



A Paleoclimate Proxy from Ammonite Suture Line Complexity

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Abstract. Changes in atmospheric composition, driven by fluctuating concentrations of greenhouse gases, are the primary driver of climate change, alongside variations in oceanic circulation. Reconstructions of temperature and climate over geological timescales rely on qualitative and quantitative proxies preserved in the geological record. Sedimentary deposits
10 such as coal, evaporites, bauxites, and tillites, although they represent specific climatic regimes, have low temporal resolution. By contrast, quantitative geochemical proxies such as $\delta^{18}\text{O}$ or $\delta^{13}\text{C}$, clumped-isotope thermometry, TEX86, and Sclerochronology offer higher temporal resolution. However, these proxies have limitations, reflecting, in some cases, local post-depositional variation or alteration, indicating a need to integrate proxy methods to establish reliable and robust paleoclimate reconstructions.

15 In this paper, we present a new qualitative method for reconstructing temperature, based on the fractal dimension of ammonite suture lines, which can integrate with and support well-established paleoclimate proxies. Suture lines mark the contact between the septum, formed by the organism, and its shell. The linear pattern of fossil sutures exhibits a fractal dimension and resembles viscous fingering—a process that depends on fluid viscosity. Based on the fractal dimension of c. 450 taxa of Cretaceous ammonite sutures (143–66 million years ago), we present a fractal dimension curve that serves as a
20 qualitative proxy for seawater viscosity and inversely correlates with seawater temperature. The curve reveals warm and cold snaps associated with geological events that may have triggered climate changes during the Cretaceous, such as Large Igneous Provinces, seafloor production, mid-ocean ridge length, and Oceanic Anoxic Events.

1. Introduction

Changes in atmospheric composition significantly influence the evolution of Earth's climate and biosphere because of the
25 varying levels of greenhouse gases. Long-term temperature variations are linked to volcanic degassing, occurring at rates of plate tectonic movements along subduction zones and seafloor spreading ridges, as well as from the weathering of continental regions (Gernon et al., 2021; 2024). Paleogeographic shifts can also affect the global climate by influencing thermohaline circulation and oceanic heat transport (Fluteau et al., 2007; Poulsen et al., 2010; Ladant et al., 2020). These factors are relevant in regulating Earth's thermal balance over periods longer than 50 million years. Conversely, short-term
30 temperature fluctuations, spanning a few million years, can result from the release of large volumes of greenhouse gases



during volcanism linked to Large Igneous Provinces (LIPs) (Ernst et al., 2015). Global warming caused by the substantial injection of CO₂ into the atmosphere associated with LIPs enhances the hydrological cycle and chemical weathering, which increases primary production and organic matter burial in the oceans. This process also causes a significant reduction in deep-water oxygen levels, leading to Oceanic Anoxic Events (OAEs), which are recorded as organic-rich black shales (Jenkyns, 2010; Gernon et al., 2024).

Reconstructions of temperature and climate over geological time scales depend on qualitative and quantitative indicators. The qualitative lithological proxies include sedimentary deposits such as coal, evaporites, bauxite, and tillites that form under conditions characteristic of specific climate regimes or environmental settings (Gornitz, 2009). These indicators generally have low temporal resolution (Shaviv et al., 2022). Quantitative geochemical indicators are based on isotope ratios, like the oxygen isotope proxy $\delta^{18}\text{O}$, which measures the ratio of ^{18}O to ^{16}O in shells of various organisms (e.g. brachiopods, foraminifera, mollusks, and conodonts) that live in different environments having shells made of calcium carbonate, calcium phosphate, and siliceous minerals. A compositional change in $\delta^{18}\text{O}$ of -1‰ corresponds to about a +4°C in the temperature at the time of mineral precipitation. This relation is, however, related to the salinity of seawater, which depends on paleoclimate (arid vs. humid climates) and also on the ratio of ^{18}O to ^{16}O in seawater. This parameter, in turn, depends on the amount of water locked in the ice caps. Although this proxy provides the benefit of high-resolution data, it also has limitations such as a bias toward tropical regions, discrepancies during periods of high temperatures and extensive glaciations, and complex effects related to ocean acidity and biological bias, as well as diagenesis (Scotese et al., 2021; Shaviv et al., 2022). In some cases, the signal from isotopes may be evidence for local variation and related to non-climatic environmental factors such as physical distance from the Precambrian basement and/or diagenesis (Mólen, 2024). A Sea Surface Temperature (SST) proxy free from diagenetic effects and salinity corrections has recently emerged from organic chemical analyses (Schouten et al., 2003). The TEX₈₆ (TetraEther indeX of 86 carbon atoms) is based upon the distribution of archaeal membrane lipids (GDGTs) in marine sediments and is ubiquitous, abundant, and relatively resistant to degradation. The TEX₈₆ paleothermometer has been used to reconstruct SST during the Cenozoic and the Mesozoic (O'Brien et al., 2017). Other methods, such as Sclerochronology, offer high-resolution records studying physical and chemical variations in the hard, accretionary tissues of aquatic organisms, but can be affected by post-depositional alteration and irregular growth increments, food availability, environmental changes, food supply, and ocean acidity. The Clumped Isotopes paleothermometer, which measures the abundance of ^{13}C and ^{18}O bound to each other in a molecule, is a powerful analytical tool, particularly for paleoclimatology, but it may suffer diagenetic effects or be affected by high burial temperatures.

In this paper, we introduce a qualitative method for reconstructing temperature based on a novel approach that measures the fractal dimension of ammonite suture lines. The complex pattern, formed by biophysical processes, corresponds to the contact between the septum, created by the organism, and its chambered shell. The suture line resembles viscous fingering—a process generating fractal patterns, directly related to fluid viscosity and inversely related to temperature. Following this approach, the fractal dimension of c. 450 suture lines from Cretaceous ammonite taxa, spanning a wide range of latitudes



(Fig. 1), was measured to generate a fractal dimension curve from c. 143 to 66 million years ago. The curve is plotted against $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and TEX86 paleotemperature curves, overlain with geological events associated with processes responsible for global temperature changes during the Cretaceous, such as Large Igneous Provinces, seafloor production and mid-ocean ridge length, and Oceanic Anoxic Events.

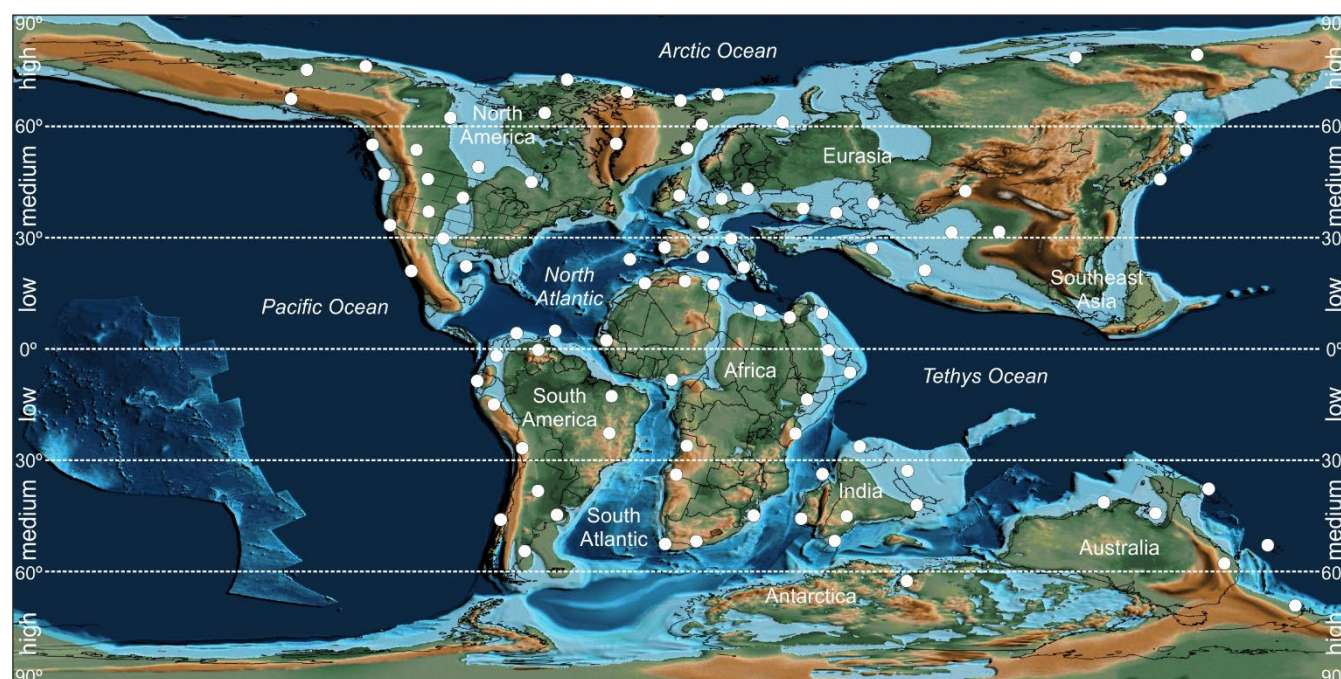


Figure 1. Paleogeographic map of the Cretaceous, approximately 100 million years ago (modified after Scotese et al., 2024), showing the worldwide biogeographic distribution of ammonite taxa (white dots) used here for fractal analysis of suture lines.

2. Methods

The new method is based on a morphogenetic hypothesis for ammonite suture lines formation, introduced by García-Ruiz et al. (1990), which draws similarities between suture lines and viscous fingers in both fractal features and physical mechanisms. We expand this hypothesis further and consider each ammonite as a device that recorded seawater viscosity in its suture line during the biophysical process of forming new septa.

2.1. Ammonite suture lines

The origin of ammonite sutures is still one of the most interesting open problems in paleontology, with different theories and hypotheses of suture formation dealing with function rather than morphogenesis (De Blasio, 2008; Inoue and Kondo, 2016; Lemanis and Zlotnikov, 2023). Sutures are thought to have increased the strength of the shell (Westerman, 1975) or provided sites for muscle attachment (Lehmann, 1981). Sutures are proxies for anatomical complexity, especially when assessing their



relationship to taxonomic longevity (Boyajian and Lutz, 1982). Sutures are also used as distinguishing features among taxa, helping determine phylogenetic relationships (Wiedmann and Kullmann, 1981). Sutures display a variety of morphological patterns that have been used by paleontologists in systematic studies, and their complexity has increased over geological time. A simple goniatitic suture was present in the Devonian–Permian ammonites. More complex ceratitic sutures occur in the Late Permian–Triassic taxa and evolved into even more intricate “ammonitic” sutures during the Jurassic–Cretaceous (Fig. 2).

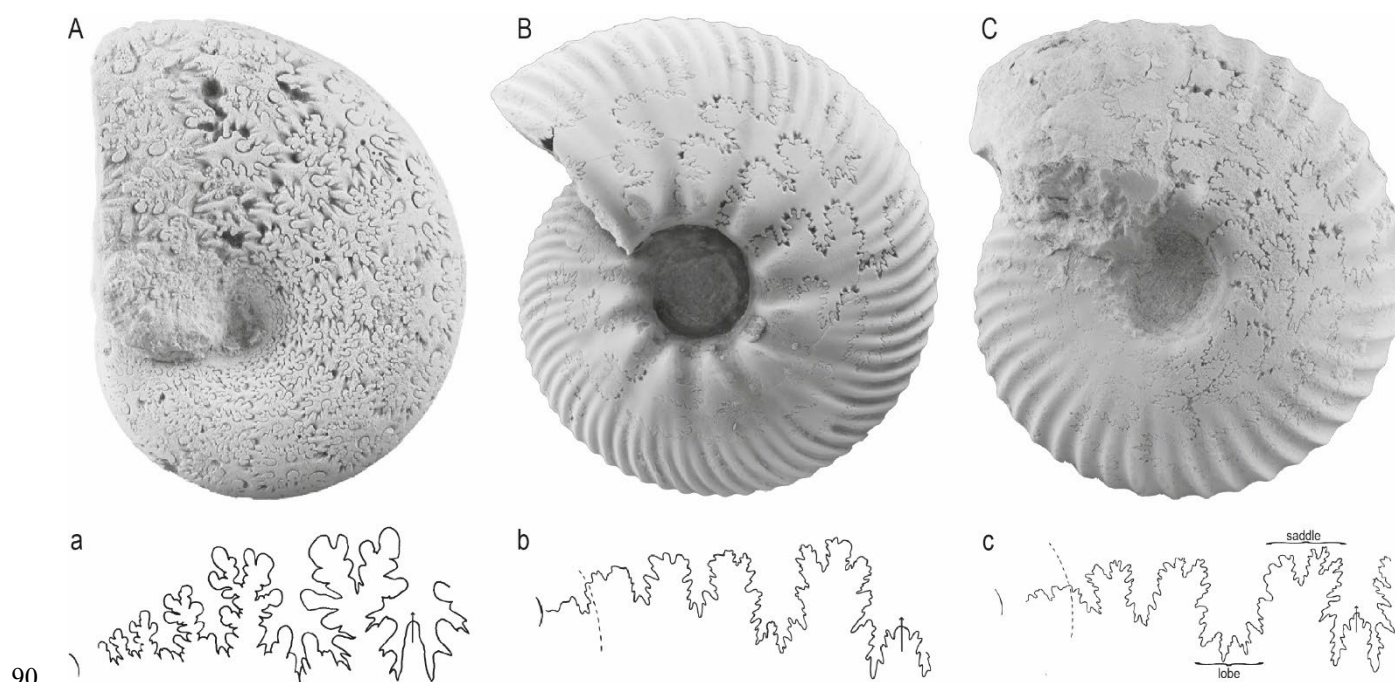


Figure 2. Examples of three well-preserved inner moulds of early Cretaceous ammonites and their drawn suture lines, respectively. A-a) *Phylloceras* aff. *semisulcatum*; B-b) *Menjaites* *groenlandicus*; C-c) *Tollia* (*Neocraspedites*) *piaseckii*. All refigured from Alsen (2006).

Based on García-Ruiz et al.'s hypothesis, the origin of suture patterns is linked to the morphological evolution of the mantle in contact with the inner shell. Ammonite chambers, separated by septa and connected via the siphuncle, are pressure vessels in which the mantle is pushed by the pressure of the gas in the last chamber against the seawater. The frilled surface of the posterior mantle can be imagined as viscous fingers that formed at the contact between gas and seawater, driven by either the muscle tissue pushing against the chamber or when it lifts from the surface. The 3D septal shape of ammonites may be explained as a mechanism of septal morphogenesis like that of extant nautiloids or nudibranchs, and other mollusks that show similar 3D fractal shape (Inoue and Kondo, 2016). Septa are biomineralized replicas of the posterior mantle at discrete time intervals, and sutures record the intersection between the septum and the shell wall. It is along this linear contact that the viscous fingers develop as features with fractal dimension and Saffman-Taylor instability (Saffman and Taylor, 1958).



Ammonites presumably lived 5-7 years and grew rapidly, recording seawater viscosity during their lifespan (Lewy, 2002; Ferguson et al., 2019; Machalski, 2020). We establish that the viscosity of seawater is documented in the fractal dimension of each ammonite suture line.

2.2. Viscous fingering

Viscous fingering refers to the onset and evolution of instabilities occurring at the interface between immiscible fluids, when a less viscous fluid displaces a more viscous one (Hill, 1952; Saffman and Taylor, 1958; Homsy, 1987). Once a viscous fluid is injected into a narrow gap between two parallel plates, as in a Hele-Shaw cell, previously filled with gas, the boundary between fluids will remain stable and the interface will be flat. If the reverse experiment is conducted with air or gas injected into a fluid of higher viscosity occupying the space between plates, the interface becomes linearly unstable and develops rapidly into a large amplitude finger-like structure of wavelength λ (Fig. 3). Similar patterns emerge in the absence of injection if the Hele-Shaw cell's lid is lifted, thereby drawing in air from the edges (Zhao et al., 2025).

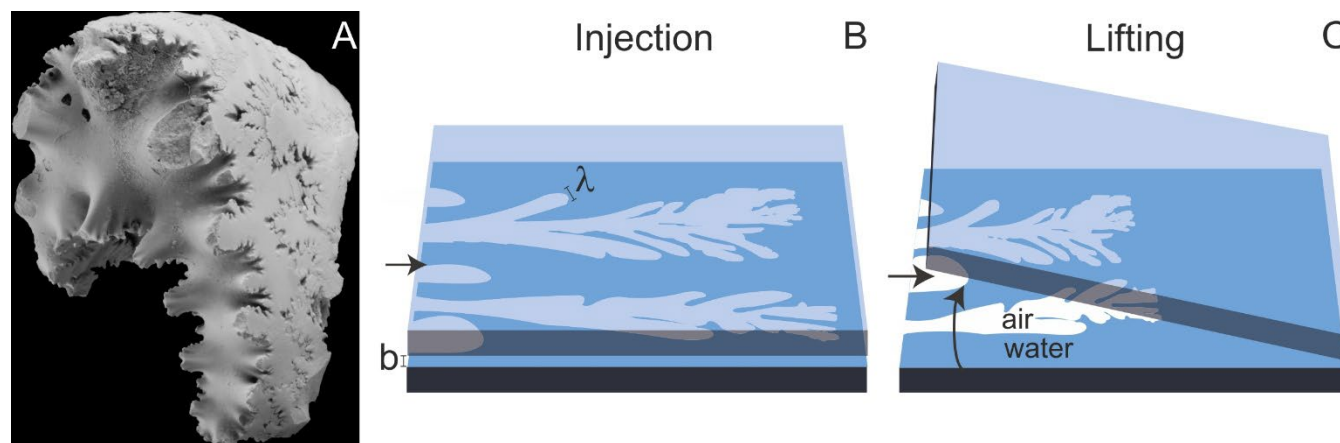


Figure 3. Comparison of ammonite septa and viscous fingers in Hele-Shaw cells. A) Oblique view of a pyrite preserved inner mould of an early Cretaceous ammonite fragment (Germany; Alsen Coll) showing both the septal wall and the fractal suture line - the trace of the suture, where the septal wall meets the shell; B) Viscous fingering generated by gas (white) injected into a fluid of higher viscosity (blue) between plates separated by a distance b ; C) Viscous fingering in the absence of injection and with the lifted lid (after Zhao et al., 2025).

Interestingly, the fingering wavelength λ depends on fluid film thickness b and on the physicochemical properties of the viscous fluid: $\lambda \sim b \text{Ca}^{-1/2}$. Where, $\text{Ca} = U\mu/\gamma$ is the capillary number, which depends on the flow speed U , fluid viscosity μ , and surface tension γ (Saffman and Taylor, 1958; Nittmann et al., 1985; García-Ruiz et al., 1990).

As the interface advances in the direction of the pressure gradient, it becomes wavy, and later it breaks into several viscous fingers. These fingers (which could correspond to lobes and saddles in ammonite sutures, see Figure 2c) can later split,



increasing the frilling and finally becoming highly branched. The wavelength $\lambda \sim \mu^{(-1/2)}$ mirrors the complexity of the fingers and is a direct function of viscosity μ . The highly branched pattern generated by the viscosity contrast shows fractal dimension (Nittmann et al., 1985; Maløy et al., 1985; Sinha and Tarafdar, 2009).

130 The viscosity of seawater is a function of temperature, pressure, and salinity (Maløy et al., 1985). However, the effect of pressure is not significant (Sinha and Tarafdar, 2009). Hence, many reported correlations considered viscosity as a function of temperature and salinity only (El-Dessouki and Ettouney, 2002; Qasem et al., 2020). Moreover, between the two variables, the temperature seems to have a stronger effect on viscosity than the salinity (Fig. 4). The effect of viscosity on marine particle flux is a relevant mechanism enhancing the sequestration of atmospheric CO₂ into the ocean, as rising
 135 temperatures reduce seawater viscosity and accelerate the sinking velocity of particles (Taucher et al., 2014). During the Cretaceous the salinity S , changed between 34.2‰ to 38.5‰ (Hay et al., 2006) corresponding to a variation in viscosity of 0.005 mPa·s (Fig. 4a). During the same period the temperature T , varied between 18.2 °C and 35.5 °C (Barral et al., 2017; Song et al., 2019; Scotese et al., 2021), corresponding to a change in viscosity of 0.36 MPa·s (Fig. 4b). The latter variation is more than 70 times larger than the variation related to salinity.

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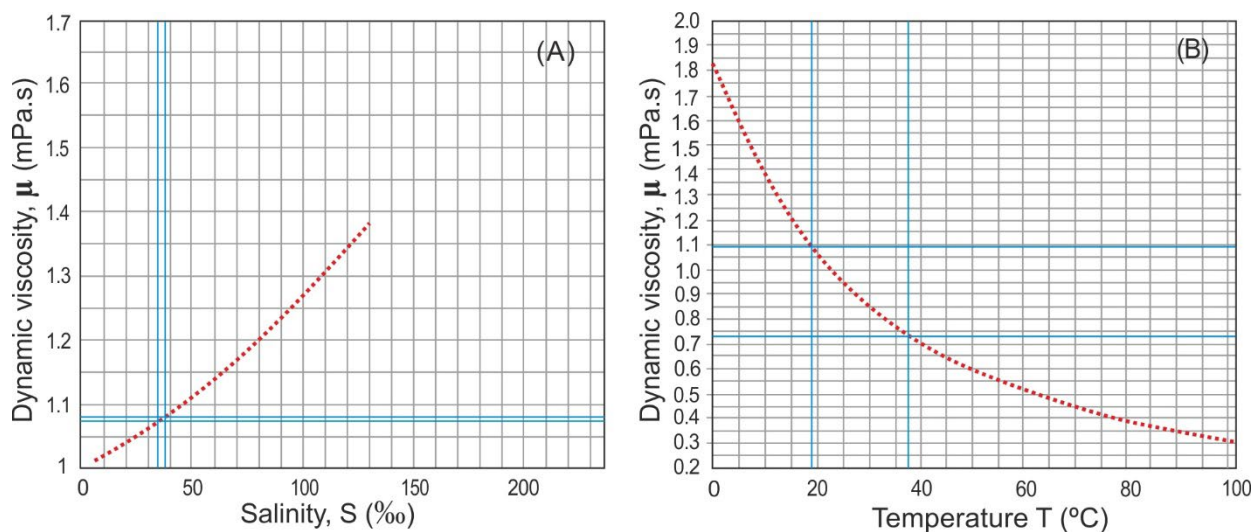


Figure 4. Salinity and Temperature vs Viscosity (modified after Qasem et al., 2020). The viscosity of saline water is a strong function of temperature and salinity and a weak function of pressure (Qasem et al., 2020). (A) calculated values of viscosity (μ), using the methods of El-Dessouki and Ettouney (2002) as a function of salinity at 20°C and 0.1 MPa; (B) effect of temperature on the viscosity (μ) using the methods of El-Dessouki and Ettouney (2002) at 32.33 ‰ and 0.1 Mpa.
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2.3. Complex patterns and fractal dimension

Complex patterns and nonlinear geometries are difficult to describe by formal analysis and documenting their link to morphogenetic processes supported by chemical and physical processes is challenging. Studies on chemical self-organization and chaos (Gershenson, 2025) have unlocked new viewpoints on biological pattern formation, and one of these biological
 150 patterns is the ammonite suture line: the intersection between the shell and the septa. The mathematical characterization of



suture complexity has traditionally been performed using the index of suture complexity (Ward, 1980; Saunders, 1985; Lemanis and Zlotnikov, 2023), that is, the ratio of the suture perimeter and the length of the segment joining the two extremities. Canfield and Anstey (1981) attempted a mathematical description of sutures using a Fourier series. However, this methodology cannot adequately describe complexity across a range of scales and only enables relatively simple suture lines to be characterized (Lutz and Boyajian 1995). Another way to quantify the degree of complexity is based on the use of fractal analysis. Various authors have described the self-similarity of ammonite suture lines (Long, 1985; Bayer, 1985; Damiani, 1986; Seilacher, 1988). Lutz and Boyajian (1995) indicate that ammonitic sutures include the necessary characteristics for self-similarity, while, in goniatitic and ceratitic sutures, this condition is more doubtful because they are self-similar over a shorter range of scale measurements. Ammonitic sutures often exhibit complex corrugations over a range of length scales, which can be quantified by a power scaling exponent or fractal dimension. A geometric pattern is fractal if it shows self-similarity (scale invariant) and follows a power law function over one or more orders of magnitude in length (Mandelbrot, 1983). Since suture lines are two-dimensional patterns lying in a plane, and exhibiting power scaling, they must have a fractal dimension between one and two (Peterman and Barton, 2019).

Using the FracLac module, the fractal analysis extension for ImageJ software (Karperien, 2004), we measured the fractal dimension of scanned suture lines using the box-counting method (Fig. 5). The method measures the scaling of a planar geometric pattern such as ammonite sutures. The fractal dimension (D_f) quantifies how suture patterns scale as a power law of size over some range of lengths and corresponds to the power scaling exponent of $N(r) = r^{-D_f}$. Where $N(r)$ = number of boxes occupied by the pattern and r = side length of the boxes (Fig. 5a–c). The data pairs r and $N(r)$ are plotted in log–log space and fit with a power law function (Fig. 5d). D_f measures the degree of space filling by the pattern.

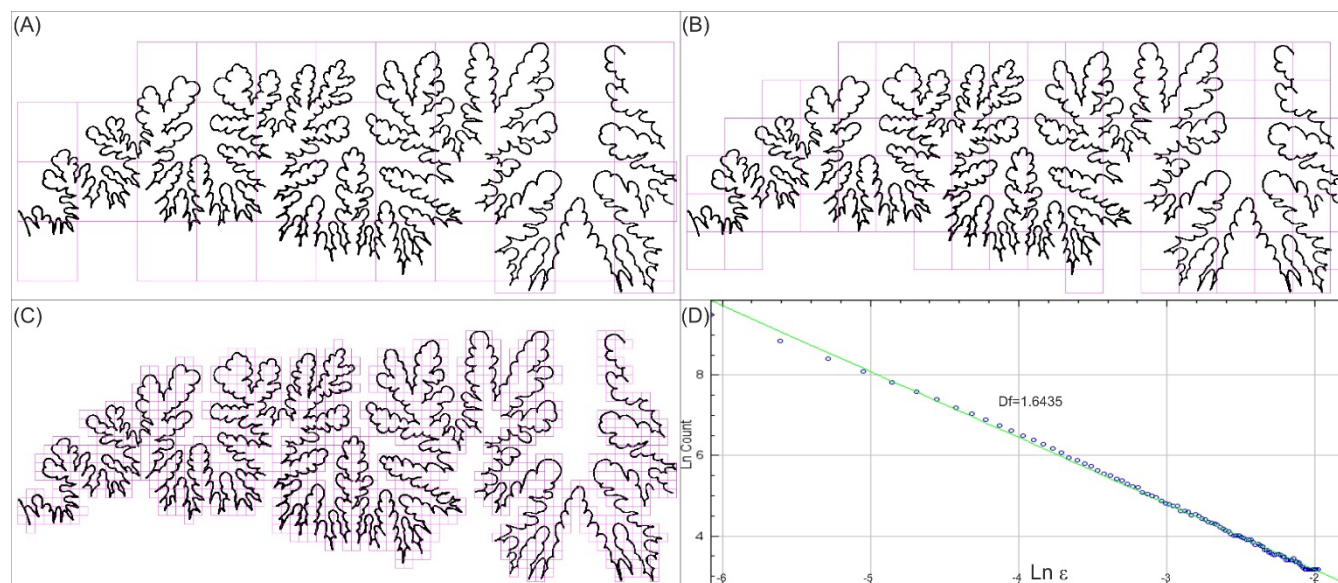


Figure 5. (A–C) Box-counting method showing the procedure to evaluate the degree of suture line complexity. Three steps of the process with boxes in purple color, and (D) fractal dimension of the Barremian ammonite *Eogaudryceras numidum* ($D_f=1.6435$) obtained using the extension FracLac of the software ImageJ (Kasperien, 2004).



3. Results

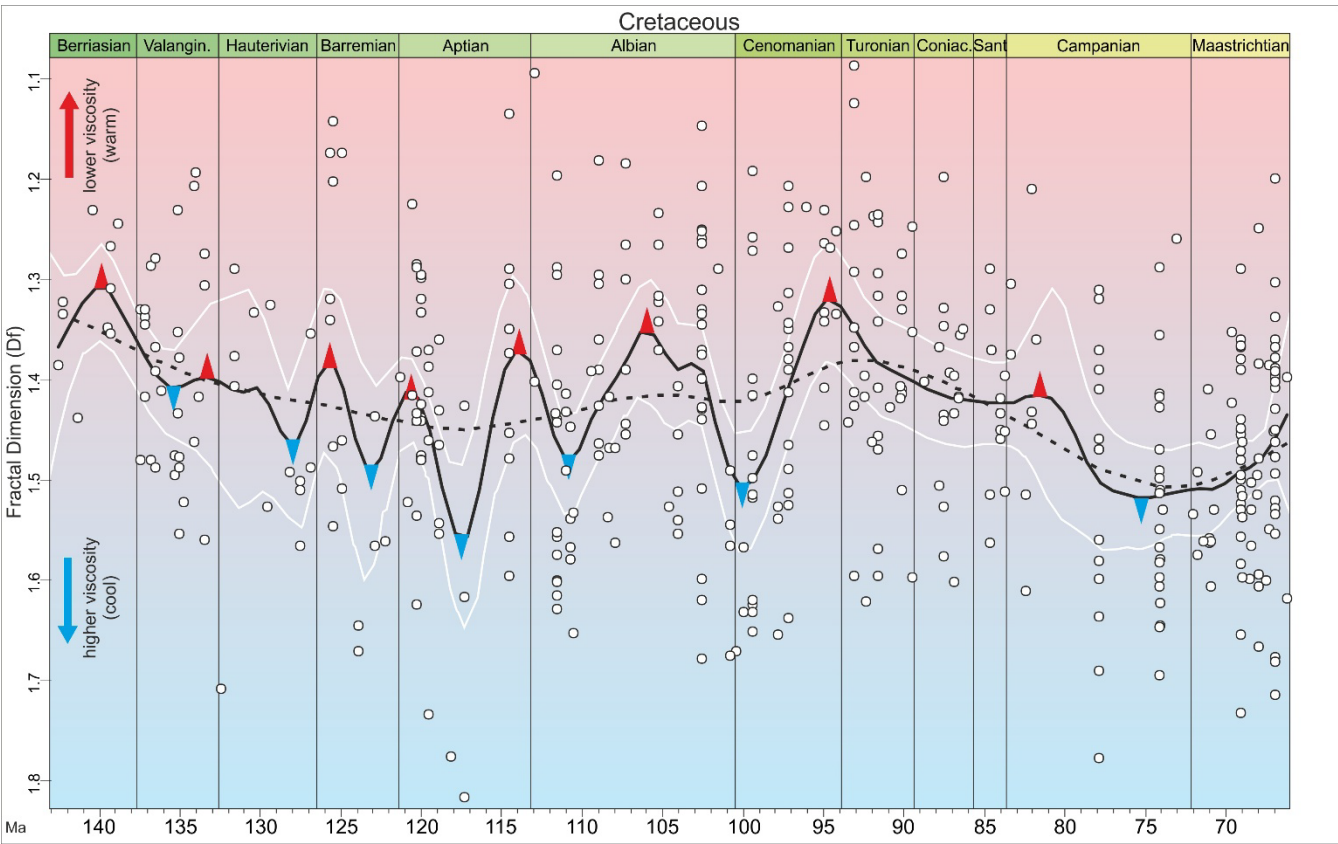
175 The dataset with c. 450 values of the fractal dimension of ammonite sutures combines published data (Peterman and Barton, 2018; Marriott and Chamberlain, 2021; Pérez-Claros, 2022) and new data analyzed in this study (Supplementary Material Table 1). The taxa analyzed have a short time range distribution (≤ 5 million years) and broad biogeographic distributions, spanning different paleolatitudinal ranges (Fig. 1). The larger group is from medium latitude (30-60°; 58%), and the smaller group represents more cosmopolitan taxa (0-90°; 3%), ranging from low to high latitude (Table 2). The average fractal dimension (Df) over the analyzed taxa is 1.4340 and shows a latitudinal trend, ranging from 1.3658 for low-latitudinal taxa to 1.4958 for high-latitudinal taxa, with an average for medium latitudes of 1.4464. The increase in sutural complexity from low to high latitudes is interpreted as evidence of a direct relationship with increased seawater viscosity and an inverse relationship with temperature.

Latitude		analysed sutures		Average Df
		amount	(% of total)	
0-30°	Low	18	4%	1,3658
0-60°	Low-Medium	105	24%	1,3936
30-60°	Medium	258	58%	1,4464
30-90°	Medium-High	32	7%	1,4773
60-90°	High	20	4%	1,4958
0-90°	Low-Medium-High	13	3%	1,4245

185 **Table 2. Average fractal dimension (Df) of ammonite suture lines grouped by Latitude.**

The fractal dimension (Df) was plot against the central age of each ammonite taxa (Fig. 6), and the points were interpolated using a polynomial curve Locfit (black solid line), to obtain the short-term variation of Df (about 6 Ma period), together with the 95% confidence interval (white lines) (Fig. 6). While the black dashed line is a polynomial smooth spline illustrating the long-term variation of Df (around 50 Ma period).

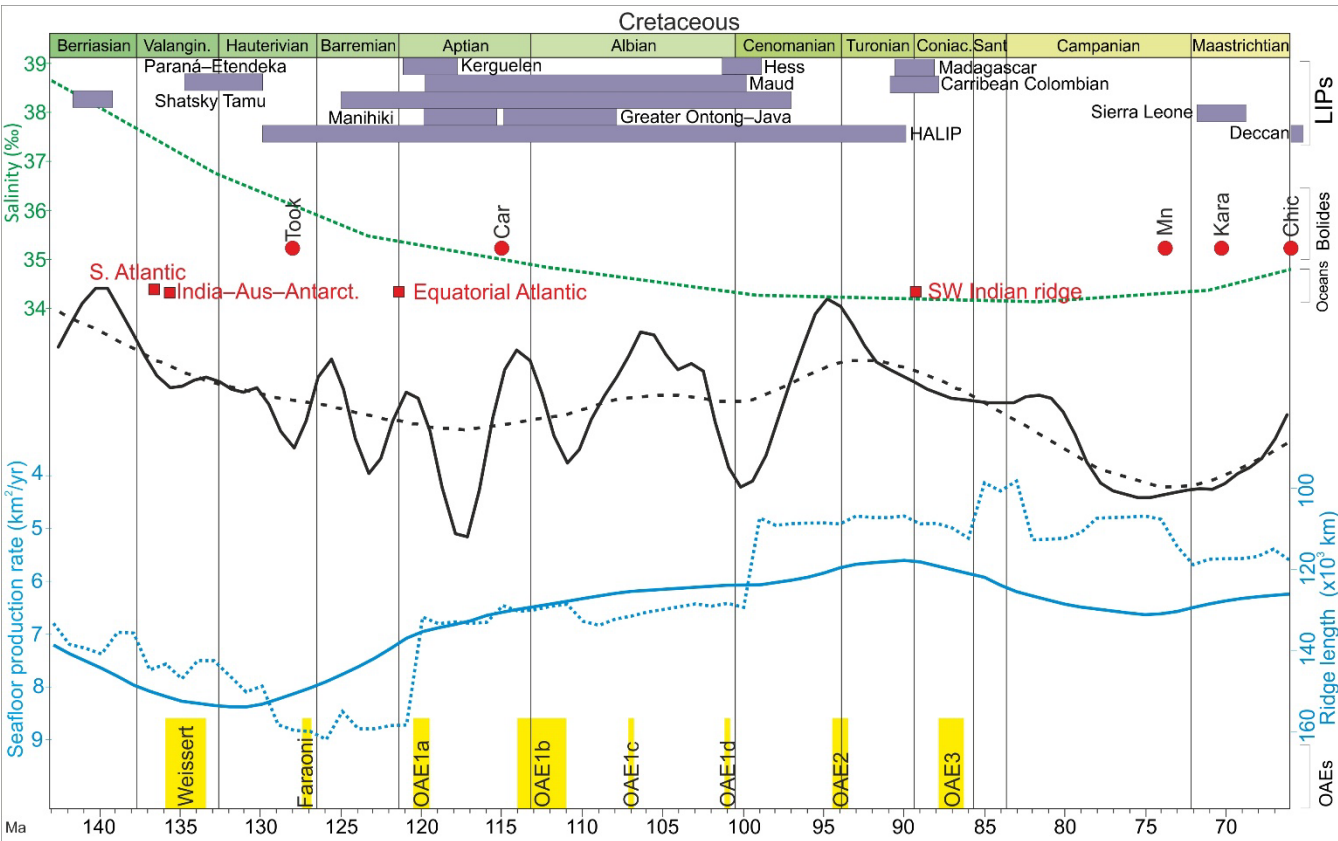
190 The fractal dimension curve represents a qualitative proxy for paleo-viscosity, in which the peaks and lows reflect variations in seawater paleotemperature, as we can neglect the effect of salinity on viscosity, as discussed previously. The fractal dimension (y-axis, Fig. 6) increases downward, indicating an increase in viscosity associated with cooler temperatures. The long-term fractal dimension curve shows an increasing trend of Df between 143–117 Ma, and a decrease between 117–93 Ma, followed by an increase during 93–75 Ma, and a final decrease until 66 Ma. This would be translated into Berriasian–lower Aptian cooling, upper Aptian–Turonian warming, Coniacian–Campanian cooling, and Maastrichtian warming. The black solid line represents the short-term fractal dimension curve and shows eight warm snaps (red triangles) and seven cold snaps (blue triangles).



200 **Figure 6. Fractal dimension curve (black line) of the Cretaceous ammonite suture lines, along with the fractal dimension Df (white dots) for each taxon (genus/species) against age (Ma, million years) and epoch based on Gale et al. (2020). Black line polynomial Locfit (nn=0.1, h=0.05, deg=2, R-package Locfit). White line 95% confidence interval; dashed black line polynomial Smooth Spline (df=2, spar=0.6, R-package splines). The red and blue triangles denote warm and cold snaps, respectively.**

4. Discussion

205 To evaluate the consistency of this method, we compared the fractal dimension curves with geological events that may have influenced the climate during the Cretaceous period, such as seafloor production, LIPs, and bolide impacts, or might represent variations in climate conditions like the OAEs (Fig. 7). We then assessed the results against published geochemical proxies, paleotemperature, and TEX86 curves (Fig. 8).

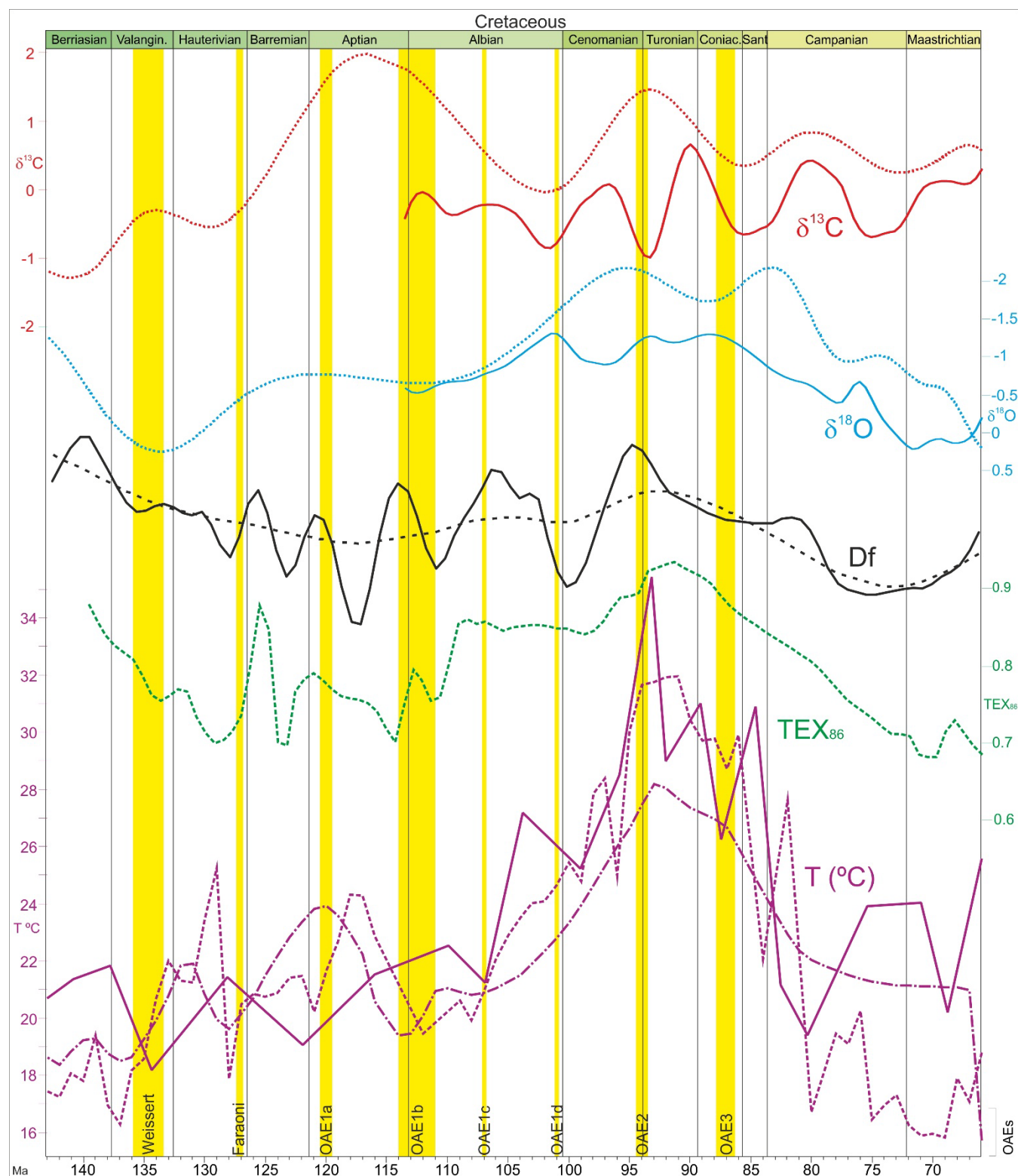


210 **Figure 7. Geological events that may have had an impact on the Cretaceous climate: LIPs (purple bars) after Scotese et al. (2020);**
salinity curve (green) after Hay et al. (2006); seafloor production rate (blue dashed line), ridge length curve (blue solid line), and
onset of major phases of ocean basin formation (red squares), after Gernon et al. (2024); bolide impact structures with diameter
>25 km (red dots) after Scotese et al. (2020): Took=Tookoonooka, Car=Carswell, Mn=Manson, Kara, Chic=Chicxulub. OAEs
(yellow bars) after Scotese et al. (2020), Dubicka et al. (2024), and Percival et al. (2025). Black solid line, fractal dimension curve
215 **(short-term), black dashed line (long-term) (see Figure 6).**

At first glance, the trend of the long-term fractal dimension curve (black dashed line, Fig. 7) shows a positive covariance with the seafloor production rate (blue solid line) and ridge length curves (blue dashed line) (Gernon et al., 2024). The latter two curves represent paleogeographic and paleoceanographic proxies indicating variations of deep oceanic basins with possible creation of seaways, and connections between high-latitude and low-latitude areas. During the Lower Cretaceous, the increase in seafloor production enhanced thermohaline circulation and oceanic heat transport, triggering global cooling (Fluteau et al., 2007; Poulsen et al., 2010; Ladant et al., 2020). During the Aptian–Turonian, a drop in seafloor production and ridge length seems to correspond with an increase in the long-term temperature as indicated by the fractal dimension curve, followed by a cooling period in the Coniacian–Campanian, again enhanced by the change in paleogeography, and a slight increase in temperature until the end of the Cretaceous. A positive covariance also exists between the short-term fractal dimension curve and the OAEs (Fig. 7). The latter are interpreted as the result of transient increases of global temperature (Jenkyns, 2010; Gernon et al., 2024), most likely associated with the greenhouse gases released during LIP



volcanism (Ernst et al., 2015). The OAEs represent well-established oceanic perturbations in the geological record and, apparently, within the uncertainty of the ammonite ages, the fractal dimension curve picks up most of them as warm snaps (Fig. 7). To be noticed is the presence of two warm snaps at c. 140 Ma and 82 Ma that might suggest global warming events not yet recognized. On the other hand, the OAE3 event is not seen in the curve, and it might suggest that the event represents a regional – not global – episode. The only anoxic event not depicted in the Df curve is the OAE1d. The possible cooling events associated with bolide impacts (Fig. 7) seem to be difficult to infer from the fractal dimension data, probably because of their characteristic short duration. In fact, their effect on climate depends on the height of injection into the atmosphere, and long-term cooling only occurs if the generated aerosols form in the stratosphere, where they have residence times of years to decades. By contrast, tropospheric aerosols are efficiently removed in a matter of weeks (Junium et al., 2022). A comparison between the fractal dimension and geochemical proxy curves (Prokoph et al., 2008; Barral et al., 2017) reveals a general correlation between the $\delta^{18}\text{O}$ curves and the long-term fractal dimension curve (Fig. 8), while the $\delta^{13}\text{C}$ curves show opposite trends during the Aptian–Albian periods. In any case, only a few of the OAEs are picked up by the isotope curves, such as the Weissert and OAE2 in the $\delta^{13}\text{C}$ data of Prokoph et al. (2018), the OAE1b in Barral et al. (2017), and the OAE1d, OAE2, and OAE3 in the $\delta^{18}\text{O}$ of Barral et al. (2017). A comparison with three paleotemperature datasets (Fig. 8) clearly shows the Cenomanian–Turonian greenhouse period corresponding to the OAE2, while the other OAEs are not picked up, except for the OAE1a event in the Scotese et al. (2021) curve.





245 **Figure 8. Comparison between geochemical proxies and fractal dimension curves. $\delta^{13}\text{C}$ curves (red color): dashed line after Prokoph et al. (2008), continuous line after Barral et al. (2017); $\delta^{18}\text{O}$ curves (light blue color): dashed line after Prokoph et al. (2008) and continuous line after Barral et al. (2017); Df-Fractal dimension curves in black color; TEX86 curve (green color) (O'Brien et al., 2017); Paleotemperature curves (purple color): continuous line after Barral et al. (2017); dashed line after Song et al. (2019) and dot-dashed line after Scotese et al. (2021). OAEs-Oceanic Anoxic Events.**

250 A notable feature is the decoupling between the paleotemperature curves (Fig. 8) and the $\delta^{18}\text{O}$ curve of Prokoph et al. (2008) (Fig. 8) in the Lower Cretaceous. In fact, the isotope curve shows a cooling trend in the Berriasian to Valanginian, while the paleotemperature indicates the opposite. Finally, a comparison between the fractal dimension curve and the sea surface temperature TEX86 curve (O'Brien et al., 2017) (Fig. 8) shows a consistent covariance in the Lower Cretaceous with a slight offset of the warm and cool snaps, probably due to the age range of the fossils used in the two methods.

5. Conclusion

255 In conclusion, this paper presents a new qualitative non-isotopic paleoclimate proxy based on the fractal dimension of a pattern generated through a biophysical process related to the formation of ammonite suture lines. The method was tested using c. 450 fractal dimensions of ammonite suture lines against geological processes that characterized the Cretaceous, demonstrating the reliability of this technique in detecting warm periods marked by OAEs compared to isotopic proxies. The method indicates that fractal analysis of complex systems could be key to understanding biophysical processes, thereby
 260 enhancing our knowledge of past and future climates. We plan to continue exploring the fractal analysis of ammonite suture lines by expanding the dataset, including the rest of the Mesozoic and extending further back to the Permian, when ammonitic sutures first appeared, intending to create a fractal dimension curve (paleo-viscosity) covering a large part of the Phanerozoic.

Author contributions

265 PG: Conceptualization, Methodology, Data Collection, Data Analysis, Writing Original Draft, Review & Editing;
 PA: Methodology, Data Collection, Writing Original Draft, Review & Editing;
 JM: Data Analysis, Writing Original Draft, Review & Editing;
 KHJ: Writing Original Draft, Review & Editing.

Competing interests

270 The authors declare that they have no conflict of interest.



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Review statement

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