Cretaceous Research 30 (2009) 424–428

Contents lists available at ScienceDirect

Cretaceous Research

journal homepage: www.elsevier.com/locate/CretRes

High resolution estimates of paleo-CO_2 levels through the Campanian (Late Cretaceous) based on *Ginkgo* cuticles

Cheng Quan[a,b,*], Chunlin Sun[a,b], Yuewu Sun[a,b], Ge Sun[a,b,*]

[a] Key-Lab for Evolution of Past Life and Environment in Northeast Asia, Ministry of Education, China
[b] Research Center of Paleontology and Stratigraphy, Jilin University, Changchun 130026, China

ARTICLE INFO

Article history:
Received 18 April 2008
Accepted in revised form 17 August 2008
Available online 30 August 2008

Keywords:
Carbon dioxide
Stomatal index
Ginkgo
Campanian
Late Cretaceous
Taipinglinchang Formation
Jiayin
China

ABSTRACT

Using the stomatal index technique, the Campanian (Late Cretaceous) atmospheric carbon dioxide levels are estimated based on a sequence of fossil cuticles of *Ginkgo adiantoides* (Ung.) Heer. *Ginkgo* cuticles were sampled from 11 beds in the Taipinglinchang Formation at Jiayin, Heilongjiang Province, northeast China. In general, the regression function based results show a gradual decrease of pCO_2 through Campanian with a background of ~550–590 ppm. The new data of the Campanian pCO_2 are more compatible with GEOCARB II model than those of GEOCARB III, although the new data have slightly higher values (30 ppm on average). A notable short-term carbon dioxide fluctuation (SCDF) is recognized in the upper Campanian (up to ~690 ppm), and is followed by a rapid return to background values of ~590 ppm.

1. Introduction

Fossil cuticles provide unique insights into paleo-CO_2 (pCO_2) and terrestrial paleo-ecosystem changes throughout the Phanerozoic (Woodward, 1987; McElwain, 1998; Beerling and Royer, 2002a; Kürschner et al., 2008; Royer, 2008). A growing number of cuticle-based studies have attempted to estimate paleo-CO_2. The published data, however, indicate a significant range of values with little congruence not only compared to those derived from geochemical methods, but also among the paleobotanical approaches themselves (Yapp and Poths, 1992; Berner, 1997; McElwain et al., 1999; Retallack, 2001; Royer, 2001; Royer et al., 2001a; Tanner et al., 2001; Haworth et al., 2005). Paleobotanically, this inconsistency may be partly explained by multispecies analyses where different taxa show variable responses to CO_2 levels and CO_2 change. The monospecies-based pCO_2 estimates are, therefore, considered to be a more effective way to reduce the potential sources of error that arise through multi-species approaches.

It is likely that the monospecies-based CO_2 reconstruction can not be implemented for long periods of geological time, since no single species is available that survived throughout the history of land plants with well-preserved cuticles. However, this solution is practical at least at the "age/stage" level of geological time. To date, most monospecies-based paleo-CO_2 estimations, which calibrate the stomatal indices (SIs) of fossil leaves to a modern reference set of the same species, are constrained to the latest Cretaceous and Cenozoic (e.g. Wagner et al., 1999; Royer et al., 2001b; Beerling et al., 2002; Kürschner et al., 2008). Few studies have quantitatively reconstructed the Late Cretaceous CO_2 based on the SIs of a monospecific sequence of fossil leaves.

This paper reports paleo-CO_2 estimates during the Campanian (Late Cretaceous) based on stomatal parameters from *Ginkgo adiantoides* (Ung.) Heer. The fossil *Ginkgo* leaves were collected from the Taipinglinchang Formation at Jiayin, Heilongjiang, northeast China (Fig. 1). We selected *Ginkgo* based on its ecological conservatism (Royer et al., 2003) and its apparent reliability as a paleo-CO_2 indicator shown through herbarium observations and plant experimentations (Chen et al., 2001; Royer, 2001; Sun et al., 2003). The present monospecies-based paleo-CO_2 estimates overcome the potential taxonomic bias imposed by multispecies studies.

2. Material and methods

2.1. Material

The *Ginkgo* fossils were collected from the Upper Cretaceous Taipinglinchang Formation along the right bank of Heilongjiang

* Corresponding authors. Research Center of Paleontology and Stratigraphy, Jilin University, Changchun 130026, China.
E-mail addresses: quan@jlu.edu.cn (C. Quan), sunge@jlu.edu.cn (G. Sun).

0195-6671/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cretres.2008.08.004

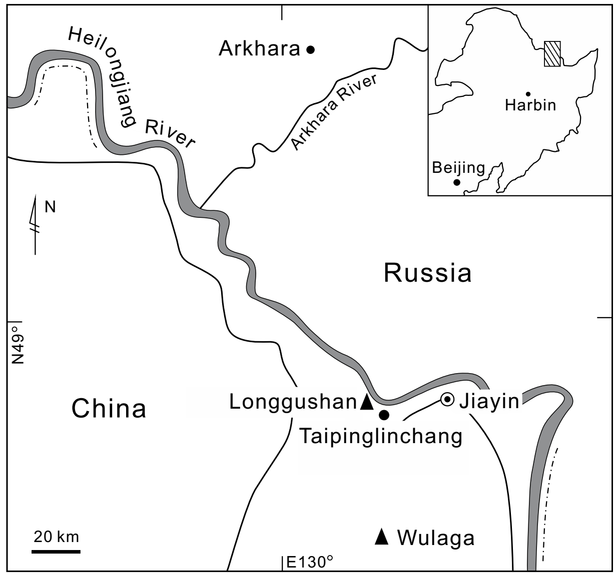

Fig. 1. Geographical position of *Ginkgo* fossil sites in Jiayin, Heilongjiang, NE China (solid triangle marks showing the sites within the Upper Cretaceous Taipinglinchang Formation).

River in Jiayin County, Heilongjiang, northeast China (Fig. 1), by the Research Team on the K-T boundary of Jilin University, during seven fieldworks since 2002. This plant-bearing formation represents a shallow lacustrine succession consisting of grey mudstone, siltstone and fine feldspathic sandstone (Fig. 2). It yields fossils of conchostacans, ostracods, fishes and plants. This formation is predominantly of Campanian age based on palynological data (Markevich et al., 2006; Sun et al., 2007b).

A total of 77 specimens of *G. adiantoides* with well-preserved cuticles were collected from 11 beds of the Upper Cretaceous Taipinglinchang Formation (Fig. 2). More than 5 leaves were sampled per bed except for beds 1 and 5. Although stomatal index (SI) measurements were made on fewer than five leaves for these two beds, we have included them here since no other species with cuticles were found in these stratigraphic levels.

2.2. Cuticle preparation and counting

For identification and stomatal analysis, the cuticle fragments of each *Ginkgo* specimen were treated by standard maceration for both SEM and LM (see Dilcher, 1974). The material was first identified by SEM, then the selected *G. adiantoides* specimens were photographed by LM.

For cuticle preparation, we selected the middle part of each *Ginkgo* leaf to obtain secure SI measurements, because stomatal parameters show less variability there than near the margins. At least three fragments were measured on each *G. adiantoides* leaf per bed; and stomatal counts were made on three or more intercostal fields per lower cuticle fragment as outlined by Poole and Kürschner (1999). In total, the counts were performed on 253 fragments from 77 specimens. The values reported here are averages of all measurements for each leaf at a particular bed.

The photographic instruments, JSM-6700F SEM and Olympus DP12 LM, were provided by the Research Center of Paleontology and Stratigraphy (RCPS), Jilin University. The fossil specimens and cuticle preparations are stored in the RCPS, in Changchun of China.

2.3. Stomatal analysis

The SI is calculated as: SI(%) = [SD/(SD + ED)]*100, where a SD = stomatal density, and ED = non-stomatal epidermal cell density (subsidiary cells and ordinary epidermal cells). The Campanian atmospheric CO_2 levels are reconstructed from fossil *Ginkgo* cuticle SIs by using the inverse regression function (RF) (Royer et al., 2001b) given by:

$$\text{paleo} - CO_2 = \frac{(415 \times \text{SI} - 1961) \times 2000}{3337 \times \text{SI} - 2000} \quad (1)$$

Eq. (1) was derived from experiments of extant *Ginkgo biloba* L. leaves collected during the anthropogenic CO_2 increases of the past 200 years and greenhouse CO_2 enrichment. This function can be used for the Campanian material (*G. adiantoides*) owing to the extreme similarity in both ecological and anatomical features of these two forms (Tralau, 1968; Crane et al., 1990; Royer et al., 2003). In addition, the sedimentological and floral data from the quantitative survey of Royer et al. (2003) on 51 *Ginkgo*-bearing fossil sites indicate that *Ginkgo* was largely confined to disturbed stream margin and levee environments. These highly disturbed environments usually support well-watered, open-canopy forests that should lack intracanopy CO_2 gradients (Royer, 2003).

To assess the results of this procedure, an alternative stomatal-based CO_2 method, nearest living equivalent (NLE) (McElwain and Chaloner, 1996; McElwain, 1998), was used, assuming a pre-industrial CO_2 concentration of 300 ppm.

3. Results

Estimated CO_2 concentrations from our stomatal index analyses vary from 558.83 ppm to 692.80 ppm for the full span of the Campanian using the RF methodology (Table 1). Overall, the records suggest a modest long-term decrease in pCO_2 with a background of ~550–590 ppm (Table 1; Fig. 3). However, a CO_2 spike, up to 692.80 ppm, is notable in the late Campanian on the basis of bed 6 (Fig. 3). This short-term CO_2 peak value is followed by a rapid return to background values of 592.02 ppm in bed 7 (Fig. 3). For the sake of simplicity in the following discussion, we refer to this type of paleo-CO_2 rise-fall as a short-term carbon dioxide fluctuation (SCDF). Similar SCDFs have been mostly recognized in the critical vegetation turnover intervals regardless of the magnitude, such as the T-J (McElwain et al., 1999), K-T (Beerling et al., 2002), Pal.-Eoc. (Royer et al., 2001b), and early-middle Miocene (Kürschner et al., 2008). All these botanical data suggest short-term couplings between atmospheric CO_2 and coeval geological events.

Table 1
Stomatal measurement and inferred paleo-CO_2 based on *G. adiantoides* from Taipinglinchang Formation

Bed	No. of leaves	SI (mean)	Standard deviation of SI	paleo-CO_2 (RF)	RCO_2	NLE			
						CO_2 (Recent standard)	Sigma−1	CO_2 (Carboniferous standard)	Sigma +1
11	10	7.01	0.14	558.53	1.62	484.78	436.30	969.55	1066.51
10	12	6.98	0.27	569.43	1.62	487.18	438.46	974.36	1071.79
9	7	6.97	0.43	571.03	1.63	487.52	438.77	975.04	1072.54
8	8	6.92	0.34	588.02	1.64	490.97	441.87	981.94	1080.14
7	11	6.91	0.27	592.02	1.64	491.74	442.57	983.48	1081.83
6	8	6.70	0.23	692.80	1.69	507.04	456.33	1014.07	1115.48
5	3	6.96	0.49	575.98	1.63	488.56	439.70	977.11	1074.83
4	5	6.98	0.31	567.38	1.62	486.74	438.06	973.48	1070.82
3	7	6.94	0.31	583.55	1.63	490.09	441.08	980.18	1078.20
2	5	6.93	0.50	584.90	1.63	490.36	441.32	980.72	1078.79
1	1	6.83	0.49	624.74	1.66	497.49	447.75	994.99	1094.49

In northeast China and the Russian Far East, there was a warming of climate from Santonian to Campanian indicated by the paleobotanical data (Herman, 1993; Sun et al., 2007b). The SCDF derived from *Ginkgo* cuticles of the Taipinglinchang Formation would be an additional evidence for paleoclimatic warming in the late Campanian.

4. Comparisons

To cross-test the Campanian CO_2 reconstructions, the new results are compared to estimates from geochemical proxies and predictions from geochemical models of the long-term global carbon cycle. Additionally, a few paleobotanical data of Campanian CO_2 have been published to date, so that the comparisons are extended to stratigraphically adjacent stages, such as to the Early Cretaceous and to the Maastrichtian.

The present data of Campanian CO_2 concentration are most similar to the levels estimated by GEOCARB II of Berner (1994), but with slightly higher values (30 ppm on average). GEOCARB III (Berner and Kothavala, 2001) estimated higher pCO_2 values, but both RF- and NLE-based estimates match the error range (Fig. 4). Moreover, the present values lie between the GEOCARB II and III except for the Recent Standardization of NLE. Some authors (e.g. Haworth et al., 2005) have argued that the GEOCARB II model might be a more accurate reconstruction of pCO_2 for the mid-Mesozoic than GEOCARB III. It appears that this may also be the case for the Late Cretaceous.

The present paleo-CO_2 estimates are also similar to Wallmann (2001) except that the latter demonstrates a slight more rapid decline. The results from box model of Hansen and Wallmann (2003) illustrates a relative higher CO_2 concentration in the Campanian, but it is in the error range of the present study by

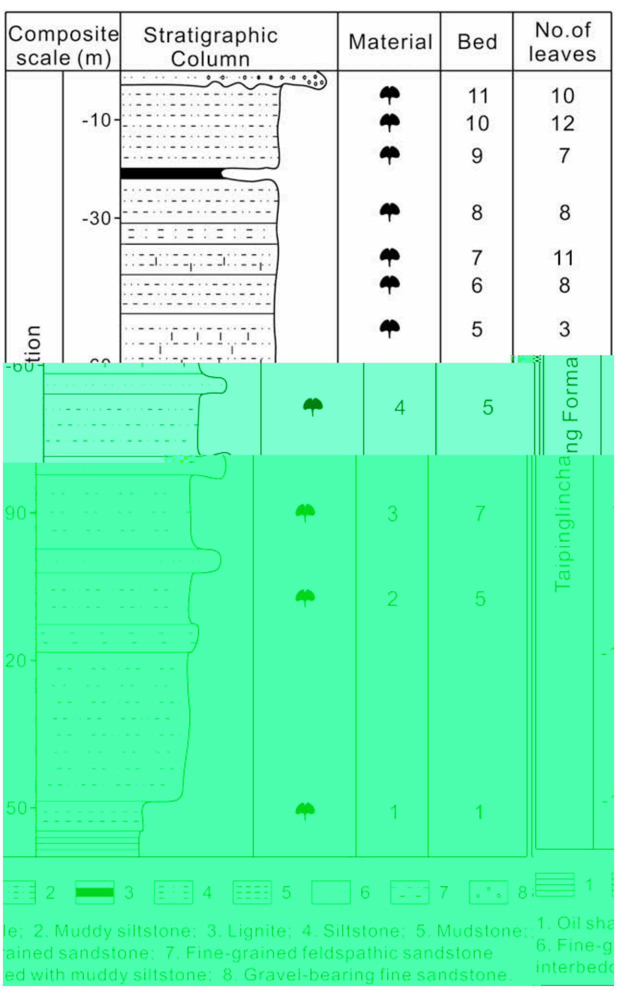

Fig. 2. Graphic log showing stratigraphic column (*Ginkgo* material sampled from 11 beds).

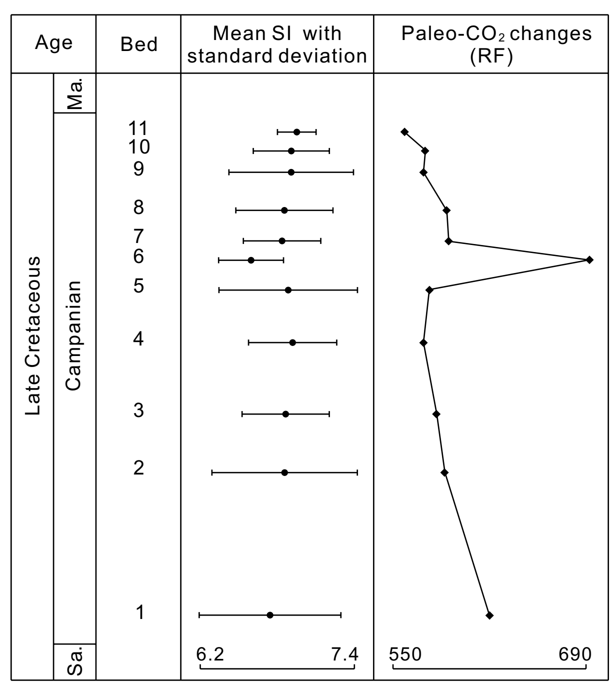

Fig. 3. pCO_2 estimates of the Campanian based on *G. adiantoides* from the Taipinglinchang Formation (stratigraphic framework after Sun et al., 2007b; error bars show standard deviation).

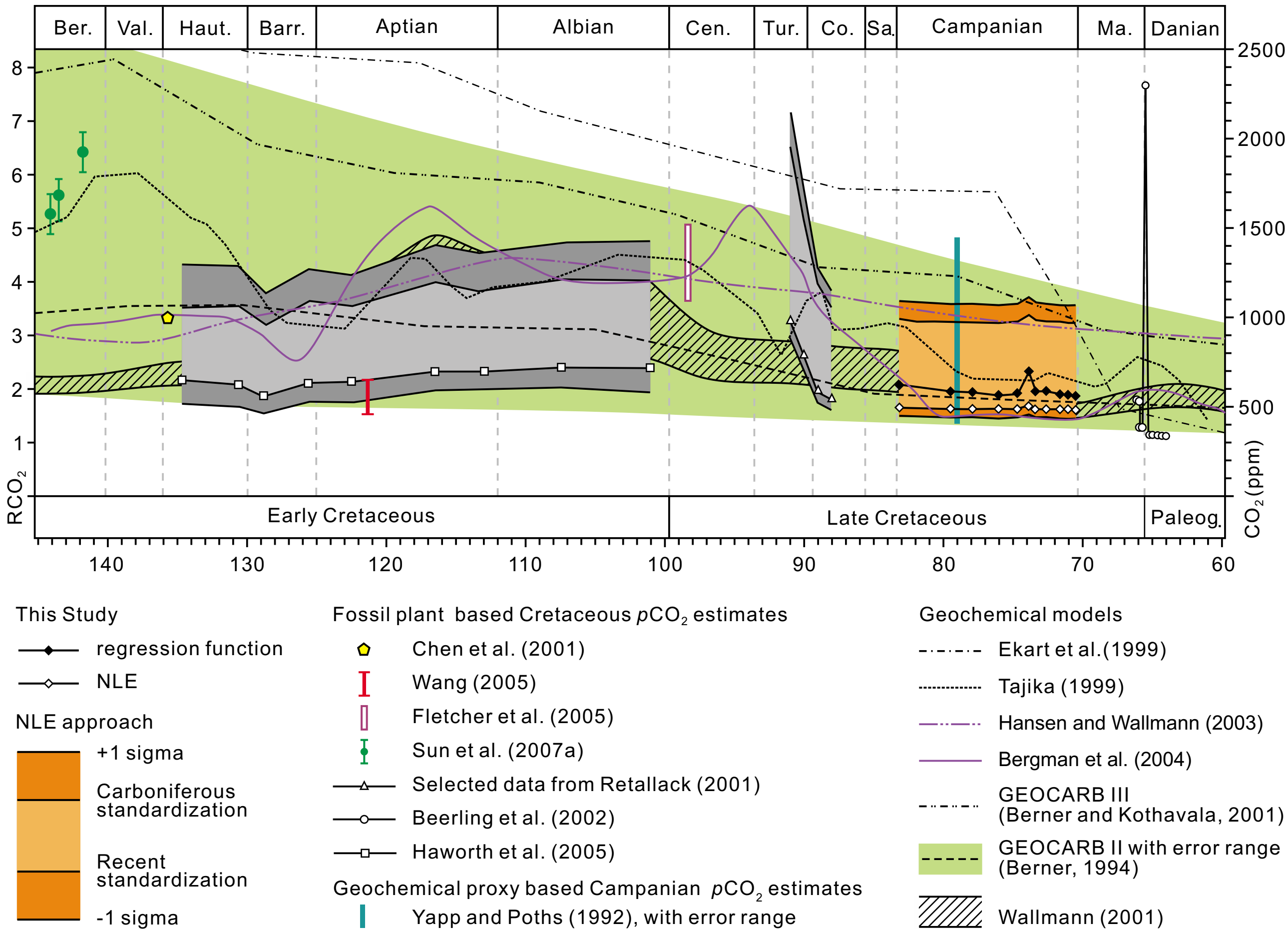

Fig. 4. Estimates of Cretaceous paleo-CO_2 from this study, previous data of geochemical models, geochemical and paleobotanical proxies.

NLE-based estimates (Fig. 4). Moreover, the minimum pCO_2 estimates by NLE of the present data strongly match those from the COPSE biogeochemical cycling model of Bergman et al. (2004) with the exception of the earliest Campanian (Fig. 4).

Ekart et al. (1999) obtained a Campanian CO_2 value of 1250 (±500) ppm, and Yapp and Poths (1992) calculated a Campanian value of 1400 ppm, with an error range of greater than 1000 ppm. Thus, the present estimate is within the ranges proposed by previously published geochemical values albeit that the latter have large error bars.

Significantly, the late Campanian SCDF has not been recognized in the geochemical proxy (Ekart et al., 1999) or most geochemical models (Berner, 1994; Berner and Kothavala, 2001; Wallmann, 2001; Hansen and Wallmann, 2003; Bergman et al., 2004). This is likely due to the lower resolution of the geochemical approaches for the Cretaceous (ca. 10 Ma.). In Tajika's (1999) geochemical model, however, a slight SCDF has been recognized in the late Campanian at a resolution of ca. 10 Ma, which occurred just after the one identified from the new data (Fig. 4). These may relate to the same late Campanian SCDF, their positions differing only due to the quality of the stratigraphic resolution.

For botanical comparison, the NLE-based Campanian ratio of CO_2 (RCO_2) values of present study are calculated (Table 1; Fig. 4). The NLE of fossil *Ginkgo adiantoides* is obviously *G. biloba*, which yields 11.33 SI on average (Beerling and Royer, 2002b). The NLE-based values are calibrated with 300 ppm of recent standardization or 600 ppm of Carboniferous standardization, which are regarded as the broad minimum and maximum estimates of paleo-pCO_2 (McElwain, 1998).

Two studies have been undertaken based on *G. coriacea* Florin from the early-middle Early Cretaceous Huolinhe Formation in northeastern China. Chen et al. (2001) reported a RCO_2 of 2.8 whereas Sun et al. (2007a) inferred a RCO_2 of 2.55–3.20. Since no detailed sampling horizon information was provided by Chen et al. (2001), we presume the different results between these two studies reflect their different sampling horizons based on their respective stratigraphic illustrations.

Haworth et al. (2005) reported stomata-based values for mid-Cretaceous pCO_2 by using NLE. Their results show relatively low and only slight varying pCO_2 over the Hauterivian-Albian interval. Wang (2005) calculated the Early Cretaceous paleo-CO_2 at 1.55-2.18 RCO_2, using NLE based on *G. coriacea*, *G. truncata* (Li) Chen, *G. sibirica* Heer and *G. adiantoides* from the Changcai Formation in Northeast China (Aptian age, Sun et al., 2005). His result is more similar to those of Haworth et al. (2005).

Retallack (2001) published fossil cuticle-based pCO_2 back to 300 Ma. However, some of the data suffer a large variability of SI because of the small sample size (commonly <4 cuticle fragments) and by the use of an inappropriate transfer function (Beerling and Royer, 2002b). We re-calculated the original ginkoalean data near the Campanian from Retallack (2001) using the NLE rather than RF, because 1) the stomatal responses to CO_2 are species-specific (Royer, 2001); and 2) the original Turonian-Coniacian materials of Retallack (2001) are *Ginkgo pilifera* Samylina and *G. transsenonicus* Krassilov, which commonly yield amphistomatic cuticles (Samylina, 1967; Krassilov, 1979). The re-calibration demonstrates a dramatic reduction, from ∼970 ppm to ∼520 ppm, during the late Turonian-middle Coniacian at a resolution of ca. 1 million years

(Fig. 4). However, this pCO_2 reduction is not recognized in most geochemical models except that of Bergman et al. (2004). More detailed paleobotanical data are needed to confirm this SCDF due to the sparse materials used for its basis.

From the Albian to the earliest Campanian, the pCO_2 estimates show a gradual decrease from ~523 ppm to 497 ppm (NLE-based). This decrease trend is also supported by the geochemical data (e.g. Hansen and Wallmann, 2003; Fletcher et al., 2005) (Fig. 4). But they cannot exclude the possibility that additional SCDFs occurred during the Cenomanian-Santonian, as there is a lack of high-resolution data during this geological interval. After the late Campanian SCDF, it appears that no striking changes in paleo-pCO_2 occurred during the Maastrichtian, and levels gradually decreased to 530 ppm until the K-T event (Beerling et al., 2002; Beerling and Royer, 2002a; Royer et al., 2007).

5. Conclusions

Stomatal indices of *G. adiantoides* produce a pCO_2 background of 550–590 ppm. The overall trend of pCO_2 shows a gradual decrease through the Campanian, which is also shown by independent geochemical methods. Our SI-based pCO_2 estimate is more comparable to the GEOCARB II model. However, a short-term carbon dioxide fluctuation (SCDF) is recognized in the late Campanian (up to ~690 ppm), and represents a brief excursion from the trend of decreasing CO_2 through the Campanian. This SCDF is followed by a rapid return to background values of ~590 ppm.

Acknowledgements

The study was supported by the NSFC (No. 3022130698; 30670138; 40842002) and Project "111" of China. The authors express thanks to all the participants of these projects working in Jiayin of Heilongjiang, China during 2002–2007. We are grateful to Dr. Dana L. Royer (Wesleyan University) for providing information on regression function of *Ginkgo*. Thanks to the anonymous reviewers for their helpful comments and suggestions.

References

Beerling, D.J., Lomax, B.H., Royer, D.L., Upchurch, G.R., Kump, L.R., 2002. An atmospheric pCO_2 reconstruction across the Cretaceous-Tertiary boundary from leaf megafossils. Proceedings of the National Academy of Sciences of the United States of America 99, 7836–7840.

Beerling, D.J., Royer, D.L., 2002a. Fossil plants as indicators of the Phanerozoic global carbon cycle. Annual Review of Earth and Planetary Sciences 30, 527–556.

Beerling, D.J., Royer, D.L., 2002b. Reading a CO_2 signal from fossil stomata. New Phytologist 153, 387–397.

Bergman, N.M., Lenton, T.M., Watson, A.J., 2004. COPSE: a new model of biogeochemical cycling over Phanerozoic time. American Journal of Science 304, 397–437.

Berner, R.A., 1994. GEOCARB II: a revised model of atmospheric CO_2 over Phanerozoic time. American Journal of Science 294, 56–91.

Berner, R.A., 1997. The rise of plants and their effect on weathering and atmospheric CO_2. Science 276, 544–546.

Berner, R.A., Kothavala, Z., 2001. GEOCARB III: a revised model of atmospheric CO_2 over Phanerozoic time. American Journal of Science 301, 182–204.

Chen, L.Q., Li, C.S., Chaloner, W.G., Beerling, D.J., Sun, Q.G., Collinson, M.E., Mitchell, P.L., 2001. Assessing the potential for the stomatal characters of extant and fossil *Ginkgo* leaves to signal atmospheric CO_2 change. American Journal of Botany 88, 1309–1315.

Crane, P.R., Manchester, S.R., Dilcher, D.L., 1990. A preliminary survey of fossil leaves and well-preserved reproductive structures from the Sentinel Butte formation (Paleocene) near Almont, North Dakota. Fieldiana (Geology) 20, 1–63.

Dilcher, D.L., 1974. Approaches to the identification of angiosperm leaves. The Botanical Review 40, 1–157.

Ekart, D.D., Cerling, T.E., Montañez, I.P., Tabor, N.J., 1999. A 400 million year carbon isotope record of pedogenic carbonate: implications for paleoatmospheric carbon dioxide. American Journal of Science 299, 805–827.

Fletcher, B.J., Beerling, D.J., Brentnall, S.J., Royer, D.L., 2005. Fossil bryophytes as recorders of ancient CO_2 levels: experimental evidence and a Cretaceous case study. Global Biogeochemical Cycles 19, 1–13.

Hansen, K.W., Wallmann, K., 2003. Cretaceous and Cenozoic evolution of seawater composition, atmospheric O_2 and CO_2: a model perspective. American Journal of Science 303, 94–148.

Haworth, M., Hesselbo, S.P., McElwain, J.C., Robinson, S.A., Brunt, J.W., 2005. Mid-Cretaceous pCO_2 based on stomata of the extinct conifer *Pseudofrenelopsis* (Cheirolepidiaceae). Geology 33, 749–752.

Herman, A.B., 1993. Stages and cycles in the Late Cretaceous floral changes of the Anadyr'–Koryak subregion (Northeast Russia) and their connection with climatic changes. Stratigraphy and Geological Correlation 1, 77–87.

Krassilov, V.A., 1979. The Cretaceous flora of Sakhalin. Nauka, Moscow. pp.96–97 (in Russian).

Kürschner, W.M., Kvaček, Z., Dilcher, D.L., 2008. The impact of Miocene atmospheric carbon dioxide fluctuations on climate and the evolution of terrestrial ecosystems. Proceedings of the National Academy of Sciences of the United States of America 105, 449–453.

Markevich, V.S., Sun, G., Ashraf, A.R., Bugdaeva, E.V., 2006. The Maastrichtian-Danian palynological assemblages from Wuyun of Jiayin nearby the Heilongjiang (Amur) River. In: Yang, Q., Wang, Y.D., Weldon, E.A. (Eds.), IPC 2006, Ancient Life and Modern Approaches: Abstracts of the second International Palaeontological Congress. University of Science and Technology of China Press, Beijing, pp. 526–527.

McElwain, J.C., 1998. Do fossil plants signal palaeoatmospheric CO_2 concentration in the geological past? Philosophical Transactions of the Royal Society, London 353, 83–96.

McElwain, J.C., Beerling, D.J., Woodward, F.I., 1999. Fossil plants and global warming at the Triassic-Jurassic boundary. Science 285, 1386–1390.

McElwain, J.C., Chaloner, W.G., 1996. The fossil cuticle as a skeletal record of environmental change. Palaios 11, 376–388.

Poole, I., Kürschner, W.M., 1999. Stomatal density and index: the practice. In: Jones, T.P., Rowe, N.P. (Eds.), Fossil Plant and Spores: Modern Techniques. The Geological Society, London, pp. 257–260.

Retallack, G.J., 2001. A 300-million-year record of atmospheric carbon dioxide from fossil plant cuticles. Nature 411, 287–290.

Royer, D.L., 2001. Stomatal density and stomatal index as indicators of paleoatmospheric CO_2 concentration. Review of Palaeobotany and Palynology 114, 1–28.

Royer, D.L., 2003. Estimating latest Cretaceous and Tertiary atmospheric CO_2 from stomatal indices. In: Wing, S.L., Gingerich, P.D., Schmitz, B., Thomas, E. (Eds.), Causes and Consequences of Globally Warm Climates in the Early Paleogene. The Geological Society of America, Special Paper, 369, Boulder, pp. 79–93.

Royer, D.L., 2008. Linkages between CO_2, climate, and evolution in deep time. Proceedings of the National Academy of Sciences of the United States of America 105, 407–408.

Royer, D.L., Berner, R.A., Beerling, D.J., 2001a. Phanerozoic atmospheric CO_2 change: evaluating geochemical and paleobiological approaches. Earth-Science Reviews 54, 349–392.

Royer, D.L., Berner, R.A., Park, J., 2007. Climate sensitivity constrained by CO_2 concentrations over the past 420 million years. Nature 446, 530–532.

Royer, D.L., Hickey, L.J., Wing, S.L., 2003. Ecological conservatism in the "living fossil" *Ginkgo*. Paleobiology 29, 84–104.

Royer, D.L., Wing, S., Beerling, D.J., Jolley, D.W., Koch, P.L., Hickey, L.J., Berner, R.A., 2001b. Paleobotanical evidence for near present day levels of atmospheric CO_2 during part of the Tertiary. Science 292, 2310–2313.

Samylina, V.A., 1967. On the final stages of the history of the genus *Ginkgo* L. in Eurasia. Botanical Journal 52, 303–316 (in Russian).

Sun, B.N., Dilcher, D.L., Beerling, D.J., Zhang, C.J., Yan, D.F., Kowalski, E., 2003. Variation in *Ginkgo biloba* L. leaf characters across a climatic gradient in China. Proceedings of the National Academy of Sciences of the United States of America 100, 7141–7146.

Sun, B.N., Xiao, L., Xie, S.P., Deng, S.H., Wang, Y.D., Jia, H., Turner, S., 2007a. Quantitative analysis of paleoatmospheric CO_2 level based on stomatal characters of fossil *Ginkgo* from Jurassic to Cretaceous in China. Acta Geologica Sinica-English Edition 81, 931–939.

Sun, G., Akhmetiev, M., Golovneva, L., Bugdaeva, E., Quan, C., Kodrul, T., Nishida, H., Sun, Y.W., Sun, C.L., Johnson, K., Dilcher, D., 2007b. Late Cretaceous plants from Jiayin along Heilongjiang River, Northeast China. Courier Forschungsinstitut Senckenberg 258, 75–83.

Sun, Y.W., Wang, Y.X., Wei, W.Y., 2005. *Ginkgo* from Lower Cretaceous Changcai Formation in Helong of Jilin, NE China. Journal of Geoscientific Research in Northeast Asia 8, 1–8.

Tajika, E., 1999. Carbon cycle and climate change during the Cretaceous inferred from a biogeochemical carbon cycle model. The Island Arc 8, 293–303.

Tanner, L.H., Hubert, J.F., Coffey, B.P., McInerney, D.P., 2001. Stability of atmospheric CO_2 levels across the Triassic/Jurassic boundary. Nature 411, 675–677.

Tralau, H., 1968. Evolutionary trends in the genus *Ginkgo*. Lethaia 1, 63-101.

Wagner, F., Bohncke, S.J.P., Dilcher, D.L., Kürschner, W.M., van Geel, B., Visscher, H., 1999. Century-scale shifts in early Holocene atmospheric CO_2 concentration. Science 284, 1971–1973.

Wallmann, K., 2001. Controls on the Cretaceous and Cenozoic evolution of seawater composition, atmospheric CO_2 and climate. Geochimica et Cosmochimica Acta 65, 3005–3025.

Wang, Y.X., 2005. Ginkgoales and Czekanowskiales from the Early Cretaceous Changcai Formation in Yanbian Area, Jilin. Unpublished Master thesis, Jilin University, Changchun, 69 pp (in Chinese with English abstract).

Woodward, F.I., 1987. Stomatal numbers are sensitive to increases in CO_2 from pre-industrial levels. Nature 327, 617–618.

Yapp, C.J., Poths, H., 1992. Ancient atmospheric CO_2 pressures inferred from natural goethites. Nature 355, 342–344.