

# Redating the formation of Lake Bafa, western Turkey: Integrative geoarchaeological methods and new environmental and dating evidence

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## Abstract

The ancient Gulf of Latmos is an iconic example of a dynamic landscape and humankind's historical relationship with it. Using extensive new primary data and original models for calibrating radiocarbon dates in transitional lagoon environments, we demonstrate that Lake Bafa (or Bafa Gölü, in Turkish) formed at a much earlier date than previously thought. In questioning the logical process by which previous dates were achieved, we re-examine the relationship between sedimentological data, archaeology and written history. We reassert the need to establish independently dated environmental data sets as the foundation of regional studies as distinct from archaeological and historical interpretive processes. **We conclude that Lake Bafa slowly transitioned to become an isolated lagoon sometime between the end of the second millennium B.C. and end of the first millennium B.C.; becoming a fully closed brackish lake during the second millennium A.D.** This marks a **major shift in our understanding** of the nature of human occupation and activity here during the last four millennia but also in the way we date ancient lagoons and integrate historical and environmental data in general.

## KEYWORDS

Büyük Menderes Valley, C-14 dating, Caria, multiproxy analysis, settlement history

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## 1 | INTRODUCTION

Lake Bafa in western Turkey formed when, at some point in the historic past, the advancing Büyük Menderes (ancient Maiandros) delta cut it off from the open sea and it is widely fêted as an exemplar of ancient human–geographic interactions. Previous geoaerchaeological studies of Lake Bafa have generally viewed it as being of secondary importance to the delta that formed it but our focus in this article is the lake itself—making this the first detailed, independent study of the lake's formation (although see Herda, Brückner, Müllenhoff, & Knipping, 2019).

That the Büyük Menderes progradation caused Lake Bafa to form was well known to ancient have no major effect on our approximate model writers (*Plin.Nat.2.41*; *Strab.7.2.11*; *Vitr.4.1.4-5*) but their writings need to be understood within particular historic and literary contexts (see below). The first geomorphological studies of Lake Bafa by Erinç (1978) and Eisma (1978) were based on these ancient sources (Brückner, 1997). Erinç (1978) concluded that Lake Bafa became separated from the sea in the ~third century A.D. whereas Eisma (1978) dated the closure to ~100 A.D. Erol (1996) took a different approach, mapping 13 different recordable delta lobes in the Büyük Menderes plain, positing a relative chronology for each lobe rather than absolute dates. Most recently, a model of asymmetric alluviation has been proposed by Müllenhoff (2005) which suggests bifurcated branches of the Büyük Menderes prograded at different rates. The northern branch started to close off Lake Bafa from the open sea around 200B.C., becoming fully separated between c. 1400 and 1600 A.D. (Herda et al., 2019; Müllenhoff 2005, pp. 41, 55, 62–63, 245). However, as Herda et al. (2019, pp. 36–60) make clear, the current dating evidence is open to interpretation.

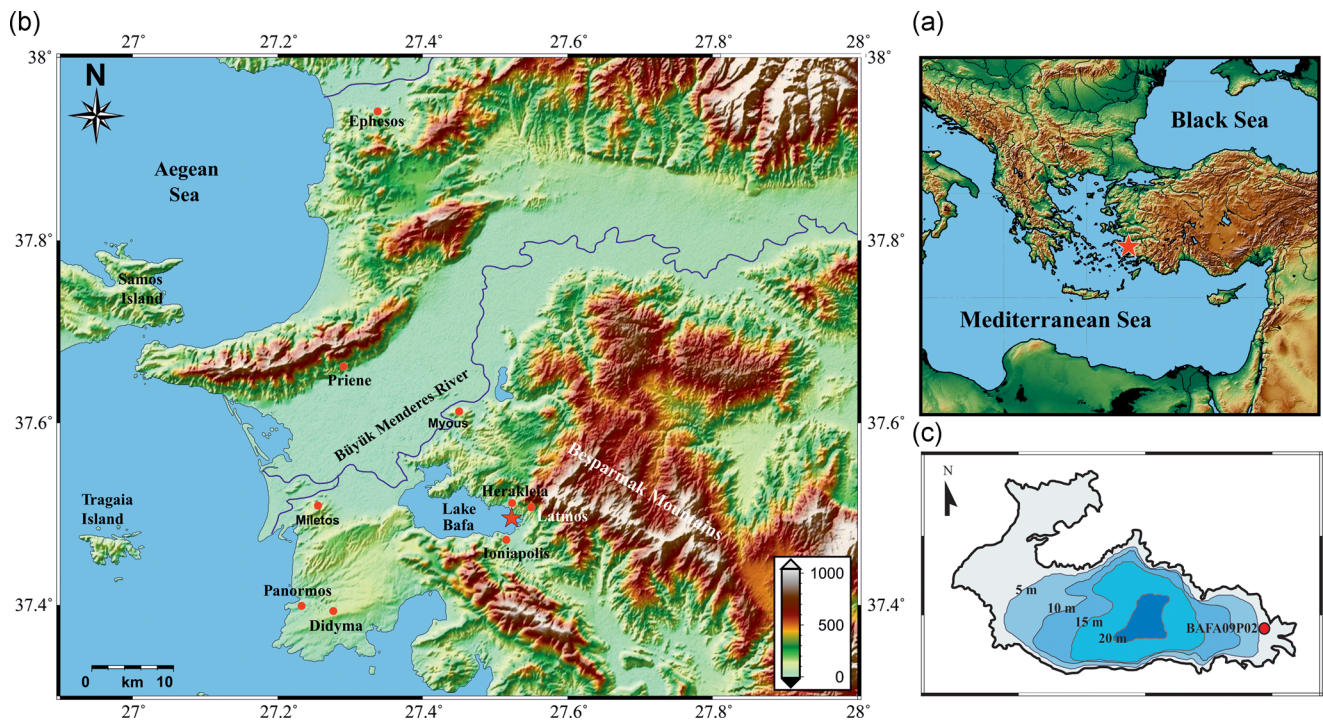
Historically, the process' impact on human settlement dominated the academic discourse but more recently the possible anthropogenic cause of the increased speed of progradation in the first millennia B.C./A.D. has gained importance (e.g., Bay, 1999; Brückner, 1996; Brückner, 2003; Brückner, Müllenhoff, van der Borg, & Vött, 2004; Brückner et al., 2006; Greaves, 2000, 2002; Kayan, 1999; Müllenhoff, Handl, Knipping, & Brückner, 2004, 2005; Herda et al., 2019; Thoenemann, 2011). Herda et al. state that the research aim has been “to create a kind of human or cultural geography—in effect, an anthropogeography—of the Maeander region” (Herda et al., 2019, p. 2) but such approaches do not always recognize the importance of natural processes upstream in the Büyük Menderes system (Greaves, 2010; Kazancı, Dündar, Alçiçek, & Gürbüz, 2009, p. 63; Gürbüz & Kazancı, 2019) or question the dating and context of the historical sources upon which they rely.

Being a by-product of the Büyük Menderes progradation, dating the formation of Lake Bafa itself has never previously been given direct consideration. The ancient harbors of Miletos, New Priene and Myous were central to Müllenhoff's work and provided typological dating evidence from pottery in anthropogenic layers (Brückner et al., 2006; Brückner, Müllenhoff, Handl, & van der Borg, 2002; Müllenhoff, 2005). They also provided sedimentological evidence and

<sup>14</sup>C samples, but anthropogenic “noise” (i.e., human disturbance) in some deposits and their proximity to archaeological sites may undermine their reliability. Large-scale human interventions in the sedimentary sequences near Ephesos, intended to counteract the effects of progradation (Kraft, Brückner, Kayan, & Engelmann, 2007; Stock, 2015; Stock, Pint, Horejs, Ladstätter, & Brückner, 2013), should also give us cause to question data from cores taken in, or near, ancient harbors. With additional core samples taken between Miletos and New Priene, Müllenhoff (2005) established a stratigraphic model of the asymmetrical progradation process but its dating still relied on dates from ancient literature.

Ancient historical sources have provided the fixed dates on which the chronological framework of the Büyük Menderes progradation and formation of Lake Bafa is constructed. Being based on such towering cultural figures as Herodotos, Pliny the Elder, Pausanias, and Strabo, we tend to attribute these historical “facts” with greater scientific significance than they deserve and this is a source of cognitive bias. Confirmation bias means that we inherently favor the first, or earliest, sources of information that we encounter over other, later sources of information when we make interpretations or evaluations—a process known as “anchoring” (Tversky & Kahneman, 1974). Even with the introduction of absolute dating methods, such as radiocarbon and varve dating from sedimentary cores (see Müllenhoff, 2005, pp. 192–193 and Knipping, Müllenhoff, & Brückner, 2008, respectively), the academic community continued to accommodate its scientific findings into the existing historical framework, rather than challenge it. In one example, even the observed scientific data itself was changed so that it would fit into the established historical dating framework (see Knipping et al., 2008, Figure 1 and Table 1 who changed an observed Sediment Accumulation Rate in sedimentary laminations in a core sample from Lake Bafa from 0.29 cm per annum to 0.22 cm). This over-reliance on historical sources for key dating evidence and interpretations is common within the discipline of Classical Archaeology, in which the written testimony of ancient authors is used to provide the basis of the historical narrative, into which new archaeological or historical discoveries are accommodated by making slight adjustments to the narrative, as required (Shanks, 1996, pp. 53–91; Greaves, 2010, p. 29). However, cognitive studies have shown that when using this “anchoring-and-adjustment” heuristic, subjects instinctively underestimate the extent of the adjustments that are needed to accurately accommodate new evidence (Epley & Gilovich, 2006) due to the greater significance they attach to primary evidence—in this case, historical sources. Archaeological evidence is similarly open to interpretation and there is nothing in the archaeological record of the region that provides definitive evidence for the closure of Lake Bafa (see Section 4).

Ancient historical sources and archaeology alone cannot provide a secure framework for understanding the evolution of Lake Bafa so, following Greaves' (2010) interpretative process, we set out to establish, for the first time, an independent, if approximate, chronology for the closure of Bafa Golü using scientific methods of palaeoenvironmental analysis and absolute dating. To do this we use an original core (BAFA09P02), the first to have been published from



**FIGURE 1** Location of the study area. (a) Study area on Eastern Mediterranean map. (b) Büyük Menderes Valley and ancient sites, red star indicates the location of the BAFA09P02 core. Both of the topographic maps have been prepared through GMT (Wessel, Smith, Scharroo, Luis, & Wobbe, 2013), version 5.2.1 using ETOPO1 relief model (Amante & Eakins, 2009). (c) Bathymetric map of Bafa Gölü (redrawn from Demir, 2007) and the location of the BAFA09P02 core [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

the region since Brückner, Müllenhoff and others in the 1990s and early 2000s (esp. Brückner, Herda, Kerschner, Müllenhoff, & Stock, 2017; Müllenhoff, 2005; see Herda et al., 2019, n. 3 for full bibliography) and the first to be analyzed using high-resolution micro-X-ray fluorescence ( $\mu$ XRF) automated core scanning. Unlike previous cores from Lake Bafa, our new core is not affected by anthropogenic contamination or inflow from the river and covers all three stages of the lake's geochemical and environmental evolution. Our  $\mu$ XRF analysis shows that as Lake Bafa became detached from the open sea, its environmental conditions changed and these conditions affected the faunal assemblage from whose shells we extract most of our radiocarbon dates. To take into account variables in the changing geochemical environment of the water body in which those shells grew, we used a Bayesian framework to model its transition from the open sea to the isolated lagoon and then to the brackish lake, and then applied that model to nine radiocarbon dates to establish an accurate age-depth model for BAFA09P02.

Our results show that Lake Bafa underwent a slow transition from an open marine environment to an isolated lagoon much earlier than previously suggested by historical, or combined historical and

radiocarbon, dating methods. We propose that Lake Bafa formed as an isolated lagoon sometime between the end of the second millennium B.C. and end of the first millennium B.C., earlier than current dating by perhaps as much as a millennium, and finally became a fully closed brackish lake during the second millennium A.D.

### 1.1 | Ancient writers' descriptions

Previous studies of Lake Bafa used ancient texts to date its formation (Aksu, Piper, & Konuk, 1987; Eisma, 1978; Erinc, 1978; Erol, 1996), even radiocarbon-based studies (e.g., Brückner, 1996; Bay, 1999; Knipping et al., 2008; Müllenhoff, 2005, and others). However, using historical texts in a positivist manner to derive *prima facie* factual data "robs them of ... their social significance" (Mac Sweeney, 2013, p. 12). In the collective literary imagination of ancient authors the Maeander Valley was not "a 'natural' space, objectively determined by geological facts." (Thonemann, 2011, p. 339), rather it was an eternally shifting, even "magical," landscape. Other than their repeated motifs of inlets, shoals, river-mouths, and bays

**TABLE 1** Classification of freshwater and marine genera of ostracods (Boxshall et al., 2014) identified in BAFA09P02 core

Freshwater genera	Brackish water genera	Marine genera
Candona, Darwinula, Limnocythere,	Cyprideis, Leptocythere, Loxoconcha	Acanthocythereis, Bosquetina, Bythocythere, Costa, Cytherella, Cytheridea, Hiltermanicythere, Paracytheridea, Paradoxostoma, Pontocypris, Propontocypris, Pterigocythereis, Xestoleberis

indicative of any alluvial coastline, there is little “hard” scientific data in the ancient sources so it is inappropriate to call ancient writers like Herodotus “geoarchaeologists” (c.f. Herda et al., 2019, p. 21).

The most cited sources of chronological data are the Greek historian Herodotus (lived c.484–c.428 B.C., *Hdt.*2.29; 7.26); the Roman geographer Strabo (lived 64 B.C.–23 A.D., on *floruit* see Syme, 1995, p. 356–367, *Strab.*14.1.8–10 [C636]), the Roman architect Vitruvius (lived c.80–70 B.C.–15 B.C., *Vitr.*4.1.4–5), the Roman natural philosopher Pliny the Elder (lived 23–79 A.D., *Plin.Nat.*2.41) and the Roman travel-writer Pausanias (*floruit* c. 150–180 A.D., *Paus.*7.2.11). Herodotus, Strabo, and Pausanias were all born in Asia Minor and were well-traveled (Dueck, 2000, 2017, on Strabo), although how much first-hand experience they had of this landscape is unknown. Ancient geographical writing spanned many different literary genres (Dueck, 2012), each with its traditions and authors quoted from other works, now lost, leading to intertextuality (e.g., Nichols, 2017, on Vitruvius). They also took inspiration from one another, as when Pausanias modeled his work on Herodotus (Bowie, 2001). In referencing others’ work, they removed that content from its intended context and by culling them in turn for historical “facts,” we do the same.

Even when “scientific” geography emerged as a genre, there were sub-genres within it—cartography, mathematical geography, and descriptive geography (Dueck, 2012). Strabo wrote descriptive geography (Dueck, 2000) and although he used maps, he was no cartographer (Moret, 2017). Of the Gulf of Latmos he wrote: “it is a voyage of about 100 stadia from Herakleia to the small town of Pyrrha” (*Strab.*14.1.8); “The voyage from Miletos to Herakleia, going through the gulfs, is a little more than 100 stadia, but the straight voyage to Pyrrha from Miletos is only 30 [stadia].” (*Strab.*14.1.9); and “From Pyrrha to the outlet of the Maiandros is 50 [stadia], a place with shoal waters and marshes. Sailing inland 30 stadia in rowboats there is the city of Myous.” (*Strab.*14.1.10, translation; Roller, 2014). Strabo placed emphasis on precise-seeming distances but we can question his measurements’ accuracy, their transmission by scribes, and even the units of measurement used—of which the Greek *stade* is just one (Geuz & Guckelsberger, 2017). The location of the *πολίχριον* (LSJ s.v. “fort, small town”) of Pyrrha is unknown. As early as 1832, Pyrrha was identified with Sarikemer (Cramer, 1832, p.393) although this tentative assumption is not archaeologically confirmed (Herda et al., 2019, pp. 69–70). If true, then by the early first century B.C. it was possible to cross the mouth of Lake Bafa by land. Following this logic, if one tries to place the river mouth (of which there were two according to Müllenhoff’s, 2005) asymmetrical alluviation hypothesis), which was located 50 stadia (7.85 km) from Pyrrha, then it could be almost anywhere, including the current coastline. Strabo states that going inland 30 stadia (4.83 km) by rowboats, one comes to Myous but does not specify whether that journey is in a straight line, as he specifies from Miletos to Pyrrha, or following the sinuosities of the gulf, as from Miletos to Herakleia (*Strab.*1.14.10). In this manner supposition is built on supposition in a conundrum of logical inference until we realize the limitations of using sources such as Strabo in an instrumentalist way.

The apparent precision of Strabo’s detailed attention to coastal routes is because he derives his information from tales of

circumnavigation in the *periplous* genre (Dueck, 2000; Shipley, 2011). This literary inheritance is evident in his use of language such as the Greek word *πλέον* (LSJ s.v. “a voyage” or “a sail”) used to describe the journey from Pyrrha to the river mouth. Similarly, recent digital network analysis of Herodotus’ text shows that his construction of terrestrial space follows a unilateral hodological model in which locations existed along “ways” or “paths” (Barker, Isaksen, & Ogden, 2015). Even when read as descriptive geographies, ancient sources provide little unequivocal evidence about the region’s physical character. In a passage concerned with mythical foundation stories, Pausanias describes the abandonment of Myous in the distant past (*Strab.*7.2.11). His reason for Myous’ abandonment is an inlet to the sea became blocked by the river, creating a marsh where *κώνωψ* bred. Although widely cited as evidence that the salinity of the waters had changed, allowing mosquitoes to breed (e.g., Sallares, 2002), the meaning of the ancient Greek word *κώνωψ* (LSJ s.v. “gnat, mosquito”) is not fully understood and could mean any biting insect. This, combined with its vague mythic setting, means Pausanias 7.2.11 cannot be used to date the lagoonal transition at Myous.

When we understand the worlds described by ancient authors as literary creations, we begin see that Pausanias’ “Greece” is a nostalgic amalgam constructed for rhetorical purposes from the tales of local informants (Elsner, 2001; Jones, 2001). Likewise, Herodotus (*Hdt.*5.32–36) mentions a fleet of 200 ships harbored in Myous in 499 B.C.—15 years before he was born—by which time we suggest Lake Bafa was an isolated lagoon and when core data show that Myous’ harbor certainly was (Brückner et al., 2002). Vitruvius wrote: *Myunta quae olim ab aqua est devorata* “Myous which was once engulfed by the water” (*Vitr.*4.1.4–5)—the Latin *quae olim* (“which once”) decisively places this event in the historical past when he was writing in the first century A.D. and he was employing the past as part of a rhetorical construct (Nichols, 2017). Also in the first century A.D., Pliny the Elder wrote: “[Nature] has taken islands away from the sea and joined them to the land ... Hybanda, once an Ionian island is now 25 miles distant from the sea” (*Plin.Nat.*2.41, translation Rackham, 1942) suggesting that he is referring to a very distant past indeed. Focussed textual analysis shows that these authors were constructing imagined geographies of the past, not describing their real-world observations.

The most prosaic ancient source we have is the *periplous* of Pseudo-Skylax (99.1), which states that Herakleia was accessible by sea in the fourth century B.C. (Shipley, 2011) by which time Lake Bafa was an isolated lagoon. This is possible because an isolated lagoon phase must be connected to the open sea and that connection could be a sea passage of considerable size, allowing for the free passage of ships yet sufficiently constrained to change its geochemistry.

## 1.2 | Regional setting

Lake Bafa is a remnant of the ancient Gulf of Latmos, formed when the advancing Büyük Menderes delta cut off a large water body from the open sea. It is located at the western end of the east-west

oriented Büyük Menderes graben (Figure 1) in the tectonic graben zone of the Menderes Massif metamorphic complex (Bozkurt & Oberhänsli, 2001). The Büyük Menderes graben is an extension zone and the subsidence rate estimations, from spatially sparse data, are between 0.6–1 mm/yr on average (Mozafari, Sümer, et al. 2019; Mozafari, Tikhomirov, et al., 2019). Due to tectonic activity and climatic factors there is a complex and hotly debated history of sea level changes on the western coast of Anatolia (Brückner, Kelterbaum, Marunchak, Porotov, & Vött, 2010). During the last 6,000 years, it is claimed that the Aegean coast experienced up to 2 m of regression (Kayan, 1997). The evolution of the Büyük Menderes delta through lobes and dejection cones was examined in detail by Erol (1996).

It has been proposed by Kazancı et al. (2009) that the Büyük Menderes Graben was inundated by the Aegean Sea four times from middle-late Pleistocene to the present day with the final inundation being relatively rapid and occurring between 7000 and 3500 BP. Other alluvial deltas in western Anatolia have been subject to geoarchaeological study, including the Karamenderes at Troy (Kayan, Öner, Uncu, Hocaoglu, & Vardar, 2003), the Madra Çayı near Ayvalık (Lambrianides & Spencer, 2007), the Küçük Menderes at Ephesos (Kraft et al., 2007; Stock, 2015; Stock et al., 2013) and the Esen Çayı at Xanthos (Écochard et al., 2009; Fouache et al., 2012; Kraft, Kayan, & Erol, 1980), but the Büyük Menderes is by far the largest and most complex of any of these.

The lake bed is composed of Paleozoic augen gneiss to the north and Mesozoic aged carbonates to the south. The eastern and western flanks of the lake are small alluvial plains and Menderes alluvium, respectively. A schist sequence outcrops to south-west of the lake (Çağlayan, Öztürk, Sav, & Akat, 1980; Dürr, 1975; Graciansky, 1966; Konak, Akdeniz, & Öztürk, 1987; Okay, 2001). Lake Bafa is an important wetland and a protected habitat for many rare species of flora, fauna and marine life (Resmi Gazete, 1994).

The lake is oriented west-northwest to east-southeast and is 15.3 km long, with an average width of 4.5 km and water depth of 21 m (Kazancı, Girgin, & Dügel, 2008). It is fed by small ephemeral streams from Beşparmak Dağ Mountain to its east and by winter runoff. It is a mesohaline lake (8–13‰) with an annual temperature range of 8–25°C and pH values between 7.8 and 8.3.

The region is subject to the effect of a Mediterranean type climate and receives intensive precipitation in winter but almost none in summer. During intense periods of precipitation, the Büyük Menderes Valley can become inundated, making it a flood plain which then feeds into Lake Bafa.

## 2 | MATERIALS AND METHODS

### 2.1 | Core sampling and analysis

In 2009, a continuous 298 cm long core (BAFA09P02) was recovered from Lake Bafa at a water depth of 4.9 m (37°29.733'N–27°31.363'E; see Figure 1) using a piston hammer corer mounted on a floating

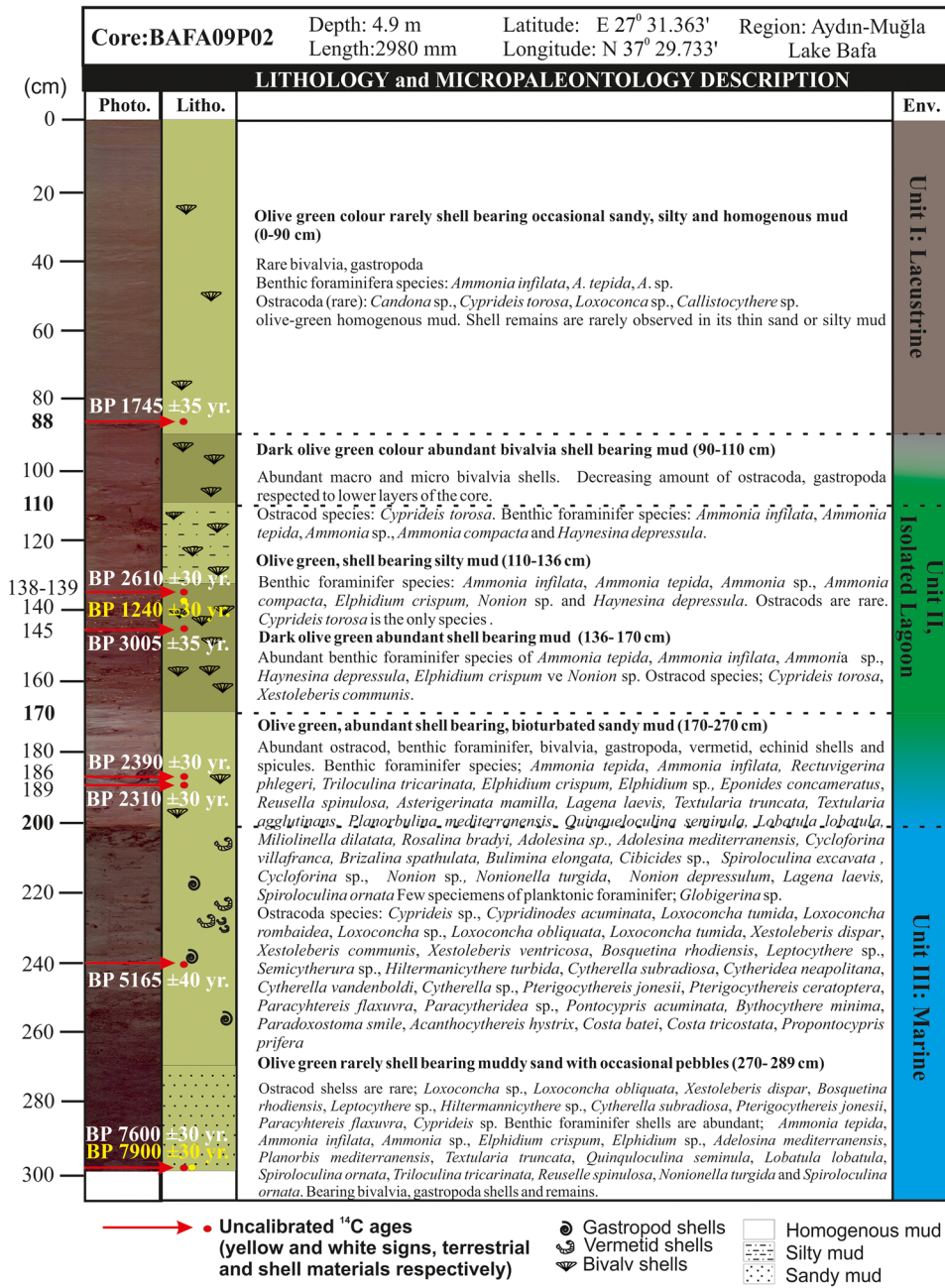
platform. The core sample was taken from the eastern part of the lake, which is the optimal location to avoid the dominant sediment input from the Büyük Menderes (Knipping et al., 2008). The core was split in half in the laboratory and a lithological description was done by eye (Figure 2). The core's geochemical composition was determined using an ITRAX  $\mu$ XRF (Mo X-ray source at 60 kV, 50 mA, and 8 s exposure time) core scanner at 200  $\mu$ m resolution at the ITU EMCOL Core Analysis Laboratory (<http://www.emcol.itu.edu.tr/>).

The core was scanned using a Geotek Multi-Sensor Core Logger (MSCL) at 0.5 cm resolution, for magnetic susceptibility (MS;  $\times 10^{-6}$  SI). Total organic (TOC) and inorganic (TIC) carbon analysis (SHIMADZU SSM-5000A Solid Sample Module) on 5 g ground freeze-dried samples at 5 cm resolution was also undertaken. A total of 50 mg of each sample was combusted at 900°C for total carbon (TC) and at 200°C after oxidization with 85% concentrated phosphoric acid for TIC measurements. Both the MSCL and TOC/TIC analyses were carried out at ITU-EMCOL.

Samples weighing approximately 10 g were sieved through a 63  $\mu$ m mesh with filtered water for micropaleontological analysis. A binocular stereomicroscope was used for identification of benthic foraminifer and ostracod species (Tables 1 and 2). The most abundant and continuous species, *Ammonia tepida*-*Ammonia* sp. (b. foraminifer) and *Cyprideis torosa* and *Xestoleberis* sp. (ostracod), were selected for stable isotope analysis at 5 cm resolution.

To reveal geochemical inter-relationships between  $\mu$ XRF data we applied principal component factor analysis (with varimax rotation and a selection of components explaining almost 80% of all the variance), which is a data exploration method that uses linear relations between variables. Since  $\mu$ -XRF data fulfill the conditions explained in Filzmoser, Hron, and Templ (2018, Ch. 1), factor analysis on  $\mu$ -XRF data should be evaluated through compositional data statistics. Compositional data should first be transformed to a different coordinate system that is suitable to Aitchison geometry (Pawlowsky-Glahn & Egozcue, 2001). Suitable transformation through the available ones is the transformation. On the other hand, the covariance matrix of transformation is singular and this makes it impossible to use in analyses which require the inverse of covariance matrix. This problem is solved by finding the covariance matrix of the data in isometric logratio space and back-transforming to space (Filzmoser, Hron, Reimann, & Garrett, 2009). As factor analysis depends on second-order statistics, we applied robust statistical methods to the data through the analysis (Filzmoser et al., 2009). All of the procedure described in this study is handled using the robust-compositions package (Filzmoser et al., 2018) in R, which applies robust statistical methods To overcome the flaws of second-order statistics. Before starting the analyses, to minimize the analytical errors, the data were subjected to a first-order Savitzky-Golay filter (Savitzky & Golay, 1964) with a window length of 11 and then each profile has been resampled 1 in 11 consecutive elements.

MS is a widely used proxy in palaeoenvironmental studies (Cohen, 2003). It is dependent upon the mineral composition of the sample and also depositional conditions. In a body of water, magnetic minerals are primarily detrital, and can therefore, be used to indicate



**FIGURE 2** Lithostratigraphic and micropaleontological description of the BAFA09P02 core. Red arrows at the left indicate the depth of the <sup>14</sup>C dated materials. Yellow dates are uncalibrated terrestrial material and white ones are uncalibrated material which needed a reservoir correction [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

**TABLE 2** Ecology of benthic foraminifera species (Kaiho, 1999; Kaminski et al., 2002; Murray, 2006; Sakıncı, 1998), identified in BAFA09P02 core

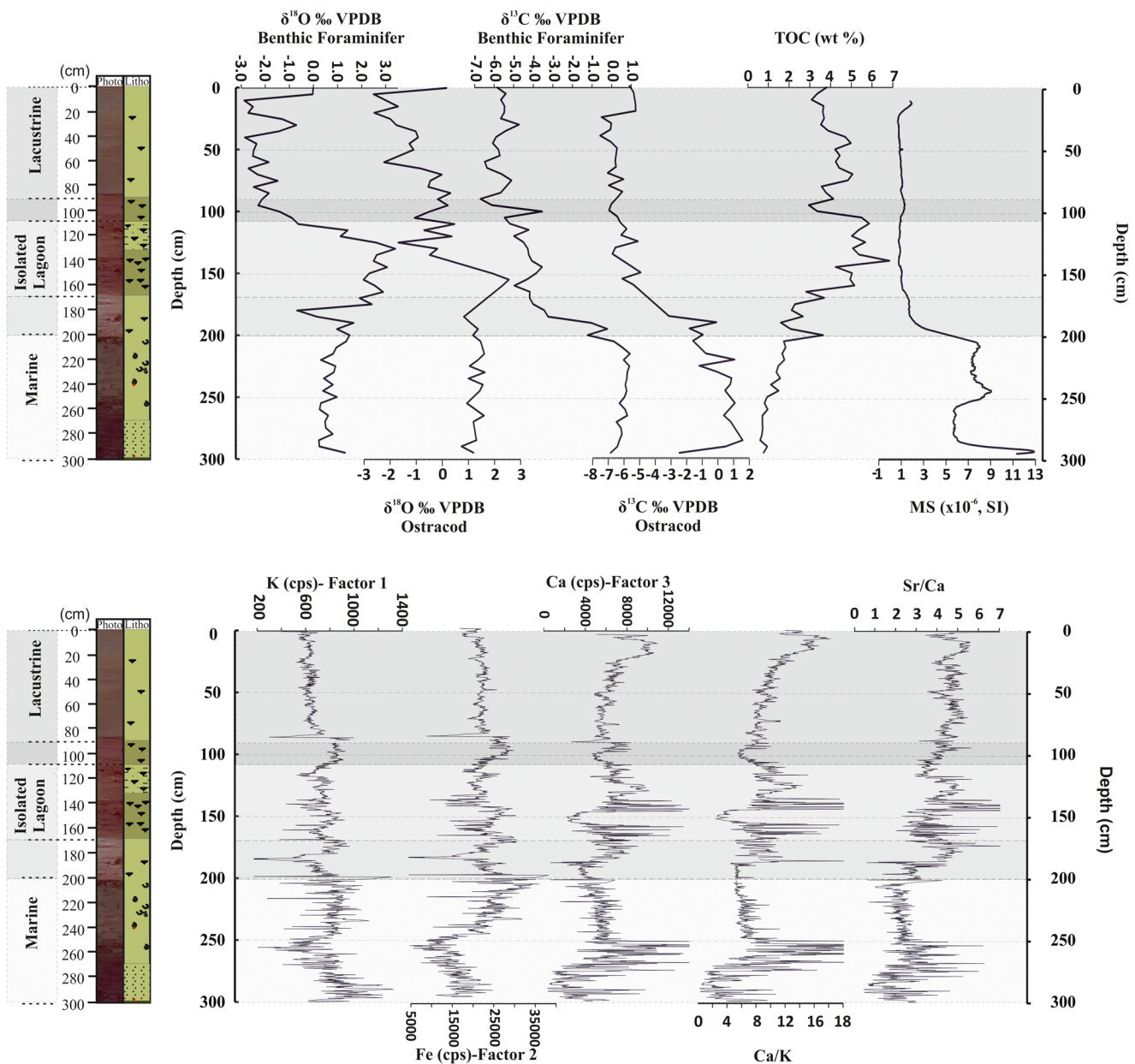
Environment	Dysoxic-suboxic and low salinity	Dysoxic-suboxic
Brackish-Lagoon	<i>Ammonia inflata</i> , <i>A. beccarii</i> , <i>A. compacta</i> , <i>A. tepida</i> , <i>Ammonia sp.</i> , <i>Haynesina depressula</i> , <i>Spiroloculina</i>	<i>Adelosina mediterraneis</i>
Marine	<i>Asterigerinata mamilla</i> , <i>Cycloforina villafranca</i> , <i>Cycloforina sp.</i> , <i>Eponides concameratus</i> , <i>Lobatula lobatula</i> , <i>Rectuvigerina phlegeri</i> , <i>Reusella spinulosa</i> , <i>Rectuvigerina phlegeri</i> , <i>Reusella spinulosa</i> , <i>Rosalina bradyi</i> , <i>Spiroloculina</i> , <i>Textularia</i> , <i>Triloculina tricarinata</i>	<i>Elphidium crispum</i> , <i>Elphidium sp.</i> , <i>Bulimina elongata</i> , <i>Lagena laevis</i> , <i>Planorbis mediterraneis</i> , <i>Nonion depressula</i> , <i>Nonion sp.</i> , <i>Nonionella turgida</i>

relative differences of lithogenic (allochthonous) and authigenic/biogenic contributions to the sediment. Furthermore, redox (reduction–oxidation reaction) conditions during early diagenesis in anoxic sediments can reduce MS values (Çağatay et al., 2014).

Potassium (representative element of f1) supply often increases during periods of rapid erosion and terrestrial sediment discharge into water bodies (Cohen, 2003). K (f1) is a lithophile element and expected to be abundant as a detrital material such as illite, mica and K-feldspar. It may also precipitate as authigenic, but only under highly saline conditions (Engström & Wright, 1984). The major bedrock constituents of Mn and Fe (f2) are redox-sensitive elements and can give important clues to deep water oxygen conditions. Even though Mn is more redox-sensitive than Fe, iron was chosen as a representative of f2 as it has the highest factor

value (Figure 3). In most surface oxygenated sediments of deep basins and shelves, Mn and Fe are highly enriched as Mn/Fe-oxhydroxide (Calvert, 1990; Calvert & Pedersen, 1993; Cronan, 1980; Lyons, Berner, & Anderson, 1993; Shaw, Gieskes, & Jahnke, 1990; Thomson et al., 1995). The abundance of Ca in sediments may be related to either detrital carbonate or biogenic carbonate. However, it is more likely that Ca precipitates as endogenic carbonate minerals and skeletal carbonates from invertebrates (Chivas, De Deckker, & Shelley, 1983, 1986a, 1986b; Cohen, 2003; Valero-Garcés et al., 1996). High Sr/Ca likely indicate the presence of aragonite which requires warm, shallow waters (e.g., Croudace, Rindby, & Rothwell, 2006).

TOC enrichment in marine and lacustrine environments may occur under conditions of high primary productivity in the water



**FIGURE 3** Three different environments in the Bafa Gölü basin by comparison multiproxy data, and lithology of BAF09P02 core [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

body and high preservation under static, anoxic conditions (Demaison, 1991; Pedersen & Calvert, 1990). During a marine phase, the high oxygenation (see Fe interpretation above) suggests lower organic matter production and/or preservation. Biological productivity in coastal lagoons is exceptionally rich due to nutrient input from run-off and agricultural irrigation (Gamito, Gilabert, Diego, & Perez-Ruzafa, 2005).

Oxygen isotope ratios in carbonates may be indicators of temperature, salinity and the isotopic composition of the surrounding water and are dependent upon the evaporation/precipitation ratio.  $\delta^{18}\text{O}$  enrichment will, therefore, differ between marine, lagoon, or lake environments (Craig & Gordon, 1965; Gat, Adar, & Alpert, 2001).

The carbon isotopic composition of sea/lake water is affected by biochemical fractionation due to the formation and decay of organic matter and the physical fractionation through the gas exchange of sea/atmosphere at the boundary (Broecker & Maier-Reimer, 1992). However, in closed systems  $\delta^{13}\text{C}$  values depend on water balance, organic productivity, and the geological composition of rocks in the drainage basin. In saline lakes  $\delta^{13}\text{C}$  values are typically higher than in freshwater cases (Leng & Marshall, 2004).

The multiproxy palaeoenvironmental data are unequivocal and there is a clear concordance in the results achieved by different

machines/laboratories and forms of analysis, all showing the transitions and phases described below (see Section 3).

## 2.2 | Radiocarbon ( $^{14}\text{C}$ ) sampling and analysis

To place our core into absolute (i.e. calendar) time we employ the radiocarbon ( $^{14}\text{C}$ ) ages obtained from our core to construct an age/depth model for the full length of the core, from top to bottom. In total we were able to sample and analyze nine usable radiocarbon ( $^{14}\text{C}$ ) dates from the 2.9-m long core BAFA09P02 and combine them into a single age model. Six analyses were on shell material (in situ unbroken bivalve and ostracod shells at 88, 139, 145, 189, 240, and 298 cm) and one each on coral (at 186 cm), charcoal (~2-year twig, at 298 cm) and a seed (*Brassicaceae*, specifically *Brassicaceae Burnett* [syn. *Cruciferae* A.L. de Jussieu] at 139 cm; Table 3) and a core-top sampling date of A.D. 2009 (treated as A.D. 2009  $\pm 5$  through the age model). AMS radiocarbon dating was carried out at University of Arizona and Beta Analytic Laboratories in the United States.

Detailed description and discussion of sampling issues, marine reservoir ( $\Delta R$ ) corrections, and comparison to previous radiocarbon ( $^{14}\text{C}$ ) dating studies of Lake Bafa are presented in the Supporting Information.

**TABLE 3**  $^{14}\text{C}$  dates for the Bafa core

Lab code or context	Depth (cm)	$\delta^{13}\text{C}\%$	$^{14}\text{C}$ age years BP	SD	Material	68.2% hpd (-BC/AD)	95.4% hpd (-BC/AD)
Coretop	0					2005 to 2015	2000 to 2020
AA91152	88	-4.3	1745	35	Shell, bivalve	1456 to 1523	1430 to 1570
90 cm Transition (end trans. to brackish water)	90					1427 to 1516	1355 to 1565
110 cm Transition (start trans. isolated lagoon to brackish water)	110					1065 to 1265	966 to 1353
Beta-466075	138	-4.0	2610	30	Shell, bivalve	693 to 754	678 to 808
Beta-470525	139	-23.6	1240	30	Seed, Brassicaceae	690 to 740	671 to 799
AA91151	145	-3.3	3005	35	Shell, bivalve	321 to 435	261 to 528
170 cm Transition (end trans. marine to isolated lagoon)	170					-126 to 70	-205 to 176
Beta-466076	186	-2.7	2390	30	coral	-326 to -233	-362 to -194
Beta-498189	189	-3.8	2310	30	Ostracod shells	-347 to -274	-377 to -218
200 cm Transition (start trans. marine to isolated lagoon)	200					-1431 to -649	-1955 to 441
AA91153	240	+0.7	5165	40	Shell, bivalve	-4308 to -4174	-4336 to -4063
Beta-470524	298	-24.8	7900	30	Charcoal, twig	-6772 to -6680	-6822 to -6650
Beta-466077	298	+2.1	7600	30	Shell, bivalve	-6772 to -6677	-6826 to -6646
Core Bottom	300					-6832 to -6689	-6992 to -6654

Note: Beta-466076 falls into the transition period from marine to the isolated lagoon. AA91152 falls into the transition from isolated lagoon to a brackish water lake. Gray shading indicates transition zone. The right-hand columns list the 68.2% highest posterior density (hpd) and 95.4% hpd ranges for the dated samples and the transitions from the "preferred" age-depth model in Figure 4. For details and considerations of other scenarios, see the Supporting Information. Note each run of such models yields slightly varying outcomes within the possible constraints. To illustrate this, the results listed in Table 3 come from one run of this model, whereas the slightly differing results for the same model in Table S4 come from a different run.



### 3 | RESULTS

#### 3.1 | Core lithostratigraphy and biostratigraphy

Three distinct units can be discerned in BAFA09P02 by their lithostratigraphic and micropalaeontological properties.

##### 3.1.1 | Unit III (298–200 cm)

This unit consists predominantly of green-colored, bivalve bearing sandy mud with 14 Mediterranean benthic foraminifer genera and 12 marine ostracod genera (see Figure 2 and Table S1). Between 298 and 270 cm, it is olive green muddy sand with rare shells and poorly sorted pebbles of maximum 5-cm diameter. The pebble and sand with mollusc shells suggests a low water level, high energy environment, typical of a beach. Between 270 and 170 cm, the mud is sandy and olive green with abundant macro and micro bivalve, gastropod, vermid, echinid plate, and spicule remains. A wide variety of benthic foraminifera and ostracod species are present (see, Figure 2 and Tables 1 and 2). The planktonic foraminifera *Globigerina* sp. species were only observed at 195 cm. The observed fauna gradually changes between 200 and 170 cm.

##### 3.1.2 | Unit II (170–110 cm)

Between 170 and 136 cm, the sediment is composed of dark olive-green homogeneous mud. Some layers bear abundant bivalve and gastropod shells. In our study, we observe a decrease in the variety of benthic foraminifera and ostracods as compared to Unit III. In this interval we also observed mostly brackish water, lagoon and dysoxic-suboxic species of benthic foraminifera that inhabit conditions of low salinity (Table 2) and non-marine ostracod species, except *Xestoleberis* (which inhabits lagoon environments). This genus was only observed at 151–150, 146–145, 121–120, and 116–115 cm intervals. Between 136 and 110 cm there is olive-green silt but with relatively fewer shell remains. Abundant brackish water representative species of *Ammonia infilata*, *A. tepida*, *Ammonia* sp., *A. compacta*, *Elphidium crispum*, *Nonion* sp. and *Haynesina depressula* (benthic foraminifera) and *Cyprideis torosa* (ostracoda) are observed. The only observed ostracod is the brackish water species, *Cyprideis torosa*. The number of benthic foraminifera is high in this unit, but there is little diversity, consisting of *Ammonia infilata*, *A. tepida*, *Ammonia* sp., *A. compacta*, and *Haynesina depressula*.

##### 3.1.3 | Unit I (90–0 cm)

This is mostly olive-green homogenous mud. In this unit, shell remains are rare and comprise bivalvia and gastropoda. Observed benthic foraminifer and ostracod species are all those that inhabit brackish lacustrine, not limnic, environments—including *Ammonia*

*infilata*, *A. tepida*, *A. sp.*, *Elphidium crispum* and *Candona* sp., *Cyprideis torosa*, *Loxococoncha* sp. (see Figure 2 and Table S1).

In summary, 28 species from 19 genera of benthic and one genus of planktonic foraminifera (at 195 cm) and 30 species from 20 genera of ostracod shells were recorded in the core (Tables 1 and 2 and Figure 2).

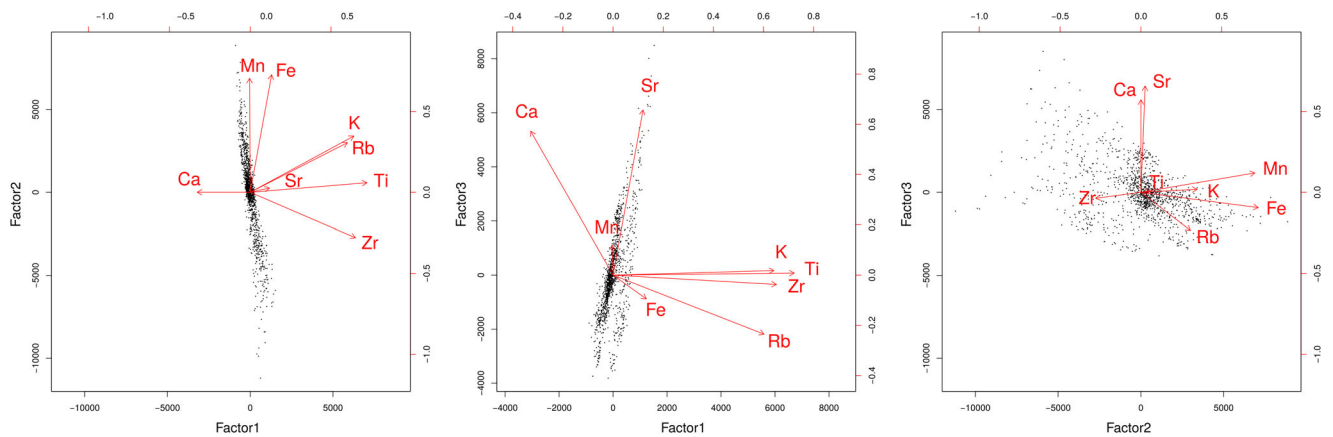
#### 3.2 | Multiproxy data

In core BAFA09P02, MS reaches its highest values (between  $8 \times 10^{-6}$  and  $10 \times 10^{-6}$  SI) between 300 and 200 cm in depth. From 200 cm it drops significantly towards the top of the core ( $1-2 \times 10^{-6}$  SI), except for a very small “anomaly” at around 95 cm (Figure 3, “MS” column).

To understand the linear relationship between the elemental profiles, eight-element profiles (Ca, Fe, K, Mn, Rb, Sr, Ti, and Zr, which account for more than 90% of the total  $\mu$ -XRF count) were subjected to factor analysis. Three main factors were extracted (see Table 4 and Figure 4). K, Rb, Ti, Zr define the first factor (f1), Fe and Mn the second (f2) and Ca and Sr the third (f3). Because of the nature of the element profiles (cf. Cohen, 2003), these factors represent detrital/allochthonous (i.e., external) sources, diagenesis/redox conditions and biogenic/autochthonous (i.e., internal) processes, respectively. K, Fe, and Ca were chosen as representatives of their groups because they have the highest values in each factor. K (cps), as a representative of f1, is highest at the bottom of the core, between 250 and 180 cm in-depth, more moderate between 180 and 90 cm and values decrease in the upper 90 cm. The representative of f2, Fe (cps) is lower and very stable from 90 cm to the top. The representative of f3, Ca (cps) shows a negative correlation with other elements throughout the core (Figure 3).

**TABLE 4** The upper panel of the table shows the loadings of elemental profiles for the whole BAFA09P02, lower panel shows the sum of squared loadings, proportional variance, and cumulative variance of each factor loading

	Factor 1	Factor 2	Factor 3
K	0.802	0.435	0.023
Ca	-0.411	0.000	0.715
Ti	0.903	0.074	0.010
Mn	-0.005	0.882	0.150
Fe	0.166	0.908	-0.118
Rb	0.753	0.384	-0.294
Sr	0.149	0.033	0.821
Zr	0.814	-0.350	-0.046
SS loadings	2.907	2.068	1.312
Proportional variance	0.363	0.258	0.164
Cumulative variance	0.363	0.622	0.786



**FIGURE 4** Biplots of loadings and scores of each factor couplet for the whole BAFA09P02 [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

To assess the endogenic versus detrital carbonate origins, we normalize Ca/K, where K is assumed to be a detrital proxy. The endogenic calcium carbonate precipitation attains its highest values at ca. 250 cm and 140 cm, where we also observed abundant CaCO<sub>3</sub> bearing shells (mollusc, foraminifera, ostracoda, etc.). Rising Sr/Ca values between 280–250 cm and 170–120 cm, suggest decreasing water level probably as a result of evaporation and beach formation, as suggested by the lithology and other proxy data (see  $\delta^{18}\text{O}$  interpretation below).

TOC values are at their lowest between 298 and 170 cm and at their highest between 170 and 90 cm. From 90 cm to the top in the core TOC levels decrease but are still higher than the core bottom. The relatively high TOC values in the lagoonal phase (Unit II) are probably due to lowering water level in the lacustrine phase, causing increased solar penetration and benthic productivity on the lagoon floor.

The  $\delta^{18}\text{O}$  (‰ VPDB) of benthic foraminifer and ostracod shells behave similarly, but not identically, throughout the core. While the  $\delta^{18}\text{O}$  values of benthic foraminifera increase between 230 and 120 cm, the ostracod values only increase up to 150 cm. The  $\delta^{18}\text{O}$  values in benthic foraminifera and ostracoda decrease after 130 and 150 cm.

Again,  $\delta^{13}\text{C}$  values of both benthic foraminifera and ostracoda co-vary throughout the core; peaking between 298 and 170 cm; decreasing between 170 and 90 cm; and low but stable from 90 cm to top.

### 3.3 | Results of radiocarbon (<sup>14</sup>C) modeling

We attempt to offer a realistic age-depth model for core BAFA09P02. We analyzed nine radiocarbon (<sup>14</sup>C) samples taken from the core, see Table 3, seven of which were marine materials (unbroken bivalve and ostracod shells). A key issue is, therefore, the approximate appropriate marine reservoir age to consider. We have two marine-terrestrial pairs of dates to give (unfortunately very limited) guidance. Given that the changing nature of the water body

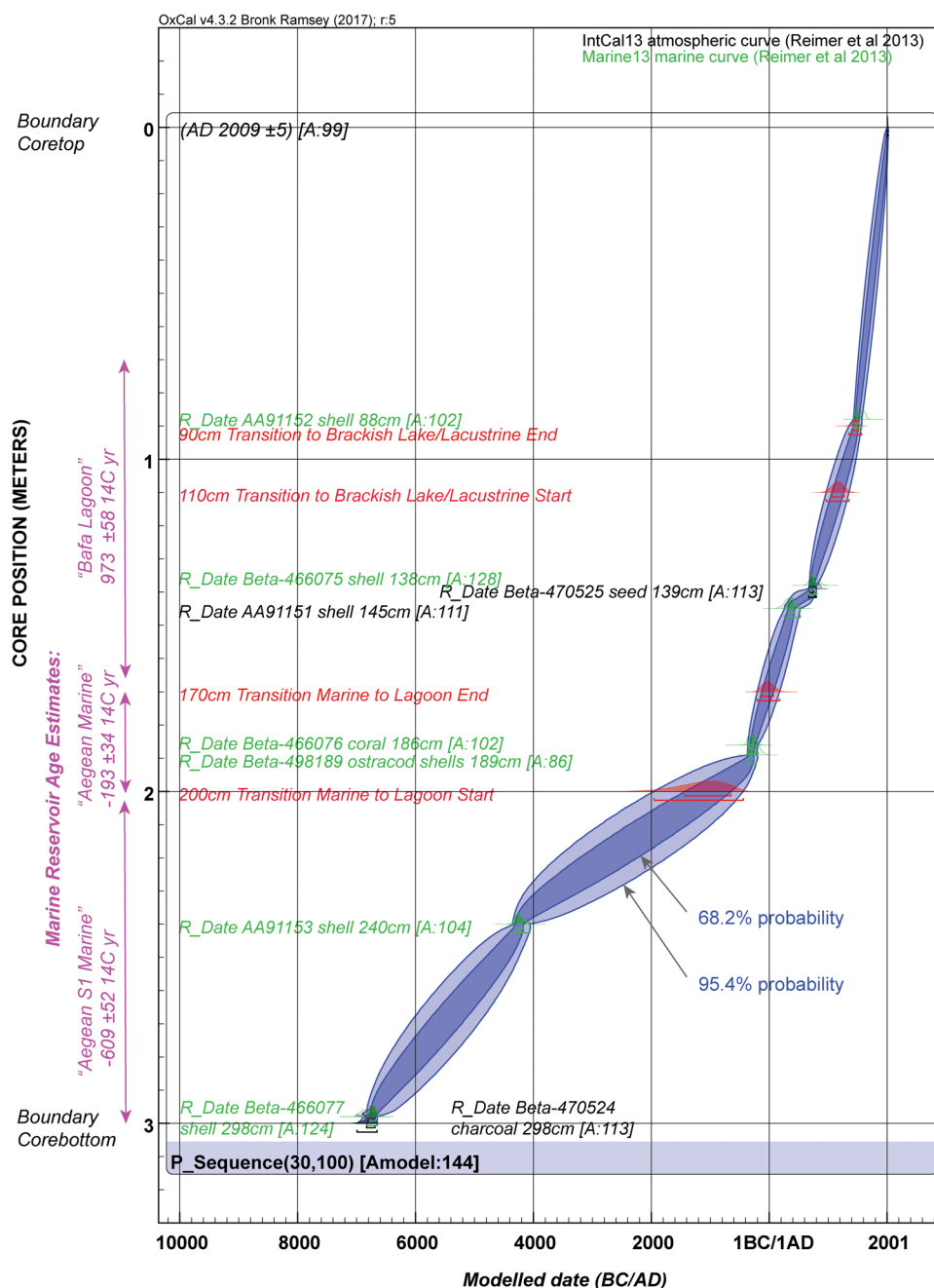
over time is evident in its geochemistry, we assume that it is very likely, as indicated by our two marine-terrestrial pairs, that the marine reservoir age varied substantially over the course of the past several thousand years. In the earlier marine phase the Aegean was also in the period leading to the sapropel S1. This means we may assume much-reduced ocean mixing and hence a lack of deep-water circulation of depleted <sup>14</sup>C (Casford et al., 2002; Mercone et al., 2000) and, as observed in other studies, marine reservoir ages can, therefore, be very low (Facorellis & Vardala-Theodorou, 2015). In complete contrast, in the latter isolated lagoon and brackish lake stages, we might anticipate the opposite, with a hard-water effect in addition, and hence a large offset in line with other observations for lagoon-like contexts in the Mediterranean (Sabatier et al., 2010; Sinai et al., 2000; Zoppi et al., 2001). Based on the marine-terrestrial pairs and comparison with other data from the region and then age-depth modeling, we estimated approximate marine reservoir ages for three successive different aquatic environments during the evolution of the Bafa sequence: Aegean S1 Marine, Aegean Marine, Bafa Lagoon. Of course these are imperfect, but they are likely considerably more relevant and accurate than using either no allowance or an (obviously incorrect) constant marine allowance.

We then employed age-depth modeling of the sequence of data considering various hypotheses using Poisson-process deposition modeling employing OxCal 4.3 (Bronk Ramsey, 2008, 2009) and the IntCal13 and Marine13 calibration datasets (Reimer et al., 2013). For a discussion of the data, the issues around estimating appropriate marine reservoir ages, and the modeling (and the various models considered), please see the Supporting Information. We note that the data are limited and imperfect. As so often in cases of marine reservoir age estimates, there are only a few marine-terrestrial pairs and these may well be imperfect for a variety of reasons. More data would be desirable. The species of the shells and coral and wood charcoal dated early on in this project's history (now over a decade) were not obtained before the destructive radiocarbon analyses were carried out. This is unfortunate, but likely not a substantial problem, since we can assume shallow-water marine/lagoon species for the shells/coral, and the wood charcoal sample was noted as a short-lived

twig with about two visible growth rings (and was noted as not being either *Quercus* sp. or a conifer) and is of clear terrestrial origin. Thus these issues likely have no major effect on our approximate model within its relatively large error margins. Nonetheless, by even approximately better addressing the nature of, and changes in, the marine reservoir age our dating exercise represents a major improvement on previous work dating the geomorphological evolution of Lake Bafa (see also Supplementary Information). Figure 5 shows our preferred age-depth model. The calibrated calendar age ranges

from this model are listed against the radiocarbon dates and the transitions in Table 3 (for details and considerations of alternative scenarios, see the Supplementary Information).

The end of the transition from marine to lagoon, at 170 cm depth, is dated around 20 B.C.  $\pm 96$  years (the range across the models in Table S4 using  $\Delta R$  values for the 189 cm and 186 cm samples of either  $-177 \pm 46$  or  $-193 \pm 34$  is small, from 33 B.C.  $\pm 76$  years to A.D. 7  $\pm 146$  years). The total modeled 95.4% range is of course wider (quoting the preferred model as listed in Table 3): for example,



**FIGURE 5** Preferred age-depth model for the Bafa Lagoon core with estimated varying marine reservoir age allowances. For explanation and discussion, see the Supporting Information. Calibration and Poisson-process deposition modeling employs OxCal 4.3 (Bronk Ramsey, 2008) and IntCal13 and Marine13 (Reimer et al., 2013). For the derivation of the approximate marine reservoir estimates for the different periods of the core, see the discussion in the Supporting Information [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

205 B.C. to A.D. 176. This places the end of the transition to the very late Hellenistic to earlier Roman period. This transition process *begins* (200 cm) around 1148 B.C.  $\pm 402$  years (range 1258 B.C.  $\pm 410$  to 1147 B.C.  $\pm 401$ ). The total modeled range here is much wider, for example, 1955 B.C. to 441 B.C. in the preferred model in Table 3. The mean value suggests that this transition likely began around the end of the Late Bronze Age. The *start* date for the final transition to a brackish lake, complete at 90 cm depth, is placed A.D. 1465  $\pm 50$  years (95.4% hpd range A.D. 1355 to A.D. 1565 from the preferred model: Table 3). The earliest estimate for the *end* of this transition to lake from the  $k = 100$  model in Figures S5 and S6 is A.D. 1399  $\pm 52$  and the latest date from the variable  $k$  models is around A.D. 1550  $\pm 101$ .

Having developed our new dating age model, with appropriate approximate reservoir allowances for each phase of the lake's developmental stages, we were able to re-visit the five radiocarbon dates previously published from Lake Bafa (see Figure S7, including dates from Knipping et al., 2008; Müllenhoff et al., 2004; see also Supporting Information). When the new calibrations are applied, the results from those previous studies for the transition to a lagoon (i.e., ca. 884–785 B.C. to ca. 310–162 B.C. recalibrated date) are consistent with the modeled transition from our new data, which is between ~1200 B.C. and A.D. 50 (Figures S5 and S6, see Supporting Information).

## 4 | DISCUSSION

Our analysis of core BAFA09P02 discerned three distinct units by their lithostratigraphic and micropalaeontological properties—III. marine, II. isolated lagoon, and I. lacustrine—each with long transitions between them. Whereas we have applied the term “marine” to describe a system open to the sea and “lacustrine” to typify a closed lake system, we use “isolated lagoon” to describe the phase in Lake Bafa's evolution when it had evidently detached from the sea, yet retained certain marine characteristics, such as micro-fauna and salinity (see Table S1).

Our dating model takes into account factors that affect radiocarbon ( $^{14}\text{C}$ ) in the specific geochemical environment of each phase of Lake Bafa's evolution in a more comprehensive way than previous work. Our new dating provides a necessarily wide age range for each key transition, due to limited data and approximate constraints. **We conclude that Lake Bafa most likely started to become an isolated lagoon ~1180  $\pm$  223/1148  $\pm$  402 B.C. with this transition to an isolated lagoon complete by ~33  $\pm$  70/20  $\pm$  96 B.C. and it then became a fully closed brackish lake ~A.D. 1397  $\pm$  52/1465  $\pm$  50.<sup>‡</sup>**

<sup>‡</sup>These are our preferred approximate dates; although it must be noted that an alternative Lagoon Transition Scenario (LTS—see Supporting Information) model would give dates for the first two stages a few centuries later (Tables S3 and S4); a variable ( $k$ ) deposition rate model would tend to push the 200 cm transition back ~60 years (1243  $\pm$  381 B.C.), place the 170 cm transition more or less the same (2  $\pm$  141 B.C.), and push the final 90 cm transition even later into the mid-16th century A.D. (A.D. 1550  $\pm$  101).

### 4.1 | Unit III—Marine conditions

This unit represents a fully marine environment, when Lake Bafa was open to the Gulf of Latmos and so to the Aegean Sea. Mediterranean benthic foraminifera and ostracod fauna populations, MS, TOC,  $\delta^{13}\text{C}$ , Fe, K, and Ti values all show an extreme change at 170 cm when the connection to the Aegean was lost. The benthic foraminifera population gradually, and ostracod population sharply, change after this point (Tables 1 and 2, and Figure 2). During the transition from marine to lagoon environment there was a change to reduced ventilation of the bottom waters and clastic input; resulting in decreases in the proxy values of MS, Fe, K, Ti, and Sr and increasing the biogenic proxy values of Ca and TOC. In particular, relatively high values of Fe and similar behavior of Mn in the marine realm may relate to the higher oxygen levels and bottom water ventilation conditions. In this unit, detrital input indicators K (f1) have relatively high values.  $\delta^{18}\text{O}$  from *Ammonia tepida* and *Cyprideis torosa* shells have positive values (0–2 ‰VPDB).  $\delta^{18}\text{O}$  from *Cyprideis torosa* has its highest value at ca. 150 cm and *Ammonia tepida* at ca. 130 cm, which can be related to the vital effect of the species (Rohling & Cooke, 1999; Von Grafenstein, Erlenneuser, & Trimborn, 1999) or relatively high evaporation.  $\delta^{13}\text{C}$  of *Ammonia tepida* and *Cyprideis torosa* shells have their highest values in the marine unit. Microscopic analysis shows this to be a shallow marine period with abundant Mediterranean type benthic foraminifera and ostracods. In some layers *Globogerina* (planktonic foraminifera) and echinid spines are also occasionally observed.

### 4.2 | Unit II—Isolated lagoon conditions

Between 110 and 90 cm a second transitional zone, from the isolated lagoon to brackish water, can be discerned. During this transition, fauna that favor lagoon environments gradually change to those that favor lacustrine conditions. This unit represents an isolated lagoon environment after the water body had gradually separated from the sea. The detrital input indicator element K (f1) is lower during this phase. Decreasing populations of Mediterranean fauna of benthic foraminifera and the absence of marine ostracods support the idea of freshwater input. Increasing values of  $\delta^{18}\text{O}$  from both benthic foraminifera and ostracod shells suggest higher evaporation during this period. The  $\delta^{18}\text{O}$  of ostracod species slightly decreases above 150 cm but  $\delta^{18}\text{O}$  data from *Ammonia tepida* (a euryhaline species that can tolerate saline conditions) shells clearly show higher evaporation conditions at this time. High TOC values also suggest lagoon conditions, with higher productivity and organic matter preservation.

### 4.3 | Unit I—Lacustrine conditions

In this phase, lacustrine conditions are evidenced with the benthic foraminifera and ostracod fauna limited to a few brackish water species. As it is today, the lake was fed only by the Büyük Menderes

River and small creeks. All proxies are lower and stable, indicating a closed lake system.

The results of our redating indicate that the transition from Unit III (marine) to Unit II (isolated lagoon) was long and slow, potentially stretching from the end of the late Bronze Age through to the late Hellenistic/early Roman period. Just as new radiocarbon analysis re-dated the stratigraphy of Gordion and necessitated the revision of the historical narrative of the Kimmerian invasion of Anatolia (Greaves, 2010, p. 9; Rose & Darbyshire, 2011), so too will this more complete, and more accurately dated, study of the Holocene depositional history of Lake Bafa will have great significance for the way in which we consider how human processes, such as settlement, trade, and warfare, played out within the reality of this physical environment.

But how best to combine the geo-environmental evidence with archaeological and historical sources? One interpretative approach that can be used to combine the slow processes of geological change with archaeological and historical evidence for activity on a human timescale is the Annaliste method pioneered by Fernand Braudel (Bintliff, 1991; Braudel, 1972; Stoianovich, 1976; Tandler, 2013). In archaeology, it informs both fieldwork methodologies (e.g., Barker, 1995) and synthetic regional analyses (e.g., Braudel, 1972; Broodbank, 2013; Horden & Purcell, 2000). In western Anatolia, Annaliste approaches have been used to frame major studies of the Madra Çayı delta (Lambrianides & Spencer, 2007), Ionia (Greaves, 2010), and the Maeander Valley (Thonemann, 2011). Greaves (2010) proposed that the Annaliste method's three historical tempos of rapid events, medium-term processes, and the slow *longue durée* of the physical environment, can also be used as a progressive process of logical inference that begins by establishing the fundamentals of the geographical environment before introducing geographically contextualized readings of archaeological/historical sources, working away from a secure basis of the "observed world" of scientific evidence toward the "described world" of historical sources (Greaves, 2010, p. 30). As Greaves writes: "Only when we have established an independent data set detailing environmental change in the Büyük Menderes ... can that information be applied to the discussion of historical or archaeological questions—thereby asserting the primacy of the natural structures and processes of the landscape over human encounters with that landscape" (Greaves, 2010, p. 64). However, we must be mindful to consider human agency in the choices made in response to geographic stimuli to counteract potential geographical determinism in our thinking (Greaves, 2010, pp. 41–42).

Looking at the archaeological finds from the shores of Lake Bafa, they show that there was a navigable connection with the open sea throughout the first millennium B.C. and into the early first millennium A.D. The size and character of this connection is unclear but our environmental data prove it was sufficiently constrained to affect the geochemistry and micro-fauna of the lagoon, whilst evidently still allowing for the free passage of ships. Braudel's definition of medium-term historical processes encompasses technical or industrial complexes that involve the coming together of multiple individuals or societies, within a geographical context, over decades, generations or

even centuries (Braudel, 1972). An example of one such process is the ancient stone-working industry that operated during Lake Bafa's lagoon phase.

Ancient marble quarries have been identified around Lake Bafa, at Gölyaka, Büyükasar Tepe, Pınarcık, and elsewhere (Peschlow-Bindokat, 1996). More than 70 column drums, in various stages of quarrying and transportation, have been recorded and their dimensions correspond to those of the temple of Apollo at Didyma ca. 26 km away to the south-west, the construction of which spanned over 600 years from the start of the third century B.C. onward. When water levels are low in Lake Bafa, semifinished column drums can be seen on the shore near Pınarcık Yaylası (identified with ancient Ionia by Peschlow-Bindokat 1981, 1996, p. 8; on changing lake levels see Herda et al., 2019) where they were left awaiting transport to Didyma. A corresponding set of column drums were found near Didyma on the seabed at Mavişehir, ancient Panormos (Blackman, 1973), where a photograph from 1972 suggests there may have been an ancient stone pier (Slawisch & Wilkinson, 2018).  $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$  and rare earth elements (REE) analyses confirm that much of the marble used in the Didyma temple can be matched with quarries around Lake Bafa (Borg & Borg, 2002), whereas the building's limestone was from local microquarries closer to the site itself (Borg & Borg, 2002). Inscriptions also appear to confirm this trade (Slawisch & Wilkinson, 2018) and Herakleia's marble was widely traded, even warranting mention in Emperor Diocletian's price edict of 301 A.D. (Corcoran, 2000; Russell, 2013). Not only were stones transported between Miletos and Ionia but also people, and an inscription (Milet 1.3, #150, 99ff) refers to a *πορθμιδος* (LSJ s.v. "ferry") between them. However, none of this implies that Lake Bafa was open to the sea because large barges with a low-draft could have traversed a shallow channel between the lagoon and the sea, even when carrying heavy loads of stone or people. Indeed, large punt barges were still used on the Büyük Menderes until recently (Chandler, 1775, frontispiece; Greaves, 2002, p. 11; Thonemann, 2011, p. 309). This enduring stone-working craft network can be read as a proxy for human geographical knowledge as "moving objects show us that 'everyday' geographical knowledge was part of people's lived experience" (Foxhall & Rebay-Salisbury, 2016, p. 300) in a way that differs from the consciously constructed geographies of our written sources but which may have informed those constructs.

Being a lagoon that was, at least partially if not substantially, open to the sea does not change the material reality of the settlement history of Lake Bafa. However, it does affect how we understand the *character* of those settlements and their interactions with one another.

Recently, three major studies have presented historical analyses of the region's culture within specific temporal and geographical contexts. Thonemann's (2011) study of the Maeander (Büyük Menderes) Valley from the fourth century B.C. to the 13th century A.D. shows that the rapidly shifting nature of the lagoons and mouths of the river, as well as its upper courses, were well-known to its inhabitants and its exceptional character was deeply ingrained in

their regional identity and cults. Mac Sweeney's (2013) political analysis of the Greek states of Ionia in the Classical period (fifth and fourth centuries B.C.) also shows that rivers and the sea featured heavily in their foundation myths. By way of contrast, Alexander Herda et al.'s (2019) diachronic study shows how the local myth of Endymion integrates a Hellenic cult from mainland Greece into the physical and cultural environment of Karian Latmos, by situating it within a cave—the dominant physical phenomenon of the mountainous landscape of eastern Lake Bafa away from the Büyük Menderes. These studies show us that the ancient historical writings about the region were contextualized within specific political and cultural milieux (e.g., Greek and/or Karian), were frequently mythologized, and always imbued with a deep sense of its unique landscape. That was partly a landscape of mountains and caves but, where the Büyük Menderes predominated, also an ever-changing landscape of rivers, deltas, shoals, sandbanks and lagoons that sometimes rendered even the land/water binary itself meaningless (Figure 6).

Although the centuries-long transition we have identified in the aquatic environment of Lake Bafa would have been imperceptibly slow, the alluvial action of the Büyük Menderes itself was observable in human timescales (Greaves, 2010, pp. 57–58). Awareness that Lake Bafa had once been part of the sea and that the Büyük Menderes

had caused its formation was evident to ancient people (e.g., Vitruvius); the Medieval Greeks who named it *Bastarda Thalassa* (“Bastard Sea”—denoting it was a hybrid, Herda et al., 2019, p. 19, n. 129); and is mentioned in the very earliest Western scholarship and travelers' accounts (e.g., Chandler, 1775). When ancient sources such as Vitruvius write about the closure of Lake Bafa as if it was already in the ancient past that is because, by the time they were writing, it was.

Our new geo-environmental evidence and nuanced readings of historical sources give us cause to question how the physical fact of being on a lagoon might have influenced the region's settlement history. Until now, the dominant historical narrative has been that the ancient settlements bordering Lake Bafa were dependent on maritime trade for their existence and without direct access to the sea they dwindled (e.g., Bean, 1966, p. 212; although see Greaves, 2000, 2002, p. 144). The presumption that archaic period settlements were necessarily coastal even influenced the search for the as-yet unidentified site of “Old” Priene (Müllenhoff, 2005, pp. 192–193). This geographical determinist view continues to influence contemporary scholarship, such as when Herda et al. (2019) write: “...harbor cities became landlocked, losing their main basis of subsistence” (p. 29). However, such cities could well have existed on a water body that was a lagoon with a substantial sea channel, or even



**FIGURE 6** View across the flooded center of the ancient city of Miletos, looking over flooded fields toward the entrance of Bafa Gölü in the far distance (center, left). Photograph by Rabe! Creative Commons licence CC BY-SA 4.0. <https://commons.wikimedia.org/w/index.php?curid=73022953> [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

multiple channels, to the sea and each had its own territory to sustain it.

The cities on this de facto lagoon would, however, have had to negotiate access to the sea with Miletos—the largest city in the region—which could easily control any sea passage into the lagoon from its strategic location on the south side, away from the rapidly prograding northern mouth of the Büyük Menderes (see Müllenhoff, 2005, p. 245). In such a geographical context Miletos' position near the lagoon's entrance(s) would have given it great military and economic significance, much as Venice's position on a lagoon worked to its historical advantage (for environmental comparison between the Venice lagoon and Lake Bafa see Supplementary Information). Indeed, Rome's own harbor town of Ostia was on a shallow lagoon, only 4-m deep, but it nevertheless supplied the greatest of all ancient cities (Vittori et al., 2015) so a lagoon location was no hindrance (and perhaps even an advantage) in premodern times. The nutrient-rich environment of lagoons make for productive fishing, for which Miletos had a considerable reputation in antiquity (Ath.7.311a; Opp.H.1.114) and the natural abundance of this body of water may have informed the character of one of its chief cults—Aphrodite—whose temples overlooked it and had a distinctively maritime character that was spread by Milesian colonists to cities across the Black Sea (Greaves, 2004; Greaves et al., forthcoming).

Being on a lagoon may also have made it easier to defend Miletos against attack from the sea as shoals and shallows may mean that ships could only approach it from the west via the nearby island of Lade even though ancient warships only had a shallow draught (Foley & Soedel, 1981). This might explain Polybius' (16.15) statement that to take the island of Lade was to control the city. Miletos was evidently able to dominate the cities and territories of the Gulf of Latmos, over which it had established a “mini-thalassocracy” (Greaves, 2000, 2002). Using its microregional maritime powerbase Miletos was able to command the smaller fleets of Priene and Myous who fought alongside its own in a sea-battle against Persia off the island of Lade in 494 B.C. (Hdt.6.8). Miletos and its allies lost that battle, the city fell, and part of its territory near Ioniapolis was handed over to the Karians (ancient Pedasa Hdt.6.20; probably Danişment near Bafa village—Herda et al., 2019). Despite this defeat, Miletos was the region's most important settlement from prehistory until the Ottoman period (Greaves, 2002) and the lagoon itself came to be called *Milesia Limne* (“The Milesian Lake”; Herda et al., 2019).

The end of this long marine/lagoon transitional phase in the late first millennium B.C. marks a period of remarkable change in settlement around the lake. With the exception of Miletos and Myous, the known archaic period settlements were all in upland locations away from the shores of the nascent lagoon—at Assesos, (187 MASL—Kalsitzoglou, 2008), “Latmos” (c.40–80 MASL—Flensted-Jensen, 2004; Peschlow-Bindokat, 1996, 2007; see Shipley, 2011 for full bibliography and discussion of the identification of this site with the name “Latmos”), Çatallar Tepe which may have been the Ionian city of Melie (800 MASL—Lohmann, 2007; Mac Sweeney, 2013, pp. 181–184) and possibly Palaiomagnesia, the location of which is uncertain (Bingöl, 2007). However, when the lagoon was most

probably fully formed, in the Hellenistic period, the new foundation of Heracleia-ad-Latmos (Flensted-Jensen, 2004; Krischen, 1922; Peschlow-Bindokat, 1996) relocated the upland settlement of “Latmos” down to shore level, as “New” Priene and Magnesia-on-the-Maeander may have done for their earlier counterparts. These relocations are in keeping with a general pattern of the period whereby kings established new cities with defined territories and orthogonally planned and heavily fortified urban centers. However, within the context of the lagoon, they may also reflect the opportunity to exploit newly formed fertile plains as the lagoon in-filled (Müllenhoff, 2005, pp. 193–196) and the additional security of being on a lagoon. Again, this challenges the geographical determinist logic that states “as the Maeander gradually converted the gulf into a lake, Heracleia became completely cut off” (Bean, 1966, p. 212). In fact, rather than being the cause of Heracleia's demise, the formation of the lagoon may have been the very reason for its existence as a coastal town.

## 5 | CONCLUSIONS

The geomorphology of Lake Bafa and the Büyük Menderes delta is one of the most iconic examples of a dynamic landscape and its interwoven human historical relationship. Previous attempts at dating the formation of Lake Bafa have relied, directly or indirectly, on written historical sources but, by so doing, they misrepresented the historical context and meaning of those sources. In this study we have followed a structured process of inference, following the Annaliste-inspired methodology of Greaves (2010), by first establishing a fully independent geo-environmental understanding of the region before reintroducing archaeological and historical material into the interpretative process.

Our high-resolution multiproxy core data show that Lake Bafa underwent two major environmental transitions: from open fully marine (Unit III) to the isolated lagoon (Unit II), and then to the current closed brackish lake (Unit I). Using a Bayesian framework to produce a plausible dating model to account for the changing geochemical environment and better include the likely factors and constraints for changing marine reservoir effects in each phase, we were able to produce an age-depth model for our core that shows that the first of these slow transitions—from marine to lagoon—occurred sometime between the later second millennium B.C. and the end of the first millennium B.C. (~1180 ± 223/1148 ± 402 B.C. to ~33 ± 70/20 ± 96 B.C.), that is, between the Late Bronze Age and the Hellenistic/Roman periods.

Using this new understanding of the physical environment we can now read the settlement history of the region differently. Unlike the slow-moving and largely unstoppable processes of geology, human societies are mutable and can adapt to their physical environment. The human settlements that bordered Lake Bafa evidently accommodated themselves to the physical realities imposed on them by its partial closure from the open sea by adapting their transport, settlement, and possibly even cult activities accordingly. Being positioned at the mouth of this lagoon undoubtedly gave Miletos strategic advantage over the cities and territories on its shores for several millennia, but it also benefitted those settlements

too—with enriched supplies of fish, new fertile lands to cultivate, and assured security.

This paper serves as a counterpoint to many established narratives about the nature of ancient Ionian maritime culture, the Milesian powerbase, community identity, and the political independence of minor Greek *poleis* in the existing scholarship on this region. However, by applying a systematic process of logical inference we find that our new geo-environmental findings are compatible with a different, more nuanced reading of the available archaeological and historical source materials that supports our findings.


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## DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information material of this article.

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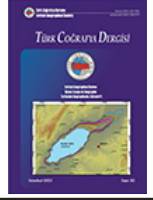
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#### SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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## Dates of Holocene environmental changes in Lake Bafa: A hierarchical Bayesian analysis of change points

*Holosen'de Bafa Gölü'ndeki ortamsal değişikliklerin tarihleri: Hiyerarşik Bayes değişim noktası analizi*

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### ABSTRACT / ÖZ

The timing of the separation of Lake Bafa from the Aegean Sea and its subsequent transition to a lake remains a topic of debate, with considerable uncertainties associated with the proposed dates for these transitions. This study introduces a novel approach, hierarchical Bayesian change point analysis (HBCPA), to identify tipping points in paleoenvironmental time series. The objective is to offer more precise and objectively selected results concerning the previously uncertain transition dates of Lake Bafa's geological evolution in the Holocene. The method presented in this study is applied to analyze stable oxygen and carbon isotope data from foraminifer and ostracod shells, as well as total organic carbon (TOC) data, obtained from the BAFA09P02 sediment core. Results indicate that the transition from a marine to an isolated lagoon environment occurred around 2060 years BP, with an 89% uncertainty interval ranging from 2250 to 1870 years BP. Additionally, the transition from an isolated lagoon to a brackish lake environment is estimated to have occurred around 595 years BP, with an 89% uncertainty interval ranging from 780 to 425 years BP. The results of this study illustrate that the suggested HBCPA approach holds the capability to identify tipping points in environmental data while quantifying their intrinsic uncertainties.

*Bafa Gölü'nün Ege Denizi'nden ayrılmasının ve ardından tatlısu gölüne geçişinin zamanlaması tartışmalıdır ve bu değişimler için önerilmiş olan tarihlerin belirsizlik aralıkları oldukça geniştir. Bu çalışmada, paleoçevre verilerinin analizinde kullanılmak üzere yeni bir yaklaşım olarak "hiyerarşik Bayes değişim noktası analizi" (HBCPA) önerilmektedir ve sonuç olarak Bafa Gölü'nün Holosen'de ortamsal değişim tarihleri için önerilmiş geniş belirsizlik aralıklarını daraltma amacını taşımaktadır. Önerilen yöntem, BAFA09P02 çökel karotu foraminifer ve ostrakod kavkılarında elde edilen duraylı oksijen ve karbon izotop verileri ile toplam organik karbon (TOC) verileri üzerinde uygulanmıştır. Sonuçlar, denizel ortamdan kapalı lagünel ortama geçişin yaklaşık GÖ 2060 yıl civarında gerçekleştiğini ve %89 belirsizlik aralığının GÖ 2250 ila 1870 yılları aralığında olduğunu göstermektedir. Kapalı bir lagüden acısu göl ortamına geçişin ise yaklaşık GÖ 595 yıl civarında gerçekleştiği ve %89 belirsizlik aralığının GÖ 780 ila 425 yıllarını kapsadığı bulunmuştur. Bu çalışmanın sonuçları, önerilen HBCPA yönteminin jeolojik verilerde çevresel değişim noktalarını, sahip oldukları belirsizlikleri ile ölçme potansiyeline sahip olduğunu göstermektedir.*

## 1. Introduction

Lake Bafa, located near notable ancient sites including Miletos, Priene, and Herakleia, is a remnant body formed by the separation of the Gulf of Latmos from the Aegean Sea. The separation took place as a result of the progradation of the delta mouth of the Büyük Menderes River (referred to as the Maiandros River in ancient times), which led to the formation of a barrier (see Figure 1). Despite its environmental, archaeological and geological significance, the timing of the lake's isolation from the Aegean Sea is still a matter of debate (cf. Akçer-Ön et al., 2020; Brückner et al., 2017; Müllenhoff et al., 2004; Salihoğlu & Akçer-Ön, 2020).

Previous studies have reported conflicting dates, with variations of more than three thousand years, regarding the period when the basin became isolated from the open sea (cf. Akçer-Ön et al., 2020; Knipping et al., 2008; Müllenhoff et al., 2004). However, Akçer-Ön et al. (2020) used up-to-date calibration curves and advanced Bayesian age-depth modeling techniques to demonstrate the potential compatibility between the contradictory hypotheses proposed by Akçer-Ön et al. (2020) and Knipping et al. (2008). Given that the temporal findings presented by Akçer-Ön et al. (2020) are in direct contradiction with all previously documented studies, the uncertainty intervals for the transition dates are approached with utmost caution, resulting in the broadest range of uncertainty being reported. They utilized a multiproxy approach that included faunal distribution, geochemical data, and physical properties of the core. The discussion focuses on different age-depth models based on diverse assumptions, leading to a

high level of uncertainty. Their results highlighted the temporal uncertainties associated with the transition from a marine environment to an isolated lagoon, spanning up to two millennia. Similarly, the transition from an isolated lagoon to a brackish lake exhibited uncertainties covering approximately 600 years (see the upper panel of Table 1).

The present study reports the results of a hierarchical (multilevel) Bayesian change point analysis (HBCPA) to estimate transition dates with greater objectivity and precision than those reported by Akçer-Ön et al. (2020). TOC data from bulk sediment, stable carbon and oxygen isotope data from foraminifer and ostracod shells (Figure 2) in the BAFA09P02 core are analyzed using HBCPA. This statistical method detects credible shifts or changes in multiple time series data simultaneously, providing an overall average that captures any type of uncertainty. The approach employs piecewise linear regression to approximate the data and estimate parameters for each segment, identifying points in time where the data deviates from the prior segment. A hierarchical Bayesian approach is advantageous for incorporating all levels of uncertainties and prior information of the data, and expressing the uncertainty of the results in an intuitive way.

Several prior studies in the field of earth sciences have utilized Bayesian hierarchical models (Ön et al., 2023, and references therein), Bayesian solutions of Kalman filter to assess potential changes through regression models (Ön et al., 2021), or Bayesian change point analysis to identify trend shifts or level changes in time series (Cahill et al., 2015; Gallagher et al.,

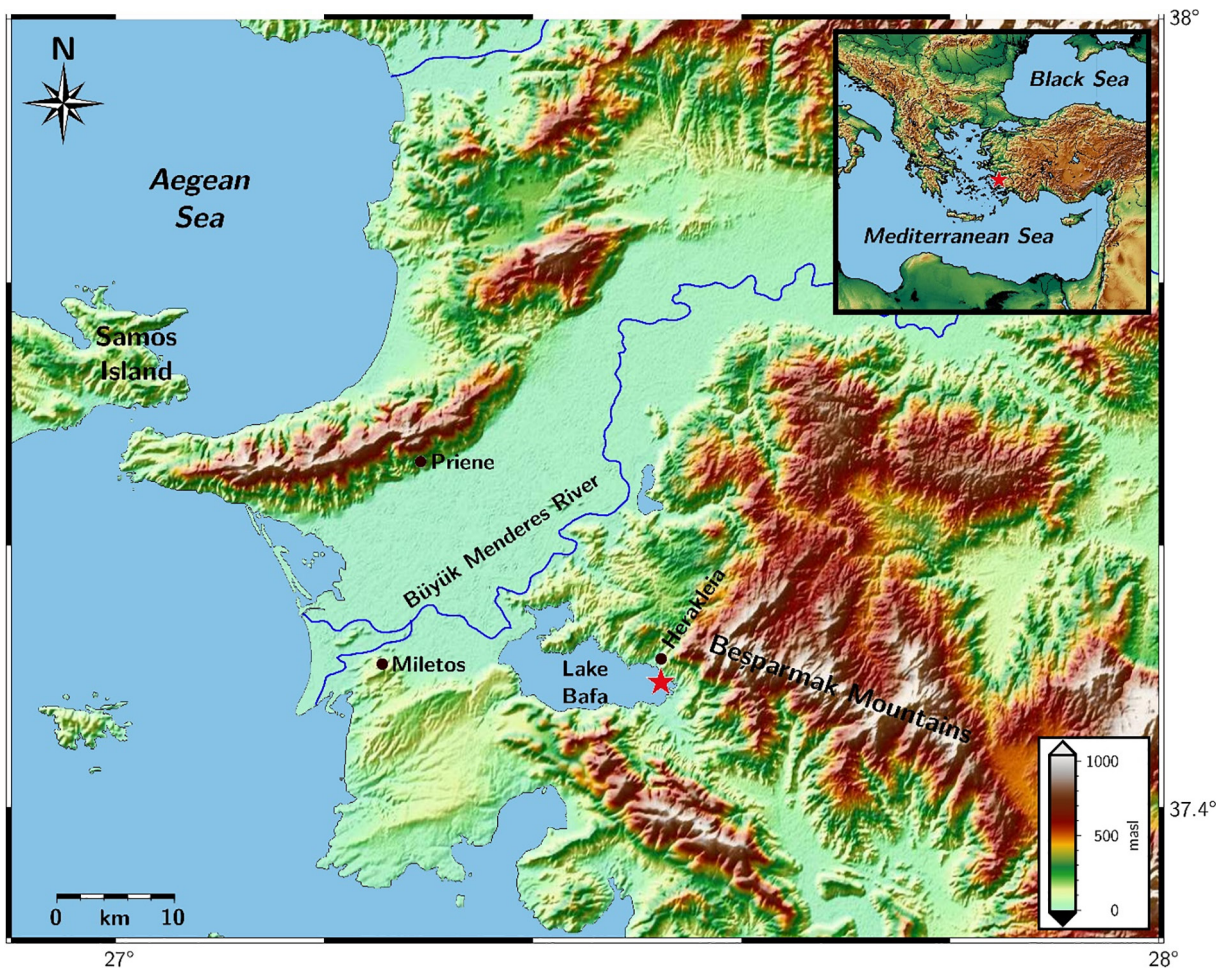
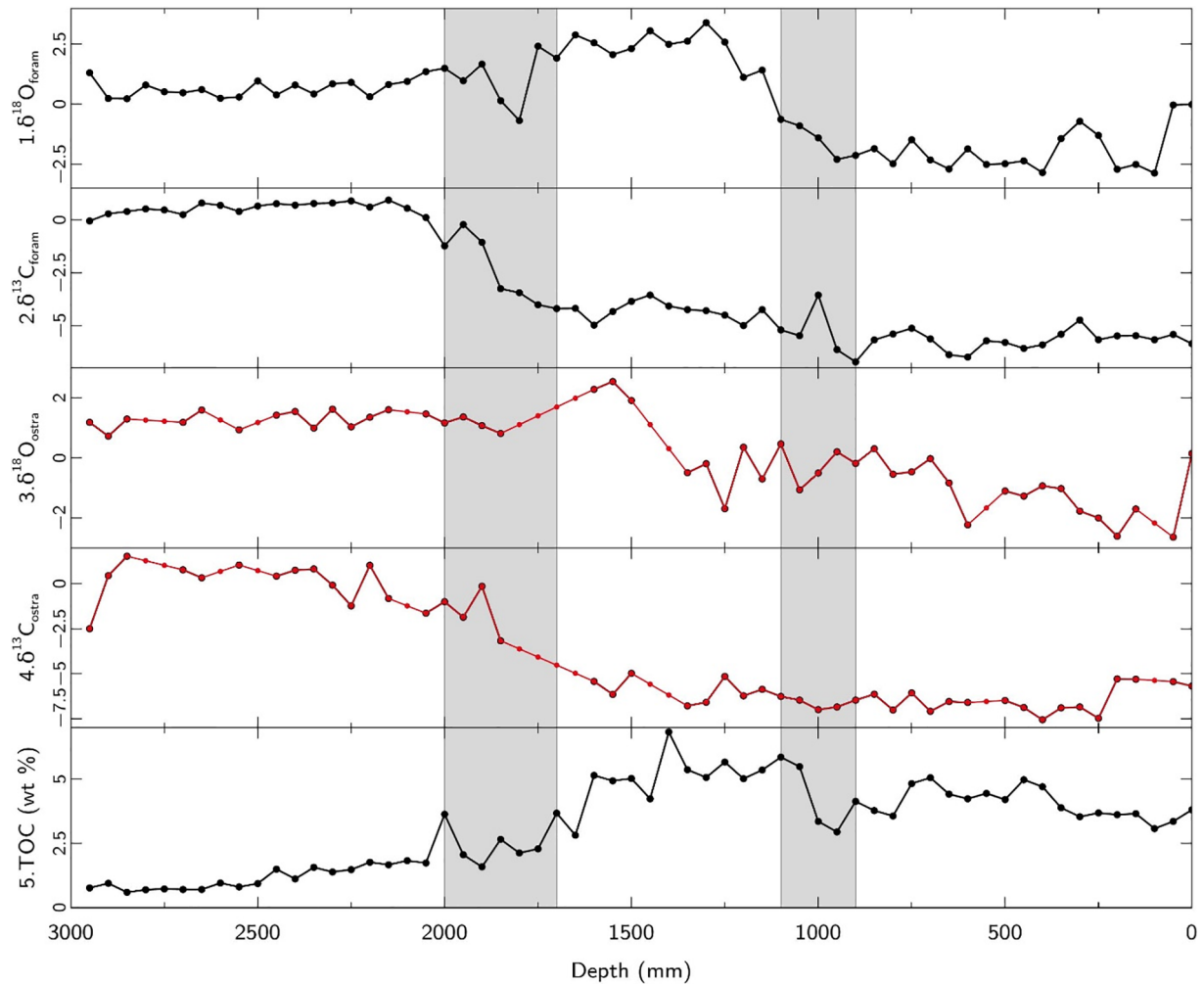


Figure 1. Location map of Lake Bafa and the drilling site (red star) of BAFA09P02 core. Modified from Akçer-Ön et al. (2020).



**Figure 2.** The figure illustrates the core depth plotted against the proxy data obtained from Akçer-Ön et al. (2020) and employed in this study. The gray shaded areas indicate the intervals of environmental change as identified by Akçer-Ön et al. (2020). The red curves represent the missing datasets, with small red dots indicating the filled data.

2011; Ön, in press). However, to the best of my knowledge, no previous studies have employed a hierarchical change point approach to analyze paleoenvironmental data. In the case of the Lake Bafa data, this approach is feasible since multiple proxy data indicate a discernible response to environmental changes. (Figure 2). Therefore, the findings of this study have the potential to offer insights into the disputed geographic history of the region in the archaeological timespan.

## 2. Regional Setting

Lake Bafa is a shallow freshwater lake located in southwestern Anatolia, Turkey, approximately 20 km inland from the Aegean Sea (Figure 1). The lake, covering an area of approximately 70 square kilometers, is a residual body of water that originated from the delta progradation of the Büyük Menderes River. The region is characterized by rugged terrain and is sparsely populated. The lake basin is situated within the Aegean extensional province, which is subject to active extensional faulting owing to significant tectonic activity (Mozafari et al., 2019). The area experiences the influence of a Mediterranean climate pattern, characterized by abundant rainfall during winter and scarce precipitation during summer. The lake is characterized as mesohaline with a salinity range of 8–13‰. Lake Bafa is fed by several small streams and is home to a diverse range of

plant and animal species, including several endemic species (Akçer-Ön et al., 2020).

## 3. Materials and Methods

### 3.1. Data

This study examines a 298 cm long undisturbed sediment core (BAFA09P02) retrieved from the eastern part of Lake Bafa (Figure 1) in 2009 at a water depth of 4.9 m. According to the “preferred” age-depth model of Akçer-Ön et al. (2020), the core approximately spans the last 8700 years BP<sup>1</sup>. Akçer-Ön et al. (2020) provided a thorough analysis and description of the sediment core, including the TOC measurements, and also the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  compositions of the shells from the most common and consistent benthic foraminifer species, *Ammonia tepida*-*Ammonia sp.*, as well as from ostracod species, *Cyprideis torosa* and *Xestoleberis sp.* To simplify notation, this study uses subscripts F and O to represent the isotope values of foraminifers and ostracods, respectively. These proxy data are suitable indicators of environmental changes, encompassing salinity, evaporation, and organic productivity. Their age-based profiles facilitate the exploration of the timing and associated uncertainties linked to the chemical and subsequent physical transitions of Lake Bafa, which was once connected to the Aegean Sea in the geological past.

<sup>1</sup> The term “years BP” is an abbreviation used to refer to years before the present, where the present is defined as 1950 CE, as established by Flint & Deevey (1962).

The data resolution for all presented data is 5 cm. However, at specific depths, as noted in the supporting information by Akçer-Ön et al. (2020), measurements of stable isotope data from ostracod species are missing. To address this, the original authors used linear regression approach, utilizing available data points from adjacent depths. Similarly, in this study, the same approach has been applied to estimate and complete the missing data points throughout the entire data matrix (Figure 2).

### 3.2. Hierarchical Bayesian Change Point Analysis

The time series of  $\delta^{18}\text{O}_F$ ,  $\delta^{13}\text{C}_F$ ,  $\delta^{18}\text{O}_O$ , and TOC in this study are assumed to have two change points, while  $\delta^{13}\text{C}_O$ , as described in Section 4, involves only one change point. All these data are assumed to be described as piecewise linear regressions between and beyond the change points. All these data are assumed to follow a piecewise linear regression model, both between and beyond the change points. In the equations below, the time axis for each series is defined by  $\{x_1, \dots, x_n\}$ , where  $x_1$  and  $x_n$  represent the first and last elements of the time vector. The piecewise regression models for each standardized  $(x_i, y_i^k)$  can be expressed as per the notation of Lindeløv (2020):

$$y_i^k \sim t_{(\nu^k)}(\mu_i^k, (\sigma^k)^2) \quad (1)$$

where  $\mu_i^k$  is given by

$$\begin{aligned} \mu_i^k = & [x_i \geq x_1][x_i < c_1^k](\alpha_1^k + \beta_1^k x_i) \\ & + [x_i \geq c_1^k][x_i < c_2^k](\alpha_2^k + \beta_2^k x_i) \quad (2) \\ & + [x_i \geq c_2^k][x_i \leq x_n](\alpha_3^k + \beta_3^k x_i), \end{aligned}$$

and

$$\sigma^k \sim N^{(0,\infty)}(0,1), \quad (3)$$

$$\nu^k \sim \text{Exp}(1/30). \quad (4)$$

In Equation 2, the mathematical statement  $[a\hat{R}b]$  represents a binary indicator function that denotes the truth value of a relational statement  $[a\hat{R}b]$  where  $\hat{R}$  denotes any given relation. This relational statement evaluates to a logical variable that equals 1 if and only if the relation holds true, and 0 otherwise. The equation presented in Equation 1 above utilizes the notation  $t_\nu$  to represent the  $t$ -distribution, where  $\nu$  denotes the degrees of freedom or the normality parameter, as described by Kruschke (2015). In order to exercise greater caution with respect to the regression parameters, a robust  $t$ -distribution was selected to prevent any potential influence of outliers on the detection of change points in the data. Moreover, the parameter  $\nu$  is assigned an exponential distribution with a mean value of 30 to create a prior that assigns equal probability to values of  $\nu$  less than or greater than 30, and thereby giving equal weight to an approximate normal distribution and a heavy-tailed distribution. ( $N^{(0,\infty)}$ ) denotes truncated normal distribution with truncation range  $(0,\infty)$  and  $\text{Exp}$  denotes exponential distribution. The upper index  $k$  represents the index of the variable, running from 1 to 5. These index numbers, as also given in Figure 2, correspond to  $\delta^{18}\text{O}_F$ ,  $\delta^{13}\text{C}_F$ ,  $\delta^{18}\text{O}_O$ ,  $\delta^{13}\text{C}_O$ , and TOC, respectively.

The uncertainty of the age model is implemented through:

$$x_i \sim N(x_i^{\text{am}}, (\sigma_i^{\text{am}})^2), \quad (5)$$

where  $x_i^{\text{am}}$  and  $\sigma_i^{\text{am}}$  are the standardized mean and one sigma error of the age model presented as the "preferred age model" in Akçer-Ön et al. (2020).

For each variable, the change points  $c_1$  and  $c_2$  are described as:

$$c_1^k \sim t_4(c_1^g, 200^2), \quad (6)$$

$$c_2^k \sim t_4(c_2^g, 200^2), \quad (7)$$

where  $c_1^g$  and  $c_2^g$  are the comprehensive change points, which from now on I will call them as general change points, which are of primary interest and assumed as such:

$$c_1^g \sim t_{\{\nu^{\text{cp}1}\}}(520, 200^2), \quad (8)$$

$$c_2^g \sim t_{\{\nu^{\text{cp}2}\}}(2545, 200^2), \quad (9)$$

where

$$\nu^{\text{cp}1} \sim \text{Exp}(1/30), \quad (10)$$

and

$$\nu^{\text{cp}2} \sim \text{Exp}(1/30). \quad (11)$$

The mean and scale values of the  $t$ -distributions in Equations 6 to 9 were standardized with respect to the mean and standard deviation of the age model before conducting the analyses. The normality parameter in each  $t$ -distribution of the model is specified using an exponential distribution with a mean value of 30.

If not defined as zero, the parameters of each regression are defined as:

$$\alpha_j^k \sim t_{10}(0, 2^2), \quad (12)$$

$$\beta_j^k \sim t_{10}(0, 2^2). \quad (13)$$

However, according to our model assumptions  $\beta_1^1, \beta_2^1, \beta_3^1, \beta_1^2, \beta_2^2, \beta_3^2, \beta_1^3, \beta_3^3, \alpha_3^4, \beta_3^4, c_1^4, \beta_1^5, \beta_2^5$  are assumed to be zero. For details, please refer to the JAGS model provided at [https://github.com/zboron/LakeBafeClosureBayesian\\_cps](https://github.com/zboron/LakeBafeClosureBayesian_cps).

The posterior distributions of the model were obtained using Gibbs sampling through the JAGS program (Plummer, 2003) and the runjags interface (Denwood, 2016) in R (R Core Team, 2023). After discarding the initial 10,000 adaptation and burn-in steps, the Gibbs sampling process was performed for the standardized data model in JAGS. To ensure convergence, four separate Markov chain Monte Carlo (MCMC) chains with random initial points were ran, each consisting of 50,000 iterations for every dataset. The convergence of the Bayesian model was assessed by examining the trace plots, autocorrelation plots, effective sample size statistics, Gelman-Rubin statistics, and density plots, stacked for all four MCMC runs for all pa-

rameters (Figures S1–S6). The 89% highest density intervals (HDI), which provide uncertainty intervals for the outcomes, are presented following the methodology outlined by Kruschke (2015).

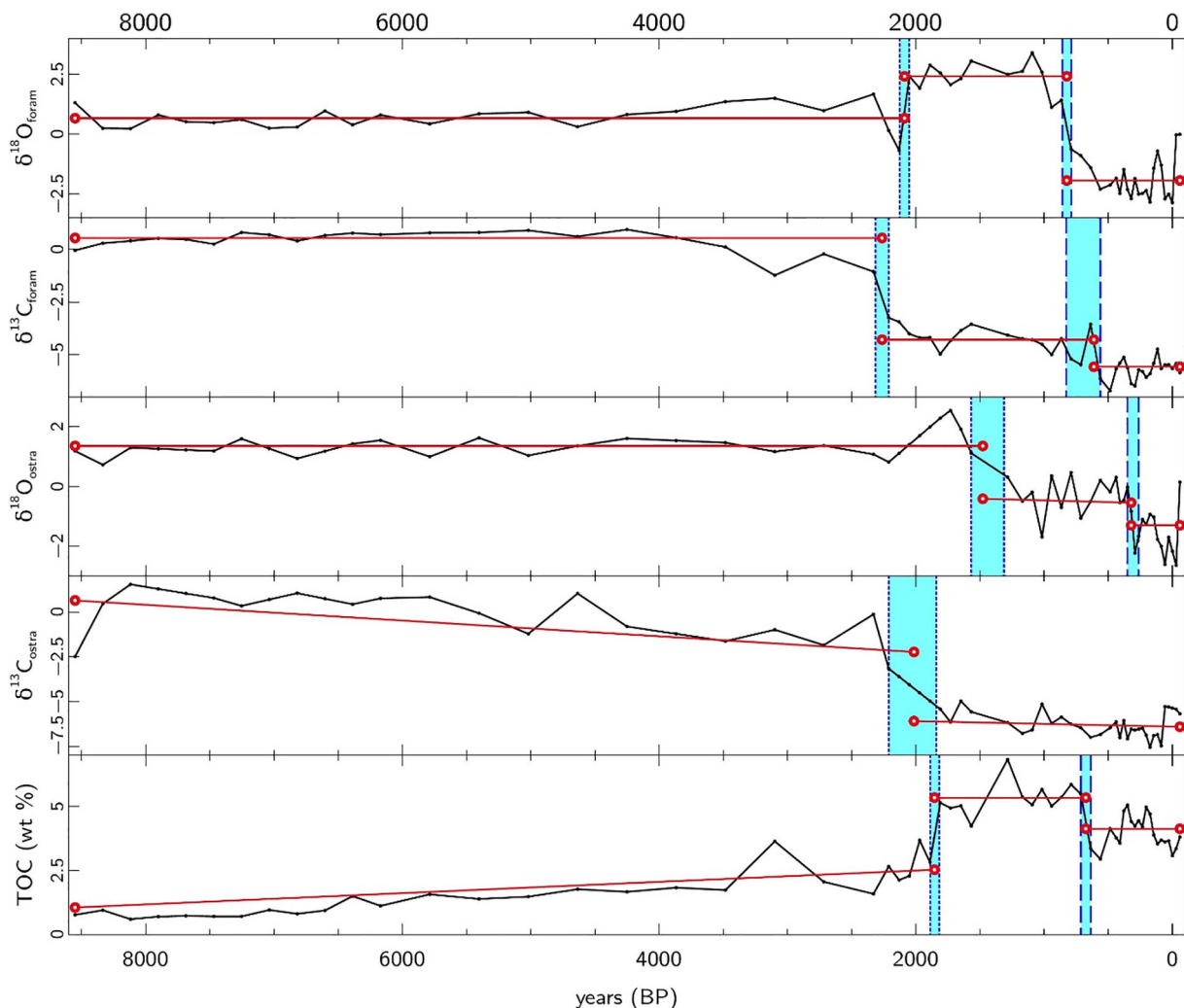
#### 4. Results and Discussion

This study utilizes a HBCPA that assumes piecewise linear regressions before and after each change point, based on the two-step closure hypothesis of Lake Bafa described in Akçer-Ön et al. (2020). The assumptions for the model vary for each dataset, with three linear levels around two change points for  $\delta^{18}\text{O}_F$  and  $\delta^{13}\text{C}_F$ , mixed levels and trends around two change points for  $\delta^{18}\text{O}_O$  and TOC, and a single change point with trend lines on both sides for  $\delta^{13}\text{C}_O$ . Prior visual observations of the data were taken into account to establish these model settings and to determine which  $\alpha$  and  $\beta$  values are zero, as explicitly given in Section 3.2 and in the JAGS model given in [https://github.com/zboraoon/LakeBafeClosure\\_Bayesian\\_cps](https://github.com/zboraoon/LakeBafeClosure_Bayesian_cps).

Additionally, alternative approaches were explored for analyzing each dataset during the research process of this study. However, these alternative approaches were not included in the main analyses and are not presented in this paper. For example, trend lines spanning between and beyond change points were utilized when analyzing the  $\delta^{18}\text{O}_O$  data (see the

top plot in Figure 3). However, the MCMC runs did not converge for this approach, possibly due to model misspecification issues. Moreover, a single change point assumption was adopted for the  $\delta^{13}\text{C}_O$  data, as alternative change point assumptions did not suggest a change at the isolated lagoon-to-lake transition. The results indicated a change occurring at a time point that is out of the context of this article. Therefore, the model specifications used in this study support the claims of a two-step transition and allow each model to converge to relatively meaningful dates.

The residual errors of the regression models in each segment are assumed to follow a  $t$ -distribution, as are the change point locations in each segment. The hyperparameters for the mean parameters of the  $t$ -distributions for the general change points (Equations 8 and 9) were selected based on the mean values reported in Akçer-Ön et al. (2020, p. 670), indicating that Lake Bafa started its transition to an isolated lagoon around 1180/1148 BCE (equivalent to 3130/3098 years BP), completed the transition by around 33/20 BCE (equivalent to 1983/1970 years BP), and fully transitioned to a closed brackish lake around 1397/1465 CE (equivalent to 553/485 years BP). The hyperparameters for the scale parameters of the  $t$ -distributions for the change points (Equations 6 to 9) were chosen with consideration given to its ability to span almost a millennium when multiplied by a factor of two. The limited



**Figure 3.** The figure displays the locations of the change points obtained from the change point analysis superimposed on the proxy time series. The cyan shaded regions represent the 89% highest density intervals (HDIs) of the posterior distributions of each change point. Within each segment, the red line segments show the piecewise linear regressions fitted to the median values of the posterior distributions of the regression parameters for each model.



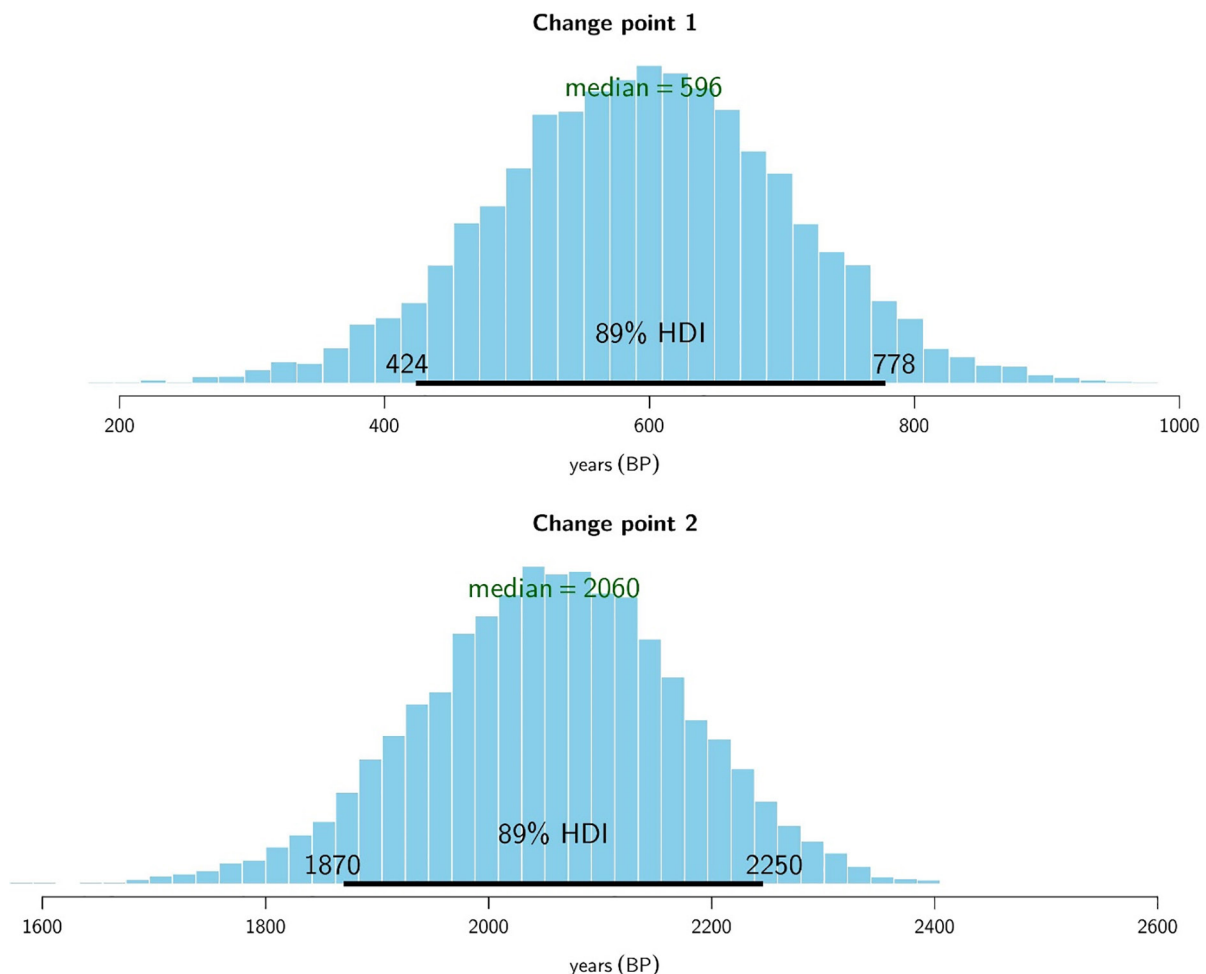
**Table 1.** The top panel shows the uncertainty intervals of the start and end dates of environmental changes, obtained from the “preferred” age model proposed by Akçer-Ön et al. (2020, Table 3). The uncertainties have been expressed as 95.4% “credible interval”. The lower panel of the table shows the results of the hierarchical change point analyses for each proxy data and the general change points obtained in this study. The columns display the median values of the posterior distributions for each change point and their uncertainties are represented as 89% HDIs.

	marine-to-isolated lagoon cp-2 (years BP)			isolated lagoon-to-lake cp-1 (years BP)		
	Start of the transition	End of the transition		Start of the transition	End of the transition	
Results from Akçer-Ön et al. (2020)	3905–1509	2155–1774		984–602	595–385	
Proxy	Median	HDI high	HDI low	Median	HDI high	HDI low
$\delta^{18}\text{O}_f$	2085	2120	2050	820	855	790
$\delta^{13}\text{C}_f$	2260	2315	2210	610	825	560
$\delta^{18}\text{O}_o$	1480	1565	1310	320	350	260
$\delta^{13}\text{C}_o$	2010	2210	1840	—	—	—
TOC	1850	1890	1815	675	710	645
General cp's	2060	2250	1870	595	780	425

number of available datasets makes it challenging to obtain reliable estimates of parameters in statistical models. While using more informative priors than those specified in Equations 6 to 9 could potentially impact the results significantly, doing so would require disregarding the proxy data utilized in this study. However, if weaker priors are adopted, it would overlook the significant findings of Akçer-Ön et al. (2020), who utilized a valuable multiproxy approach with a primary

focus on the faunal distribution within the core. To address this issue, the information from the faunal distribution data and other geochemistry data (specifically,  $\mu$ -XRF elemental counts) are incorporated into the model through prior distributions and their hyperparameters (Equations 6 to 9).

The dates of the transitions obtained from the “preferred” age model are listed in Table 3 of Akçer-Ön et al. (2020) and sum-



**Figure 4.** The figure exhibits the posterior distributions of the general change points, including their median values and 89% HDIs. The results of the transition from isolated lagoon-to-lake are displayed in the upper figure, while the results of the marine-to-isolated lagoon transition are shown in the lower figure.

marized in Table 1 of this study. These dates were determined based on the transition depths identified using multiproxy data, which included changes in faunal, lithostratigraphic, and geochemical characteristics along the core. The study aimed to demonstrate that the timing of the closure of Lake Bafa differed significantly from previous studies (Aksu et al., 1987; Knipping et al., 2008; Müllenhoff et al., 2004). Therefore, in order to be as cautious as they can, the presented dates include the widest possible uncertainties, taking into account different age-depth models.

The results of this study for each proxy data (Figure 3 and Table 1) show slightly different transition dates than those presented by Akçer-Ön et al. (2020), where each of the transitions of each proxy data are assumed to reflect phase transitions of environmental conditions. The dates and associated uncertainties of the general change points (Table 1 and Figure 4) obtained via the hierarchical model, which are 2060 (2250–1870) years BP and 595 (780–425) years BP, does not contradict with the proposed intervals by Akçer-Ön et al. (2020). The discrepancies in the transition dates between the results of each single proxy dataset, the multiproxy results of Akçer-Ön et al. (2020), and the general change points of this study are probably attributable to differences in sampling methods, sampling resolutions, bioturbation in the sediment column, and sensitivity of different proxies to transitions. Moreover, Salihoğlu & Akçer-Ön (2020), who conducted a recent study based on the cluster analysis of ostracod and foraminifer species counts, reported transition dates of  $2200 \pm 70$  and  $600 \pm 80$  years BP for marine-to-isolated lagoon and isolated lagoon-to-lake transitions, respectively. These dates are in close agreement with the results of our study.

## 5. Conclusions

The proposed method in this study employs a hierarchical Bayesian change point analysis to address the issues of “subjective” selection of transition points and large uncertainties of transition dates in a previous study on Lake Bafa. The proposed method is applied to the TOC data, and stable oxygen and carbon isotope data of foraminifers and ostracods from the BAFA09P02 core. The results suggests that, the transition from marine to isolated lagoon of Lake Bafa might have taken place within the period of 2250–1870 years BP (equivalent to 300 BCE–80 CE), with a median value of 2060 years BP (equivalent to 110 BCE), where the uncertainty is expressed as 89% HDI. And, the transition from isolated lagoon to lake is estimated to have occurred within the period of 780–425 years BP (equivalent to 1170 CE–1525 CE), with a median value of 595 years BP (equivalent to 1355 CE), where the uncertainty is expressed as 89% HDI. Furthermore, the study contributes to the field of earth sciences by utilizing a hierarchical change point approach for analyzing paleoenvironmental data.

**Acknowledgements** Figures 2-3 were produced utilizing Veusz 3.6.2, an open-source scientific plotting program, while Figure 4 was generated using the R software package. In addition, the language of this study was subject to editorial and refinement by OpenAI’s ChatGPT, and then further reviewed by Dr. Sena Akçer-Ön and the author of this study.

**Code and data availability** All the data and codes used to gen-

erate the results can be found at [https://github.com/zboran/LakeBafeClosure\\_Bayesian\\_cps](https://github.com/zboran/LakeBafeClosure_Bayesian_cps).

Appendix 1. Supplementary figures

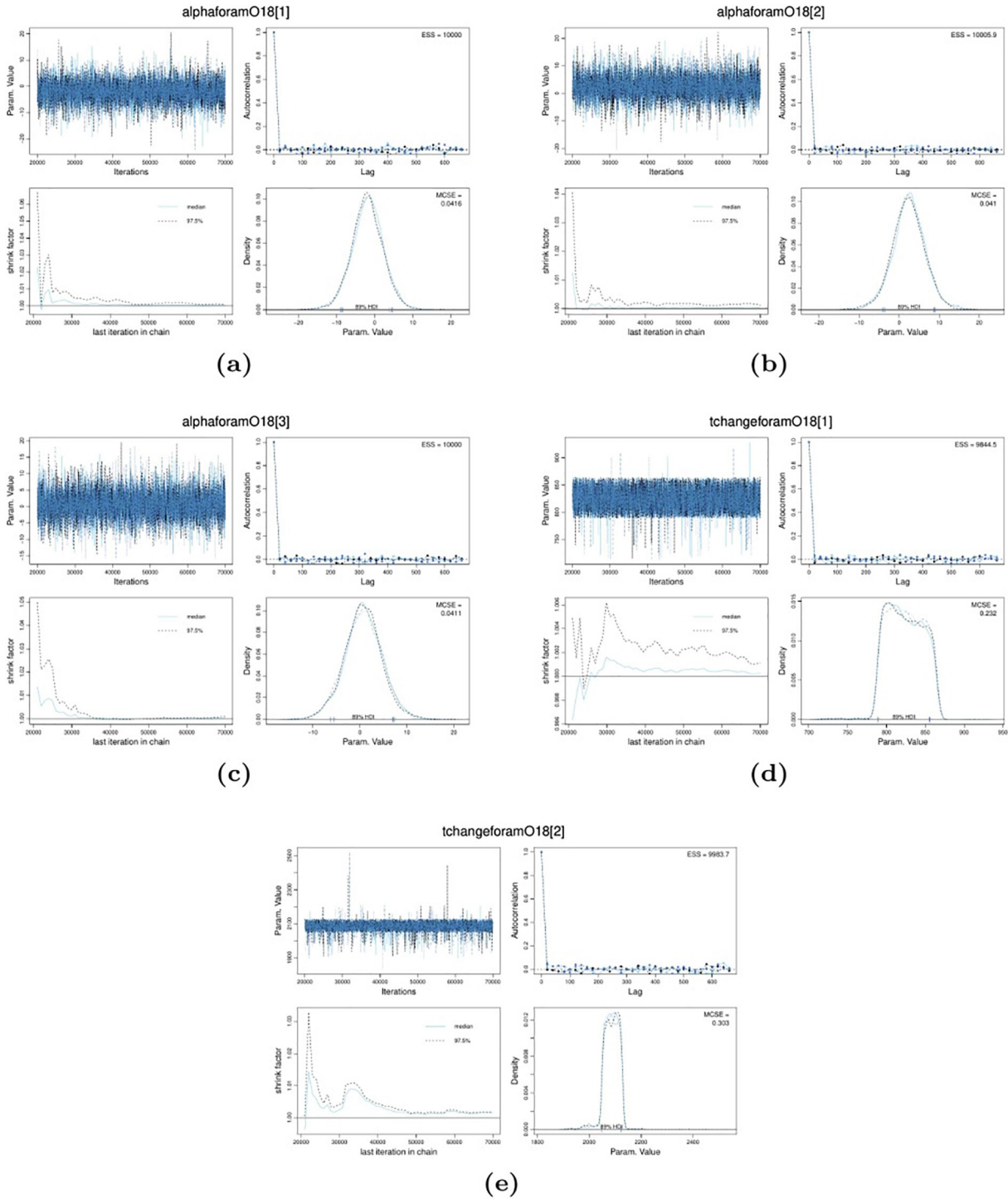


Fig. S1: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$ ,  $c_1$ , and  $c_2$  pertaining to  $\delta^{18}O_p$ .

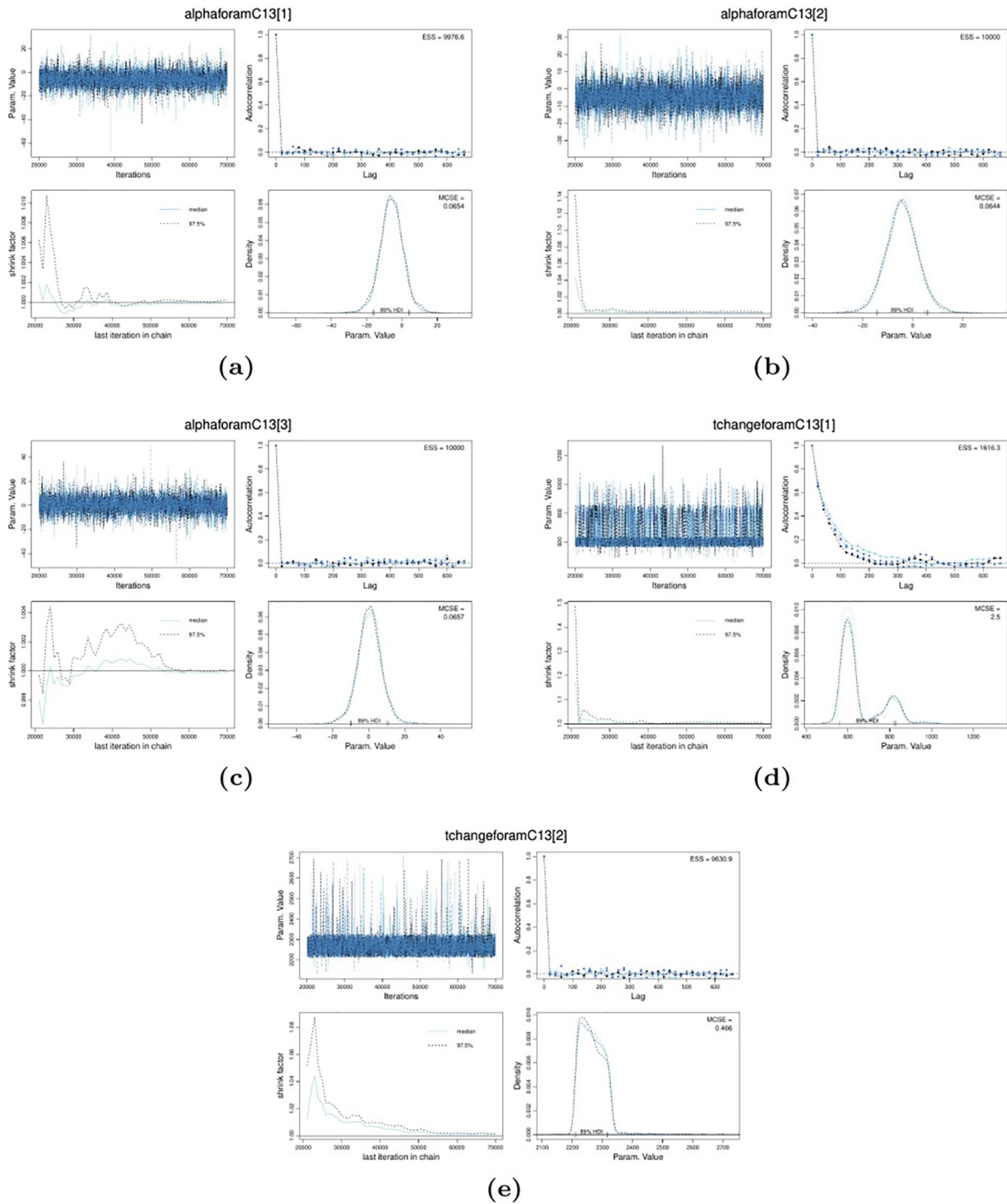


Fig. S2: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$ ,  $c_1$ , and  $c_2$  pertaining to  $\delta^{13}C_r$ .

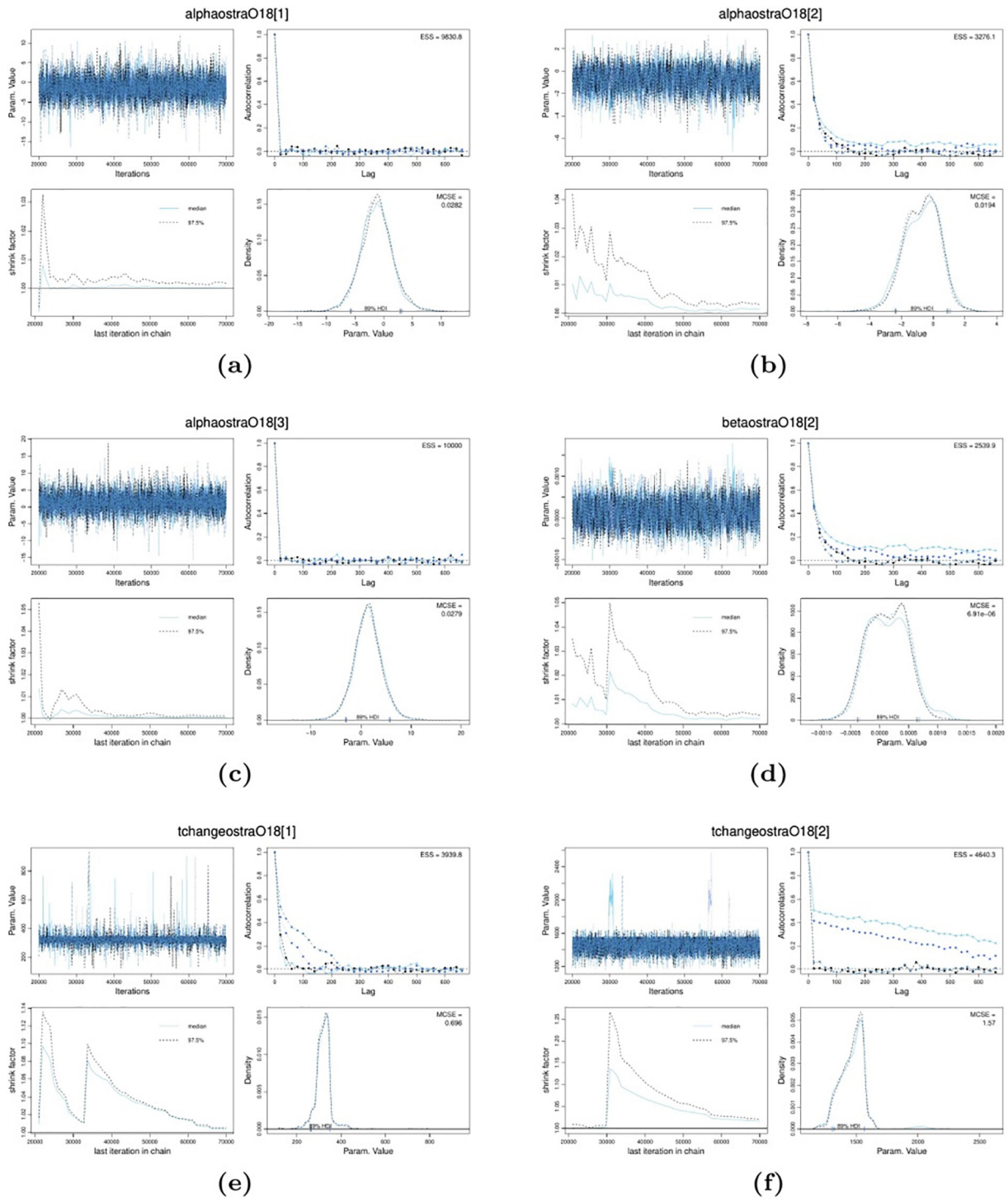


Fig. S3: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$ ,  $\beta_2$ ,  $c_1$ , and  $c_2$  pertaining to  $\delta^{18}O_o$ .

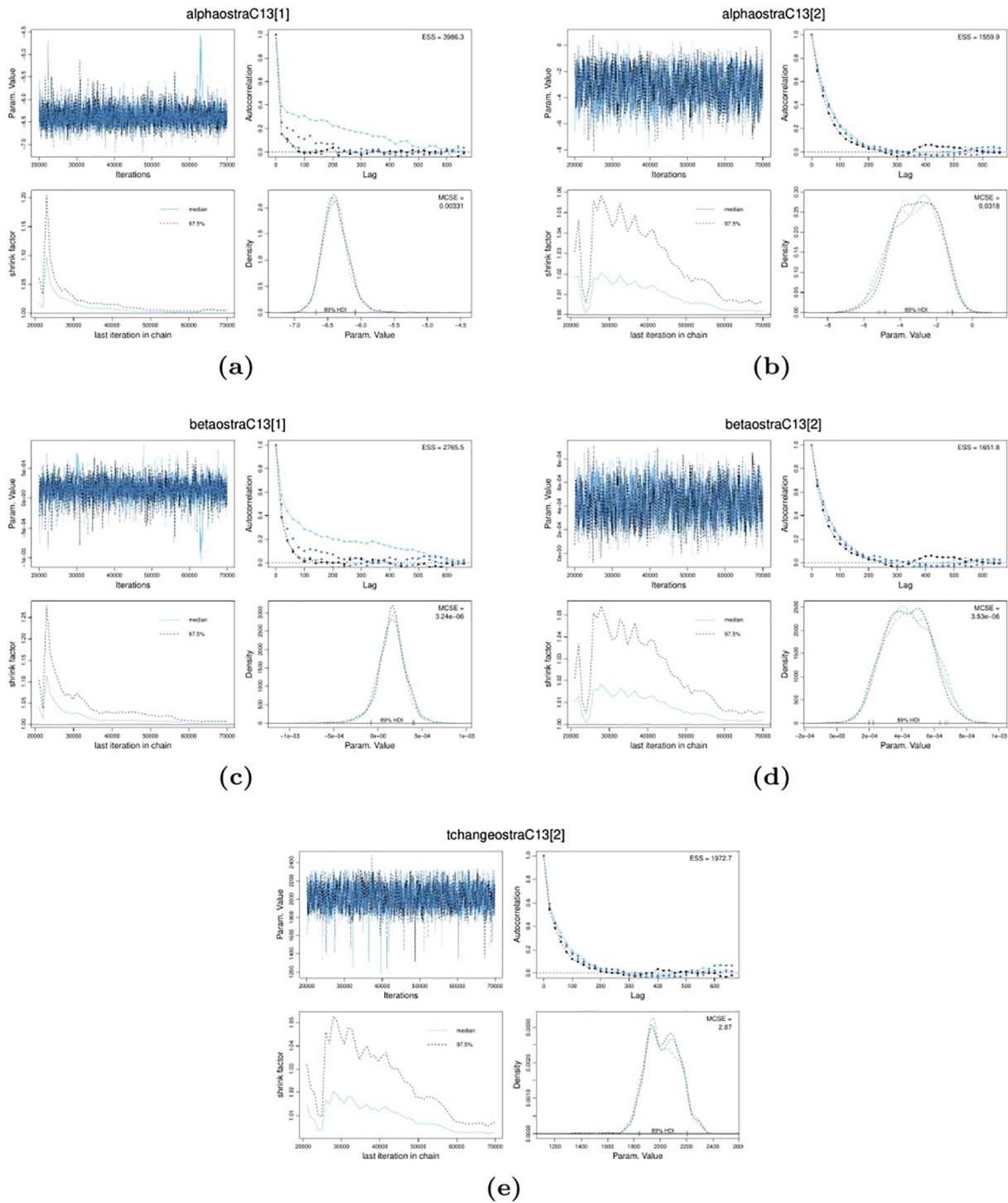


Fig. S4: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of  $\alpha_1$ ,  $\alpha_2$ ,  $\beta_1$ ,  $\beta_2$ , and  $c_2$  pertaining to  $\delta^{13}C_o$ .

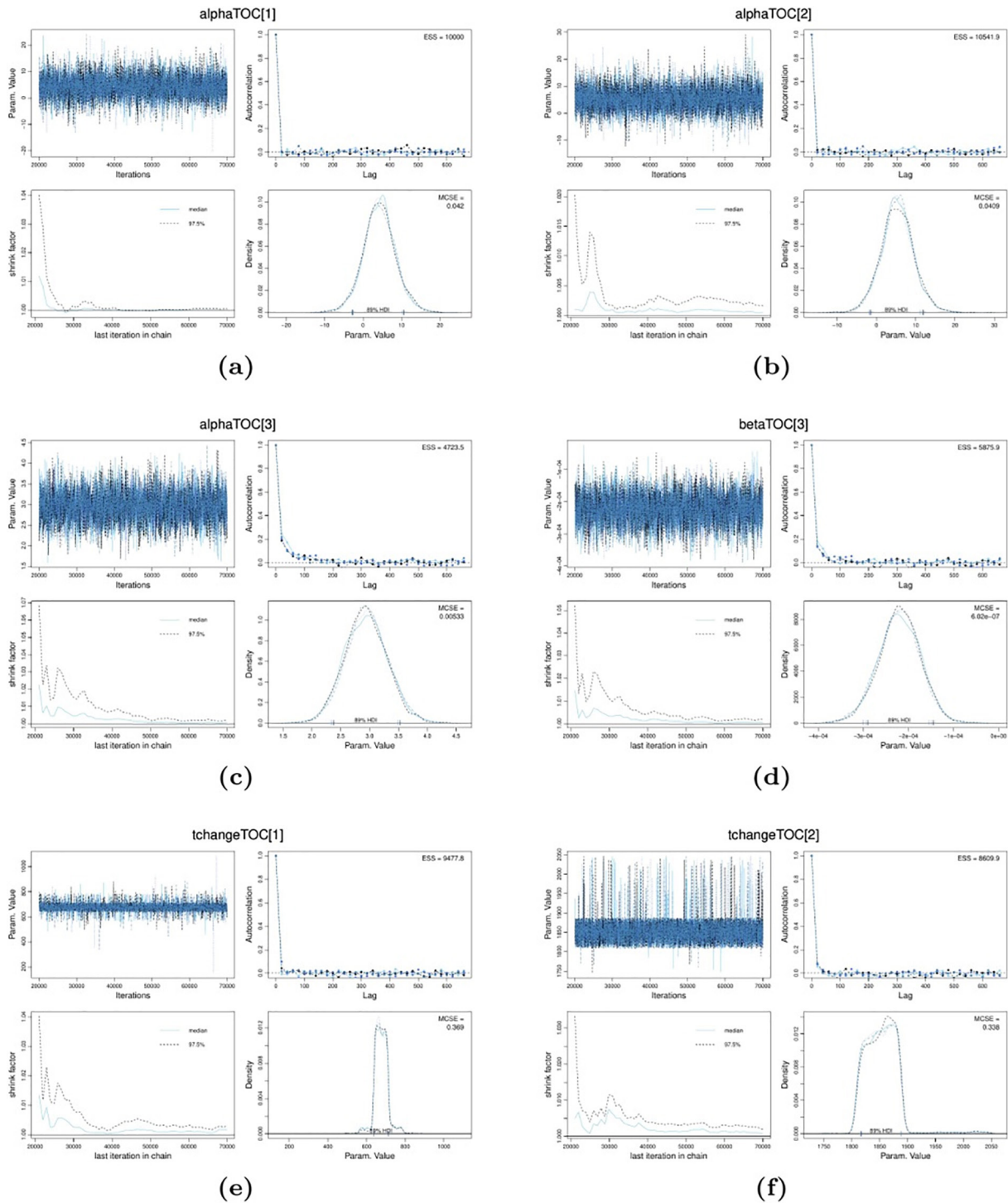


Fig. S5: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$ ,  $\beta_3$ ,  $c_1$ , and  $c_2$  pertaining to TOC.

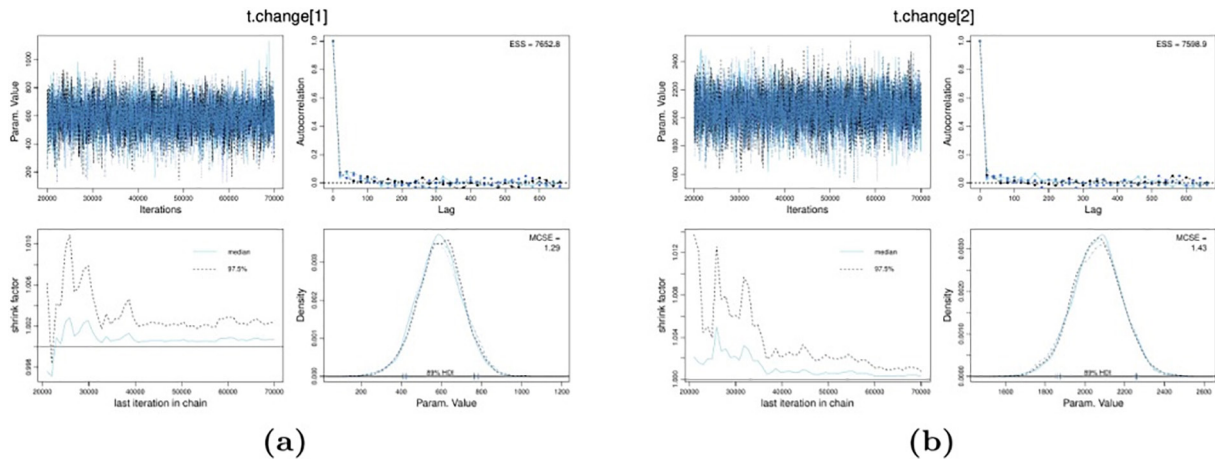


Fig. S6: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are displayed for all four runs of the first and second general change points.

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