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

S1. STUDY SECTIONS IN NORTH CHINA.

Figure S1. Field photographs of the studied sections.

Figure S2. Integrated biostratigraphy of Lopingian–Middle Triassic in North China.

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.

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

R SCRIPTS.

REFERENCES CITED

Supplementary Data Files

1. Geological distributions of fossil plants, sporomorphs and fossil woods

2. Detailed descriptions of the Voltziales, the *Pleuromeia–Neocalamites*, the *Pleuromeia–Tongchuanophyllum* and the *Lepacyclotes–Voltzia* floras in North China

3. Plant genera distributions and number of genera in each stratigraphic unit

4. Plant zones, subzones and assemblages from Cisuralian to Anisian in North China

5. Invertebrate genera distributions and number of genera in each stratigraphic unit

6. Insect genera distributions and number of genera in each stratigraphic unit

7. Vertebrate genera distributions and number of genera in each stratigraphic unit

8. Global floral changes from Lopingian to Middle Triassic

9. Hygrophyte, mesophytes and xerophyte element distributions

10. Hygrophte and Xerophyte ratios.

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.

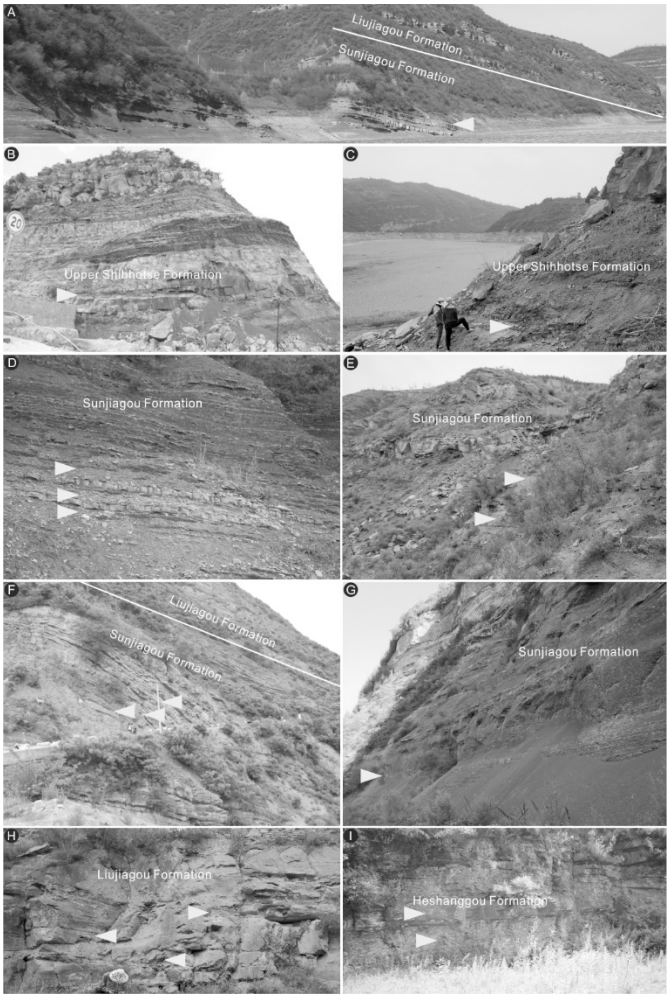


Figure S1. Field photographs of the studied sections. A. the Shichuanhe section showing the Sunjiagou and Liujiagou formations; triangular arrow indicates horizon of mixed biota fossils. B. the Liulin section showing the Upper Shihhotse Formation; triangular arrow marks horizon of fossil plants. C. the 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 offossil 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 Heshanggou Formation; triangular arrow indicates horizon of fossil plants.

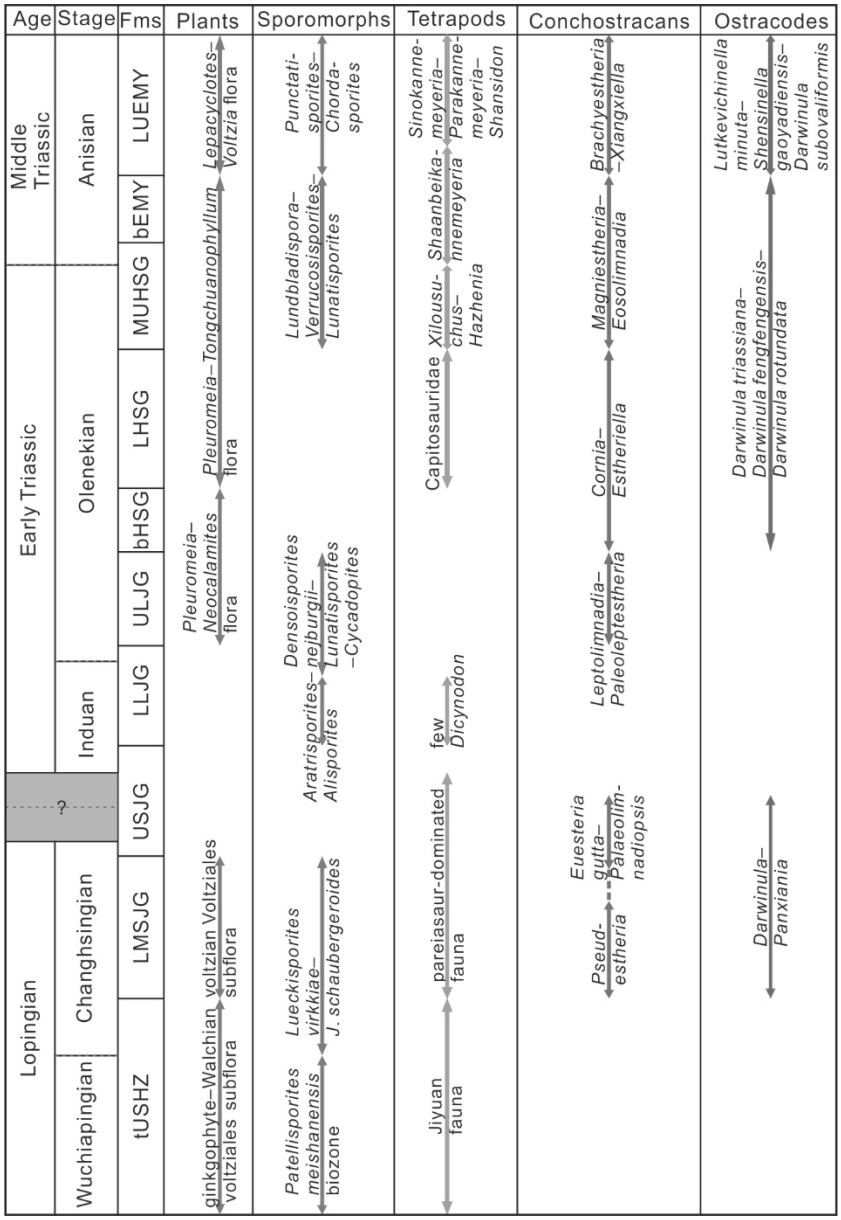


Figure S2. The integrated biostratigraphy of Lopingian—Middle Triassic in North China. Fms–formations; tUSHZ–top part of Upper Shihhotse Formation (= Pingdingshan Sandstone); LMSJG–Lower and middle Sunjiagou Formation; USJG–Upper Sunjiagou Formation; LLJG–the lower part of Liujiagou Formation; MULJG–Middle 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.

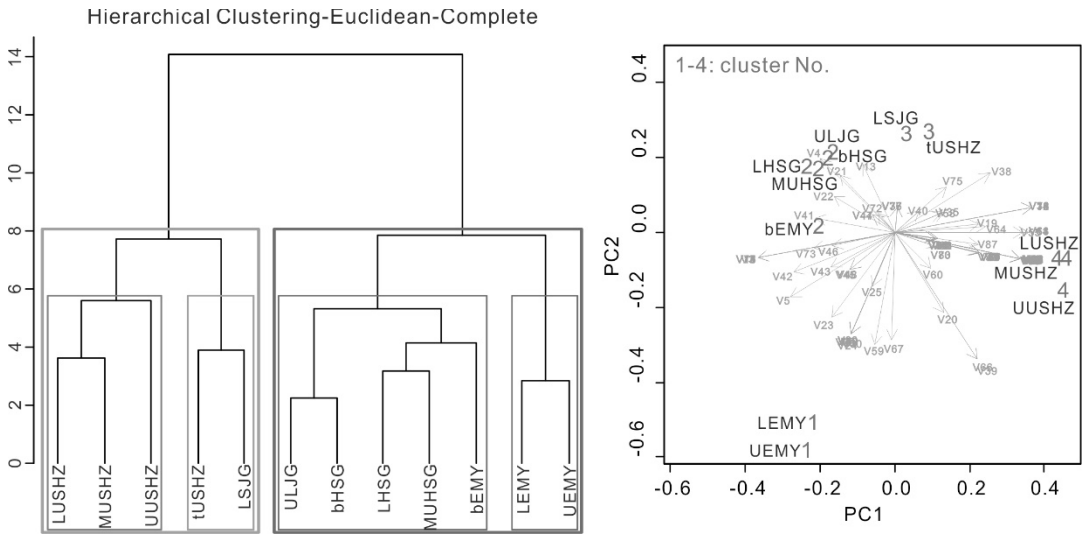


Figure S3. Hierarchical clustering using Euclidean complete methods and PCA plot for viewing result.

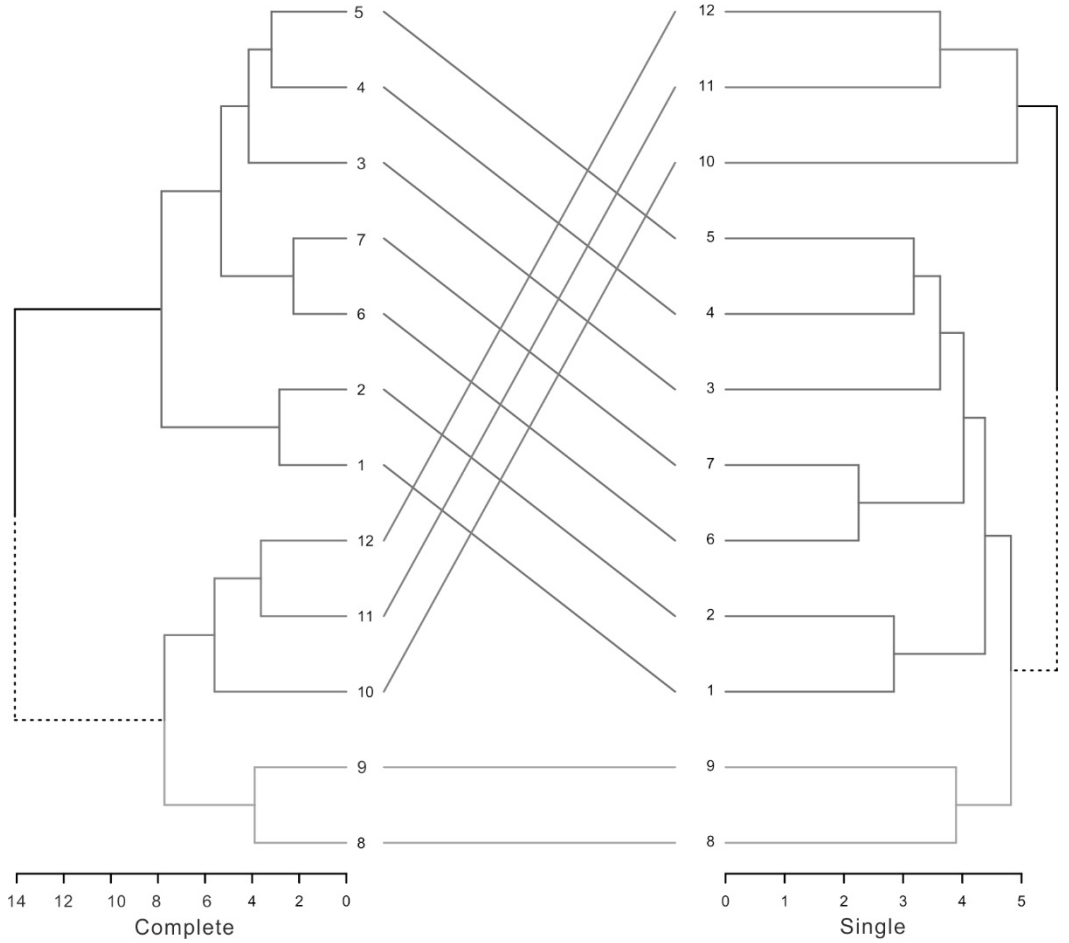


Figure S4. Comparison of the hierarchical clustering Euclidean single and complete methods, 1–UEMY, 2–LEMY, 3–bEMY, 4–MUHSG, 5–LHSG, 6–bHSG, 7–ULJG, 8–LSJG, 9–tUSHZ, 10–UUSHZ, 11–MUSHZ, 12–LUSHZ.

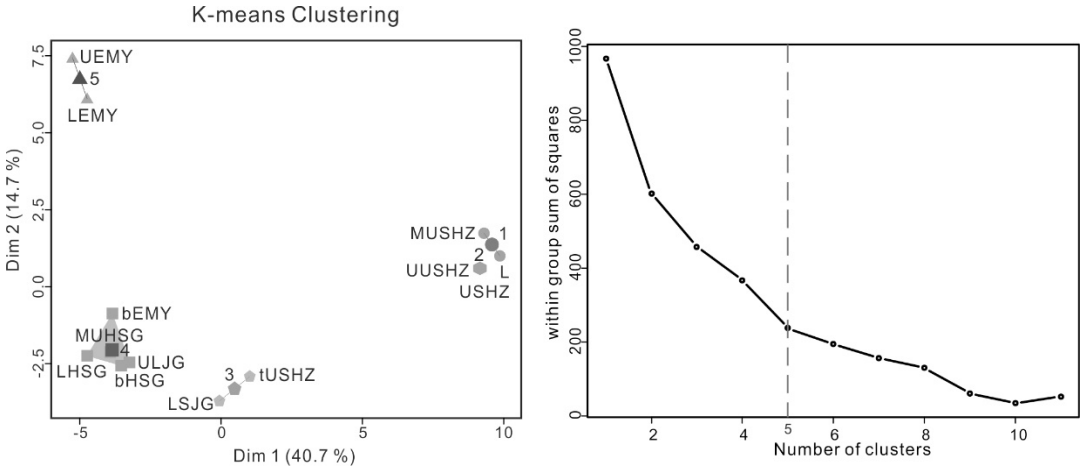


Figure S5. The *k*-means clustering with the WGSS screen plot.

R SCRIPTS

```
##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))
screeplot(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)}
```

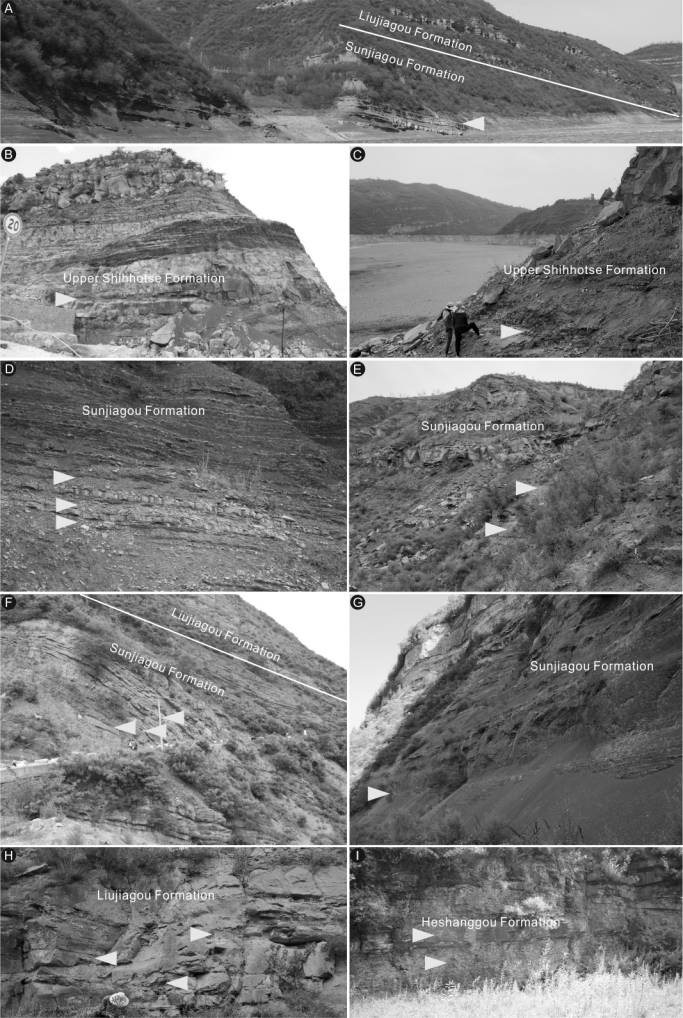
```
plot(1:11, wgss, type="b", xlab="Number of clusters",ylab="within group sum of squares")
##plot k-means clustering"##
km_clust<-kmeans(df, centers=5, nstart=30)
fviz_cluster(km_clust,data=df)
```

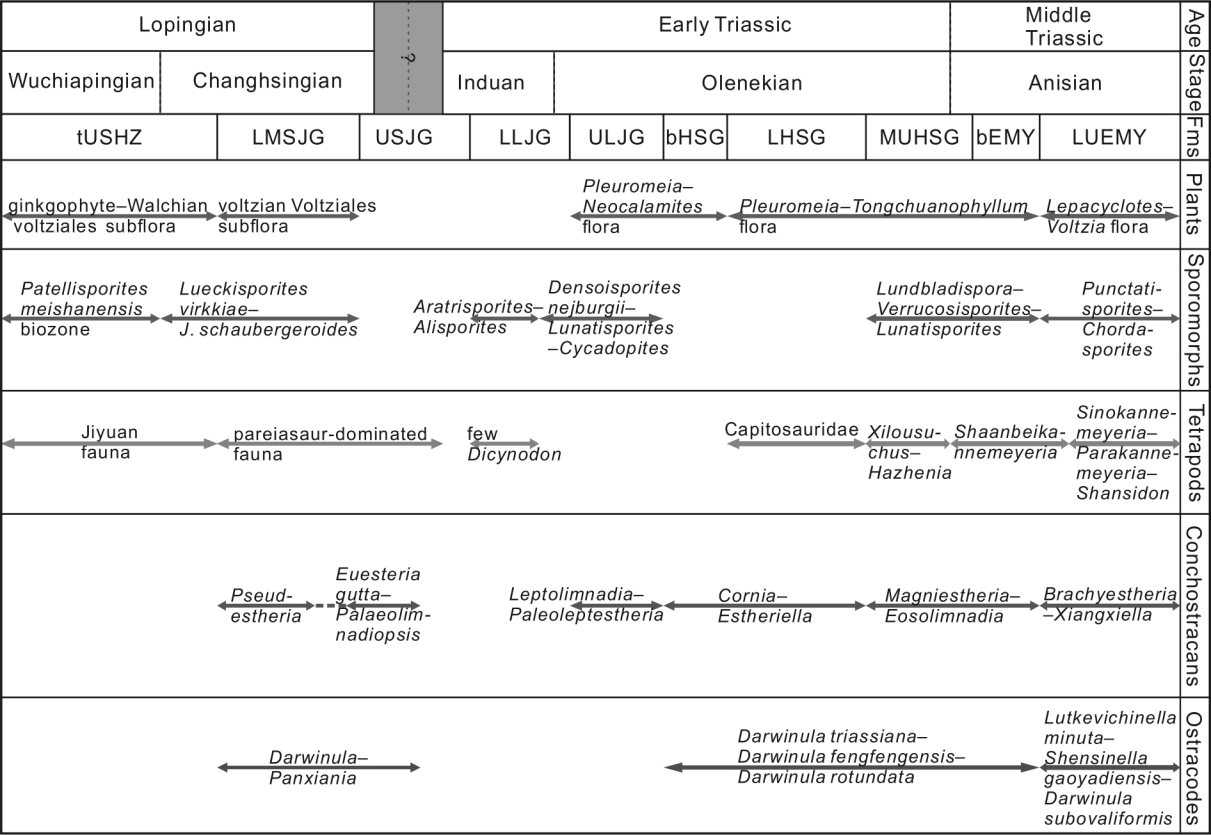
REFERENCES CITED

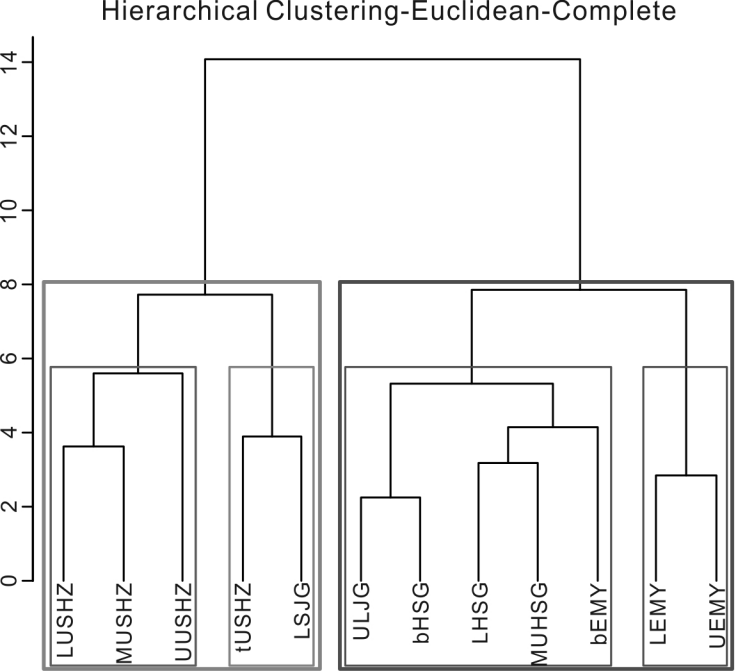
Chu, D., Tong, J., Benton, M.J., Yu, J. and Huang, Y., 2019. Mixed continental-marine biotas following the Permian-Triassic mass extinction in South and North China. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 519, p. 95–107.

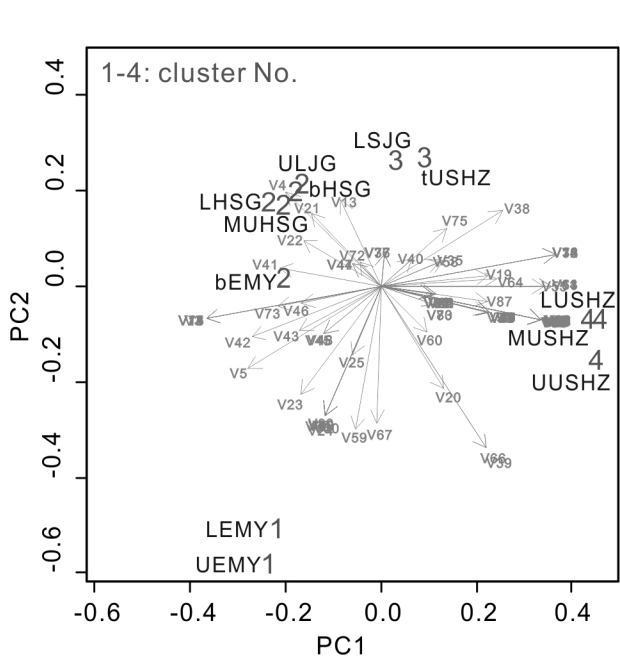
Guo, W.W., Tong, J.N., Tian, L., Chu, D.L., Bottjer, D.J., Shu, W.C., and Ji, K.X., 2019, Secular variations of ichnofossils from the terrestrial Late Permian–Middle Triassic succession at the Shichuanhe section in Shaanxi Province, North China. Global and Planetary Change, v. 181, p. 102978.

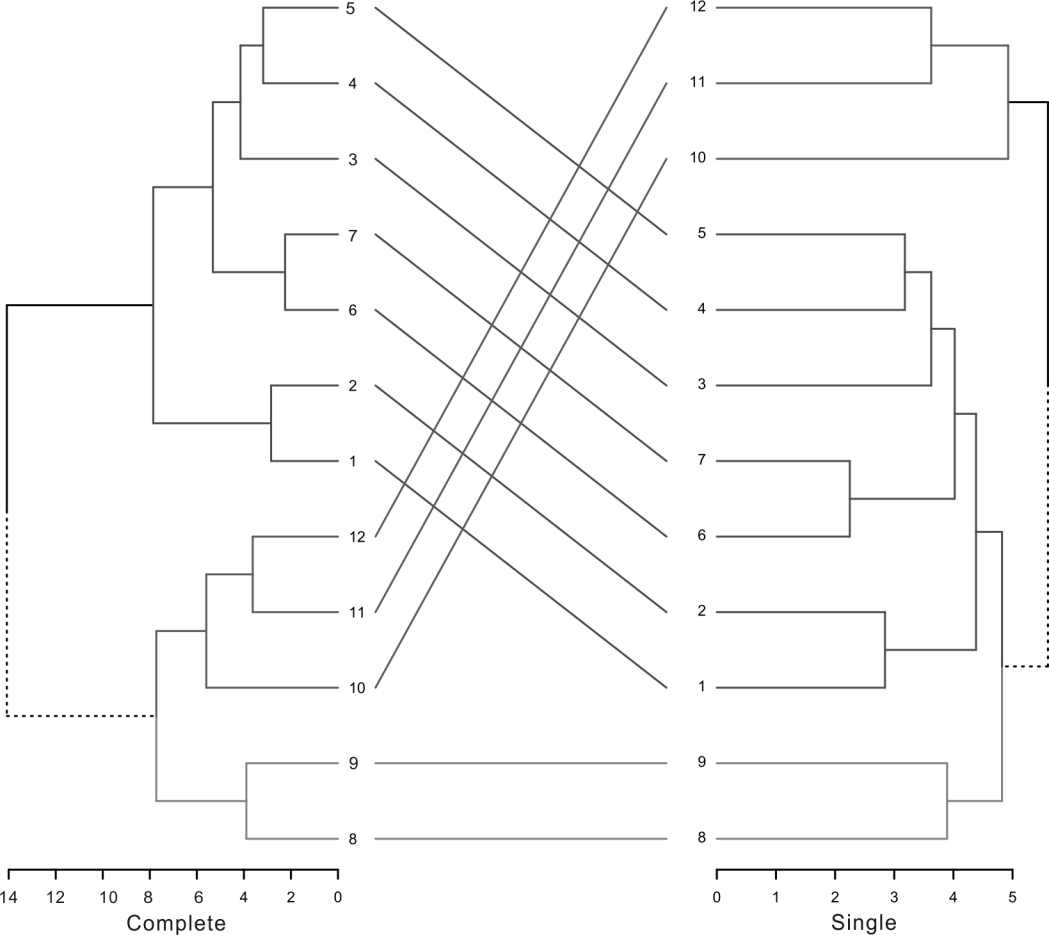
Shu, W.C., Tong, J.N., Tian, L., Benton, M.J., Chu, D.L., Yu, J.X., and Guo, W.W., 2018, Limuloid trackways from Permian-Triassic continental successions of North China. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 508, p. 71–90.

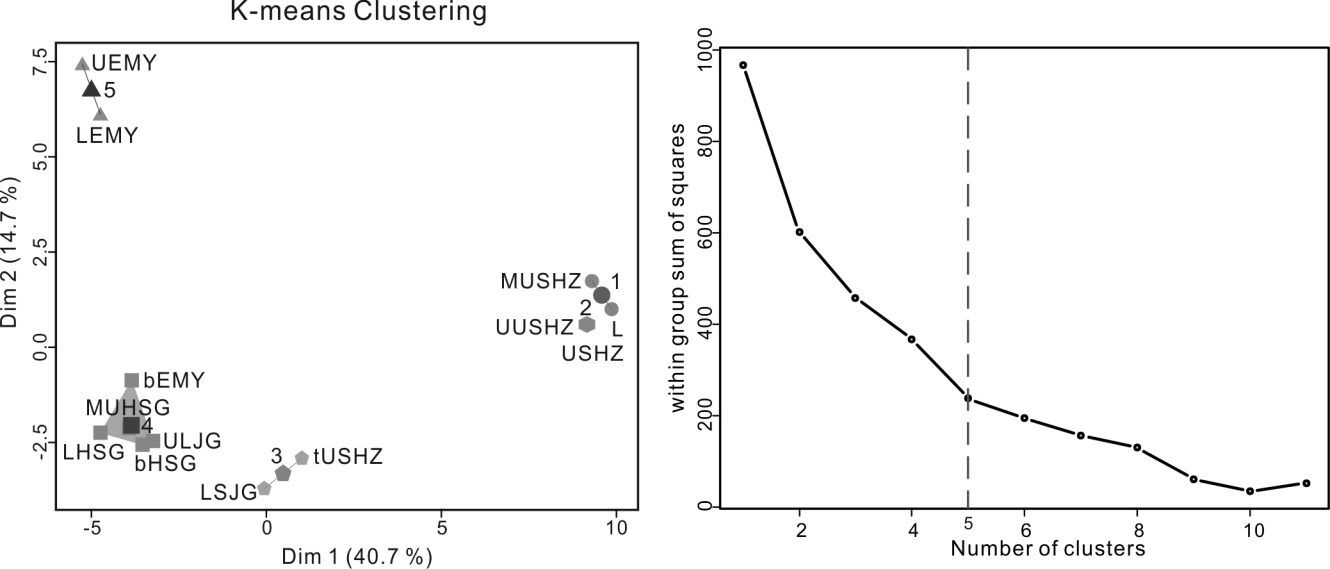

A
Liujiagou Formation
Sunjiagou Formation
B
20
Upper Shihhotse Formation
C
Upper Shihhotse Formation
D
Sunjiagou Formation
E
Sunjiagou Formation
F
Liujiagou Formation
Sunjiagou Formation
G
Sunjiagou Formation
H
Liujiagou Formation
I
Heshanggou Formation


Lopingian
?
Early Triassic
Middle Triassic
Age
Wuchiapingian
Changhsingian
Induan
Olenekian
Anisian
Stage
tUSHZ
LMSJG
USJG
LLJG
ULJG
bHSG
LHSG
MUHSG
bEMY
LUEMY
Fms
ginkgophyte–Walchian voltzialesubflora
voltzian Voltziales subflora
Pleuromeia–Neocalamites flora
Pleuromeia–Tongchuanophyllum flora
Lepacyclotes–Voltzia flora
Plants
Patellisporites meishanensis biozone
Lueckisporites virkkiae–J. schaubergeroides
Aratrisporites–Alisporites
Densoisporites nejburgii–Lunatisporites–Cycadopites
Lundbladispora–Verrucosisporites–Lunatisporites
Punctati-sporites–Chorda-sporites
Sporomorphs
Jiyuan fauna
pareiasaur-dominated fauna
few Dicynodon
Capitosauridae
Xilousu-chus–Hazhenia
Shaanbeika-hnemeyeria
Sinokanne-meyeria–Parakanne-meyeria–Shansidon
Tetrapods
Pseud-estheria
Euesteria gutta–Palaeolim-nadiopsis
Leptolimnadia–Paleoleptestheria
Cornia–Estheriella
Magniestheria–Eosolimnadia
Brachyestheria–Xiangxiella
Conchostracans
Darwinula–Panxiania
Darwinula triassiana–Darwinula fengfengensis–Darwinula rotundata
Lutkevichinella minuta–Shensinella gaoyadiensis–Darwinula subovaliformis
Ostracodes


Hierarchical Clustering-Euclidean-Complete
0
2
4
6
8
10
12
14
LUSHZ
MUSHZ
UUSHZ
tUSHZ
LSJG
ULJG
bHSG
LHSG
MUHSG
bEMY
LEMY
UEMY


1-4: cluster No.
LSJG
3
3
ULJG
2
tUSHZ
bHSG
LHSG
2
2
MUHSG
bEMY
2
LUSHZ
44
MUSHZ
4
UUSHZ
LEMY
1
UEMY
1
PC1
PC2
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.6
-0.4
-0.2
0.0
0.2
0.4


5
4
3
7
6
2
1
12
11
10
9
8
14 12 10 8 6 4 2 0
Complete
12
11
10
5
4
3
7
6
2
1
9
8
0 1 2 3 4 5
Single


K-means Clustering
UEMY
5
LEMY
MUSHZ
1
2
UUSHZ
L
USHZ
bEMY
MUHSG
4
LHSG
bHSG
ULJG
3
tUSHZ
LSJG
Dim 2 (14.7 %)
Dim 1 (40.7 %)
7.5
5.0
2.5
0.0
-2.5
-5
0
5
10
within group sum of squares
Number of clusters
1000
800
600
400
200
0
2
4
5
6
8
10