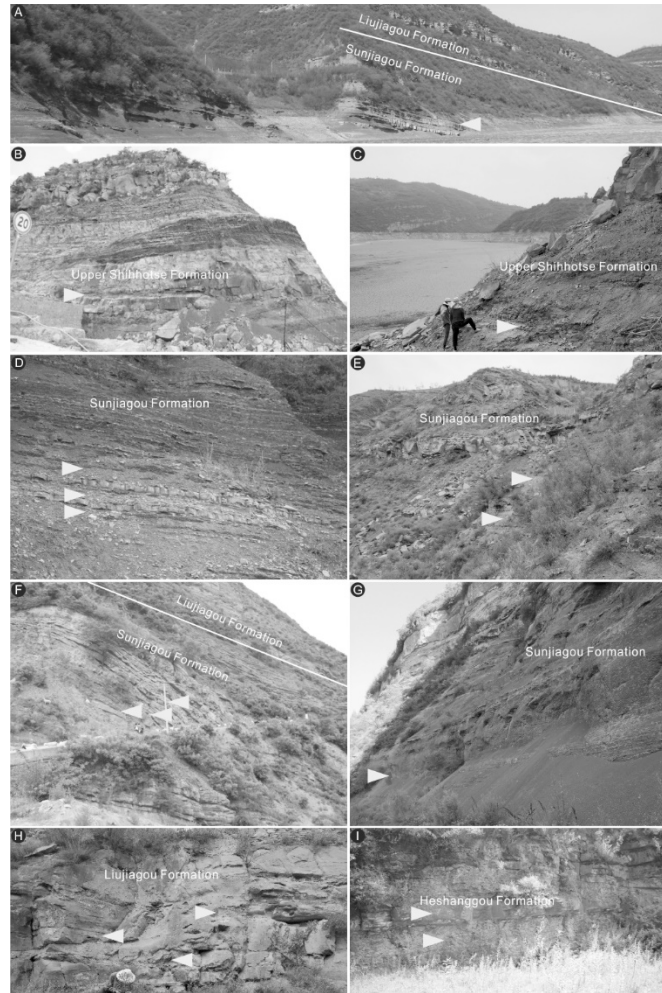


Figure S1. Field photographs of the studied sections. A. the Shichuanhe section showing the Sunjiagou and Liujiagou formations; triangular arrow indicates horizon of mixed biota fossils. B. the Liulin section showing the Upper Shihhotse Formation; triangular arrow marks horizon of fossil plants. C. the Shichuanhe section showing the Upper Shihhotse Formation; triangular arrow marks horizon of fossil plants and one vertebrate tooth fossil. D. the Shichuanhe section showing the horizon of mixed biota fossils; triangular arrow marks palynological samples with rich sporomorph fossils. E. the Liulin section showing the Sunjiagou Formation; triangular arrow marks horizon of fossil plants, wood and conchostracans. F. the Dayulin section showing the Sunjiagou Formation and Liujiagou Formation; triangular arrow indicates horizon of fossil plants and conchostracans. G. the Zishiya section showing the Sunjiagou Formation; triangular arrow indicates horizon of fossil plants, wood, conchostracans and bivalves. H. the Peijiashan section showing the Liujiagou Formation; triangular arrow indicates horizon of fossil plants. I. Field photograph of the Shichuanhe section showing the Heshangou Formation; triangular arrow indicates horizon of fossil plants.

Age	Stage	Fms	Plants	Sporomorphs	Tetrapods	Conchostracans	Ostracodes
Middle Triassic	Anisian	LUEMY	Lepacycloles-Voltzia flora	Punctatisporites-Chordasporites	Sinokanneyia	Brachyestheria-Xiangxiella	Lutkevichinella
		bEMY		Lundbladispora-Verrucosporites-Lunatisporites	Shaanbeikameyeria	Magniestheria-Eosolimnadia	minuta-Shensinella
Early Triassic	Olenekian	MUHSG	Pleuromela-Tongchuanophyllum flora		Capitosauridae	Cornia-Estherella	Darwinula triassiana-Darwinula fengtengensis-Darwinula rotundata
		LHSG				Leptolimnadia-Paleoleptestheria	
		bHSG	Pleuromela-Neocalamites flora	Densosporites			
		ULJG		Aratrisporites-neiburgii-Lunatisporites-Cycadopites			
Lopingian	Changhsingian	LLJG			few Dicynodon		
		USJG					
		LMSJG	ginkgoephyte-Walchian-voltzian Voltziales subflora	Patellispores Lueckispores	pareiasaur-dominated fauna	Euestheria	Darwinula-Panxiania
		tUSHZ	voltziales subflora	meishanensis-virkkiae-J. schaubergeroides	Jiyuan fauna	Pseud-estheria-Palaeolimnadiopsis	

Figure S2. The integrated biostratigraphy of Lopingian–Middle Triassic in North China. Fms–formations; tUSHZ–top part of Upper Shihhotse Formation (= Pingdingshan Sandstone); LMSJG–Lower and middle Sunjiagou Formation; USJG–Upper Sunjiagou Formation; LLJG–the lower part of Liujiagou Formation; MULJG–Middle and upper part of Liujiagou Formation; bHSG–basal part of Heshanggou Formation; LHSG–lower part of Heshanggou Formation; MUHSG–middle and upper part of Heshanggou Formation; bEMY–basal part of Ermaying Formation; LUEMY–lower and upper part of Ermaying Formation; Asse., Assemblage.

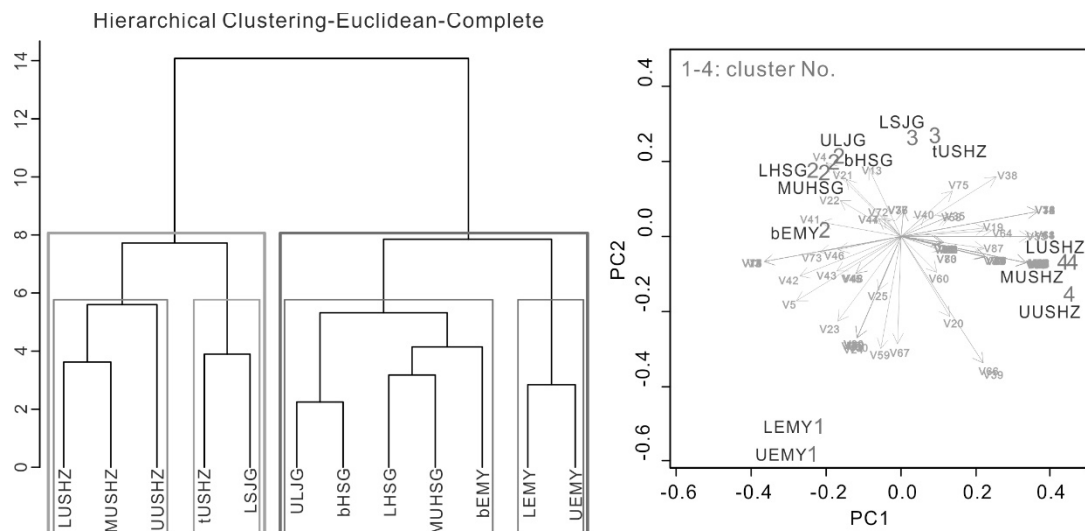


Figure S3. Hierarchical clustering using Euclidean complete methods and PCA plot for viewing result.

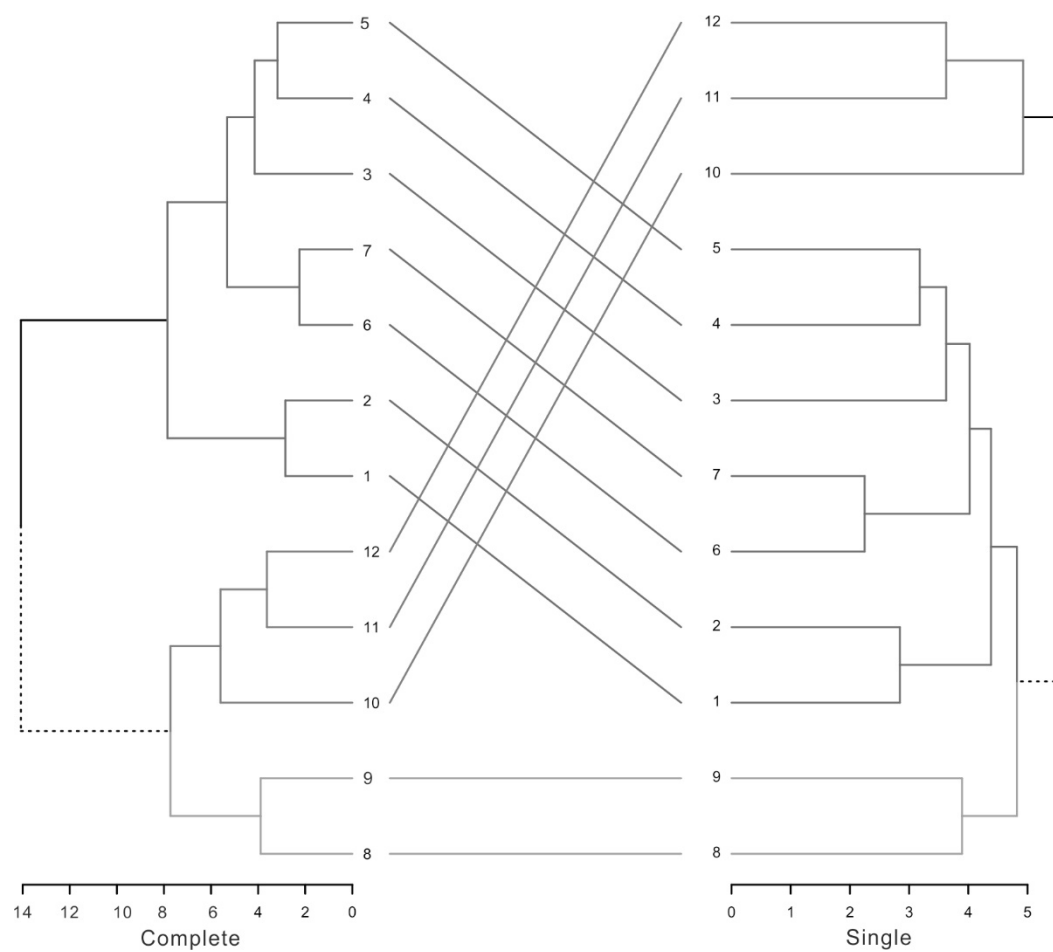


Figure S4. Comparison of the hierarchical clustering Euclidean single and complete methods, 1-UEMY, 2-LEMV, 3-bEMY, 4-MUHSG, 5-LHSG, 6-bHSG, 7-ULJG, 8-LSJG, 9-tUSHZ, 10-UUSHZ, 11-MUSHZ, 12-LUSHZ.

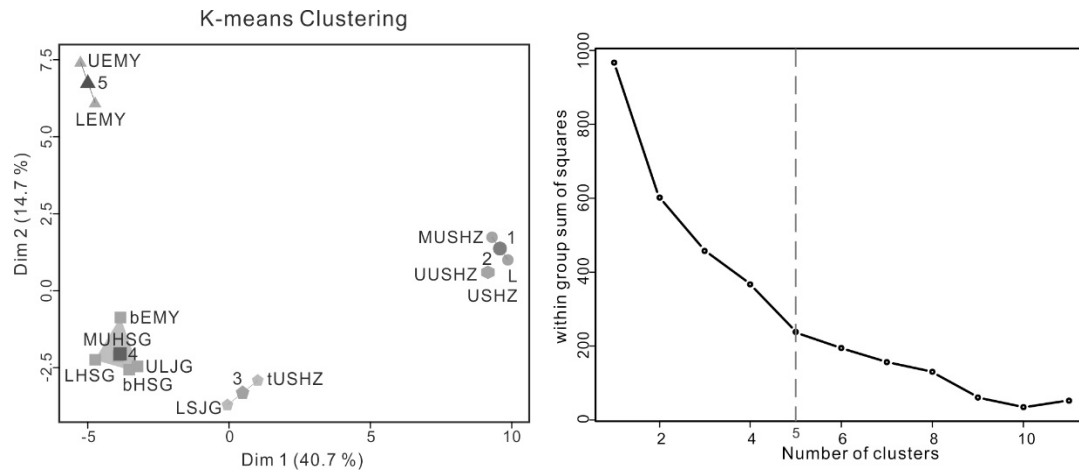


Figure S5. The *k*-means clustering with the WGSS screen plot.

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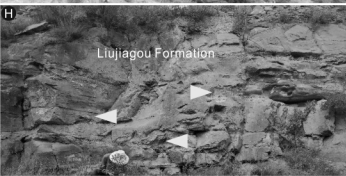
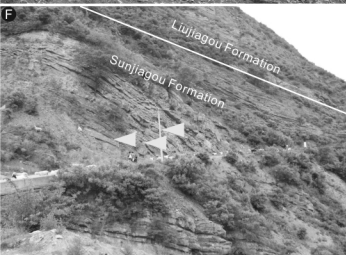
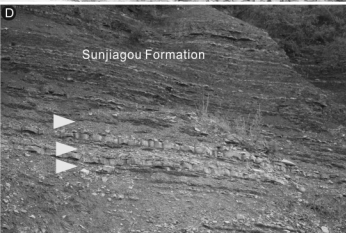
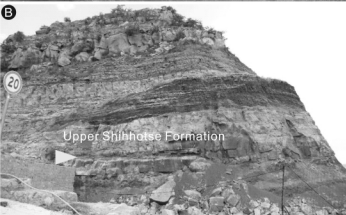
```
##Hierarchical clustering euclidean complete method##
library(tidyverse)
library(cluster)
library(dendextend)
library(ggplot2)
library(factoextra)
data<-read.csv("D:/2019-
NorthChinaFossilplants/2020NCnPAPER1/version5/R_Hierarchical&KmeansClustering/R_NorthChinaFloralChangesClustering
.csv")
data
head()
df<-na.omit(data)
df<-round(scale(df),3)
head(df)
dist_df<-dist(data, method='euclidean')
hier_clust<-hclust(dist_df, method='complete')
plot(hier_clust, cex=1, hang=-1)
rect.hclust(hier_clust, k=2, border=2:5)
rect.hclust(hier_clust, k=4, border=2:5)
##PCA analysis for visual result of clustering##
data1<-read.table("RNCFlora.txt")
data_pc<-prcomp(data1)
summary(data_pc)
biplot(prcomp(data1))
screplot(prcomp(data1), npc=8, type="lines")
lab<-cutree(hier_clust, h=6)
lab
##use dendextend to compare different euclidean clustering methods (single and complete)##
df<-na.omit(data)
df<-round(scale(df),3)
head(df)
dist_df<-dist(df, method='euclidean')
hc1<-hclust(dist_df, method='complete')
hc2<-hclust(dist_df, method='single')
dend1<-as.dendrogram(hc1)
dend2<-as.dendrogram(hc2)
tanglegram(dend1, dend2,
  color_lines=2,
  lwd=2,
  edge.lwd=1,
  lab.cex=1,
  margin_inner=8,
  main_left = "complete",
  main_right = "single",
  highlight_distinct_edges=T,
  common_subtrees_color_lines=F,
  common_subtrees_color_branches=T)
##k-means clustering method##
library(tidyverse)
library(cluster)
library(dendextend)
library(ggplot2)
library(factoextra)
data1<-read.table("RNCFlora.txt")
df<-na.omit(data1)
df<-round(scale(df),3)
head(df)
##WGSS screen plot for the number of clusters##
n<-nrow(df)
wgss<-rep(0,11)
for(i in 1:11) {wgss[i]<-sum(kmeans(df, centers=i)$withinss)}
```



```
plot(1:11, wgss, type="b", xlab="Number of clusters",ylab="within group sum of squares")
##plot k-means clustering##
km_clust<-kmeans(df, centers=5, nstart=30)
fviz_cluster(km_clust,data=df)
```

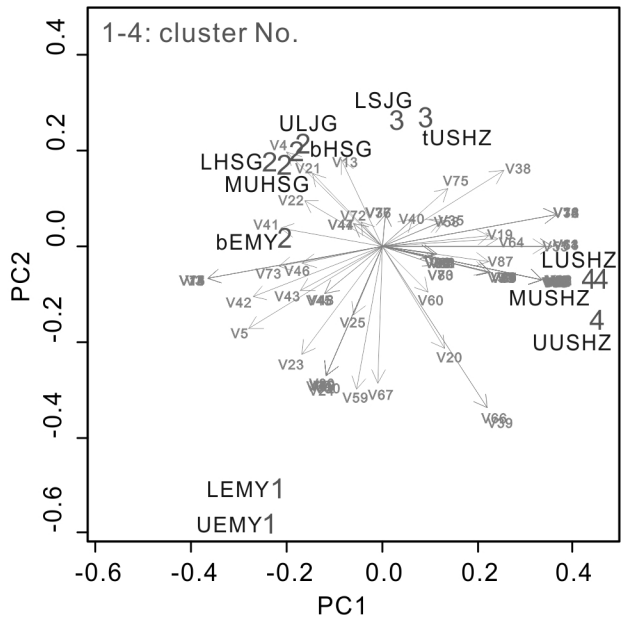
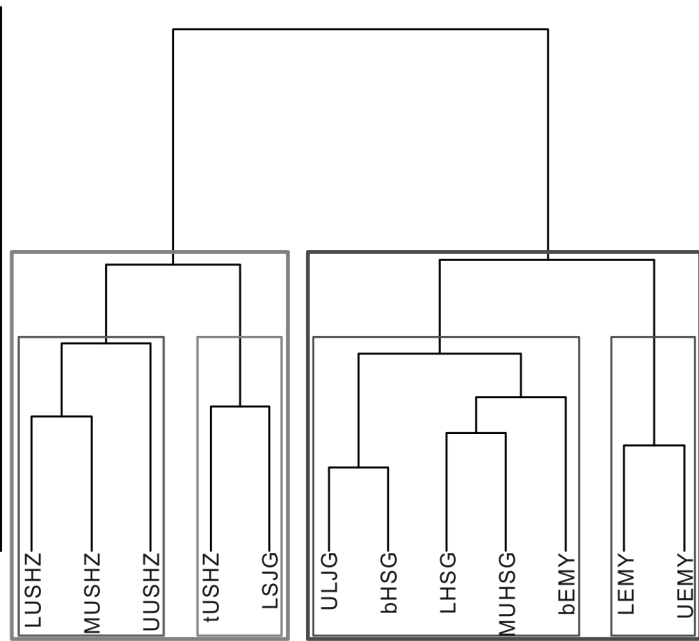
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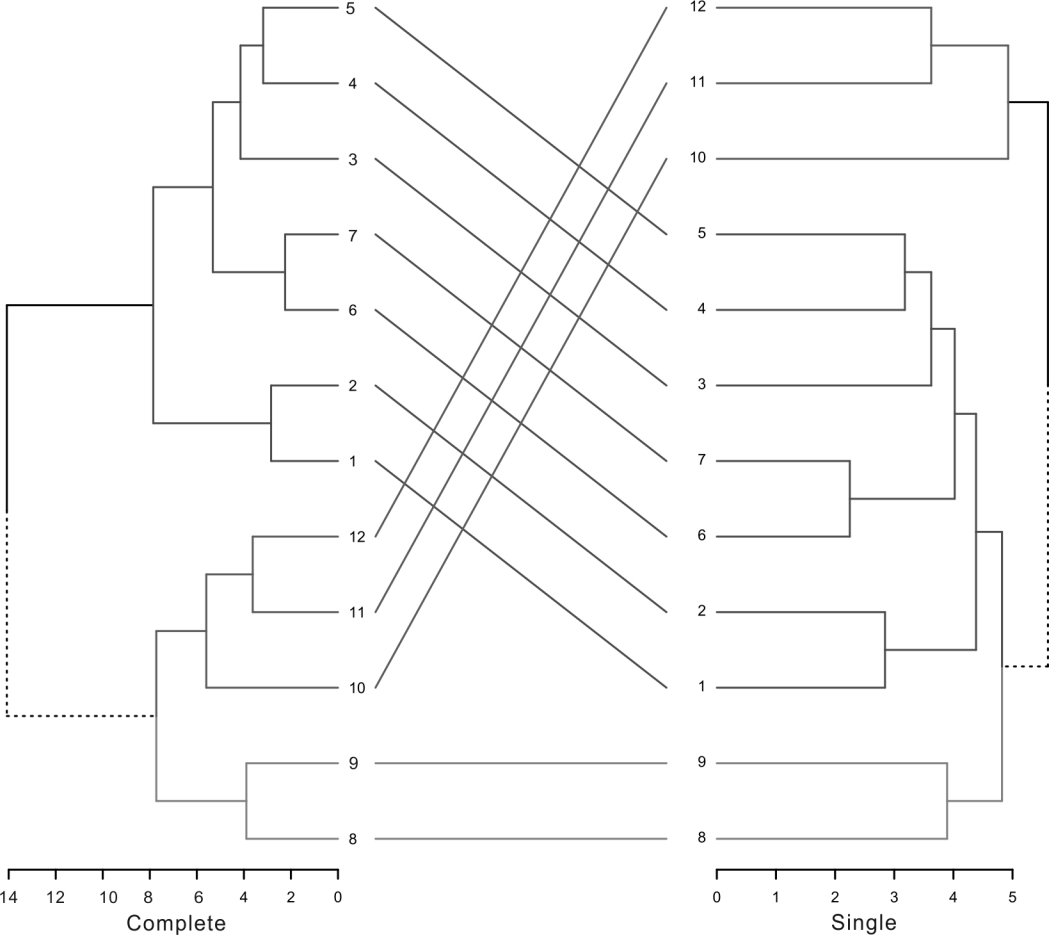
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Age		Stage		Fms		Plants		Sporomorphs		Tetrapods		Conchostracans		Ostracodes			
Middle Triassic		Early Triassic		Anisian		LUEMY		Lepacycloles-Voltzia flora		Punctatisporites-Chorda-sporites		Sinokanneyia-Shansidon		Brachyestheria-Xiangxiella		Lutkevichinella minima-Shensinella gaoyadiensis-Darwinula subovaliformis	
Early Triassic		Olenekian		bEMY		MUHSG		Pleuromeia-Tongchuanophyllum flora		Lundbladispora-Verrucosisporites-Lunatisporites		Capitosauridae-Xilousuchus-Hazhenia		Magniestheria-Eosolimnadia		Darwinula triassiana-Darwinula fengfengensis-Darwinula rotundata	
Induan		LHSG		LLJG		ULJG		Densoisporites-neiburgii-Lunatisporites-Cycadopites		Aratrisporites-Alisporites		few Dicynodon		Leptolimnadia-Paleoleptestheria		Lutkevichinella minima-Shensinella gaoyadiensis-Darwinula subovaliformis	
Lopingian		Changhsingian		USJG		Pleuromeia-Neocalamites flora		Aratrisporites-Alisporites		few Dicynodon		Leptolimnadia-Paleoleptestheria		Lutkevichinella minima-Shensinella gaoyadiensis-Darwinula subovaliformis			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
tUSHZ		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
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Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
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Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
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Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Lopingian		Changhsingian		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
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Wuchiapingian		LMSJG		USJG		ginkgophyte-Walchian voltziales subflora		Patellispores Lueckispores meishanensis virrkiae-J. schaubergeroides		Jiyuan fauna		Pseud-estheria		Darwinula-Panxiania			
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Hierarchical Clustering-Euclidean-Complete





K-means Clustering

