

Including explicit priors on phase duration in Bayesian ¹⁴C dating: re-evaluating the dates for basal Knossos and for Nea Nikomedeia (Early Aegean Neolithic)

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ABSTRACT – Bayesian modelling of radiocarbon dates directly integrates information obtained through archaeological analysis. Here, I explain how to add known information/reasonable assumptions about the length of a deposition phase, using the example of date sequences from two Early Neolithic communities in the Aegean whose dating has been hotly debated, i.e. basal Knossos (Crete) and Nea Nikomedeia (Northern Greece). The consequences of the re-evaluation of their dates are discussed for the broader picture of the Neolithisation in the Aegean and for the chronology of the regional use of stamps.

KEY WORDS – radiocarbon dates; Neolithic; clay stamps; Knossos; Nea Nikomedeia

Vključevanje nedvoumnih apriornih verjetnosti v čas trajanja faz v Bayesovem ¹⁴C datiranju: ponovna ocena datumov iz najdišč Knosos in Nea Nikomedeia (zgodnji egejski neolitik)

IZVLEČEK – Bayesovo modeliranje radiokarbonskih datumov neposredno vključuje podatke, ki jih pridobimo z arheološko analizo. V članku pojasnujem, kako dodati znane podatke / utemeljene predpostavke o dolžini faze odlaganja na primeru časovnih zaporedij dveh zgodnjeneolitskih najdišč v Egejskem morju, o katerih se je že intenzivno razpravljalo, in sicer o temeljih v Knossosu (Kreta) in Nea Nikomedeiji (Severna Grčija). Razpravljam tudi o posledicah ponovne ocene teh datumov za širšo sliko neolitizacije v Egejskem morju in za kronologijo regionalne uporabe pečatnikov.

KLJUČNE BESEDE – radiokarbonski datumi; neolitik; glineni pečatniki; Knossos; Nea Nikomedeia

Introduction

This paper has two goals. The empirical goal is to re-evaluate the dating of two important Early Neolithic sites in the Aegean, i.e. basal Knossos and Nea Nikomedeia. The methodological goal is to show how more precision and, crucially, accuracy may be achieved when a Bayesian dating analysis employs constraints on deposition durations obtained through archaeological analysis.

Section 1 introduces the broader context for the re-evaluated sites: the 7th millennium BCE in South-western Asia and Southeastern Europe. Sections 2 and 3 are technical, and describe the new Bayesian dating analyses of the previously available data for basal Knossos and Nea Nikomedeia, respectively. Section 4 discusses the archaeological consequences of obtaining these new dates with respect to the

broad picture of Neolithisation in the Aegean and the chronology of the use of stamps/seals/pintaderas in the Aegean and Anatolia. Section 5 then concludes this paper.

The 7th millennium BCE and the need for more precise dating: an introduction

The 7th millennium BCE was a dynamic and interesting time in Southwestern Asia and Southeastern Europe. In the Fertile Crescent, which had been developing its food-producing Neolithic for several millennia by that point, different and complex histories emerged during this concluding Neolithic phase. In northern Levant and Upper Mesopotamia, the millennium's beginning marks the adoption of pottery, but its initial use hardly revolutionized the local lifeways (Nieuwenhuys, Campbell 2017); it is only in the centuries mid-7th millennium that pottery becomes more abundant, and towards 6250 BCE true seals and actual sealings appear in Upper Mesopotamia (Nieuwenhuys, Akkermans 2019). Interesting social processes surely accompanied these developments, but the evidence is for now insufficient to see which exact ones. To use the settlement pattern as an example, Olivier Nieuwenhuys and Peter Akkermans (2019) argue that it is currently unclear whether there is a retraction of settlement at the time when pottery is introduced and then gains in variety and quantity, or it is rather the case that not all communities actually had any use of pottery until much later into the period. Be that as it may, in the last quarter of the 7th millennium decorated pottery and rapid stylistic innovation spread across vast expanses in this region, plausibly associated with new norms regarding mobility and hospitality (Nieuwenhuys et al. 2016).

Meanwhile in southern Levant a very different history was unfolding. The later 8th millennium BCE was characterized by the appearance of 'mega-sites' in the Jordanian highlands, while in the early 7th millennium the population of such sites apparently disperses into smaller places (see Rollefson 2019 with references). Unlike in the north,

no sign of an actual pottery tradition is to be seen until the second half of the 7th millennium, when the Yarmukian and several other regionalized cultural entities apparently develop, and are already using pottery technology (Garfinkel 2014; Goring-Morris, Belfer-Cohen 2019). At the spectacularly large site of Sha'ar Hagolan in the Jordan valley in the second half of the 7th millennium, complex village planning was practiced and a rich material culture developed, characterized by considerable public works and an art that follows a very strict and formalized canon (Garfinkel 2019). In sum, while the overall trajectory towards greater involvement with ceramic technology and an apparent rise in symbolic production is in common with the northern part of the Fertile Crescent, the local history of the southern Levant of the 7th millennium is markedly different.

In Anatolia, things similarly depended on the specific region involved. In the Cilician plain, the local pottery sequence of the 7th millennium has been analysed as exhibiting a growing sophistication over time, as well as regional connections (Balossi Restelli 2006; 2017), but otherwise we still know very little about the period, though new excavations at Mersin-Yumuktepe promise to add considerably to our knowledge (Caneva, Jean 2016.21–23). Across the Taurus range to the northwest, some economies included food production far earlier (Baird et al. 2018), but it is the 7th millennium BCE that sees the rise of Çatalhöyük, one of the largest agglomerations of its time, without anything comparable known in



Fig. 1. Selected sites mentioned in the text: Kn Knossos; NN Nea Nikomedea; Ma Mavropigi Filotsairi; Pa Paliambela Kolindrou; Re Revenia Korinou; Ul Ulucak Höyük; Çu Çukuriçi Höyük; Bar Barcın Höyük; Bad Bademagacı Höyük; Ça Çatalhöyük; Yu Mersin-Yumuktepe. Base map made with R (R Core Team 2020) and Natural Earth, @ naturalearthdata.com; site locations from the DEFC database (defc.acdh.oew.ac.at), Karamitrou-Mentessidi et al. (2015), Adaktylou (2017).

Central Anatolia. The existence of this large population centre was not ahistorical either: for example, its pottery usage undergoes significant changes as the millennium goes by (Özdöl 2012), while architectural practices change roughly over the course of its third quarter (Brami 2017.102–105). Further west still, in the Turkish Lake District it is not yet clear what exactly the first half of the 7th millennium looked like,¹ but in the second the region definitely experiences the flourishing development of archaeologically recoverable material culture (see overview in Duru, Umurtak 2019.251–269). At the very western edge of Anatolia, close to the Aegean coast of Turkey, new agriculturalist sites also appear, including Ulucak (Çevik, Erdoğan 2020) and Çukuriçi (Horejs 2017), with long stratified sequences spanning the last three quarters of the 7th millennium. In northwestern Anatolia, in comparison, on current evidence Neolithic occupation starts a little later, with the earliest known such site in the region, Barcın Höyük, beginning slightly before the middle of the millennium (Gerritsen et al. 2013). After this start, the Eastern Marmara region appears to feature continuous development through the second half of the 7th millennium, developing its material-cultural peculiarity, which can be described as a single 'Fikirtepe culture' (Özdoğan 2013) despite considerable variations between settlements (Karul 2019; Özbal, Gerritsen 2019).

Turning from Turkey to Greece, two regions are known to have been rather densely populated by agriculturalist communities by the end of the 7th millennium: Macedonia and Thessaly (see Reingruber et al. 2017 and Urem-Kotsou, Kotsos 2020, respectively, for current chronology and references). Despite a number of recent and active excavations adding to the evidence in Macedonia, it is still hard to discern, behind inter-site variability, unambiguous patterns of development other than in specific domains: (uncontestable) pottery changes and (apparent; the review of evidence in Reingruber (2008) still remains relevant) changes in 'small find' categories such as figurines and stamps/seals/pintaderas (henceforth I'll use 'stamps' without prejudice to the function, after Çilingiroğlu 2009). However, as these very specific categories of evidence are particularly likely to be preserved for archaeological investi-

gation, it is often through their comparison that we can identify prehistoric relations between different sites and regions. To use stamps as an example, in the Turkish Lake District's Bademağacı, they first occur in a stratified context from Level 3 (Duru, Umurtak 2019.207, Pl. 123), i.e. apparently in the third quarter of the 7th millennium. In contrast, in Ulucak, near the Western Turkish coast, stamps occur from level Vb, in the last quarter of the 7th millennium (Çevik, Erdoğan 2020).²

To better understand the actual histories revealed by such archaeologically visible phenomena, we need to know the precise chronological relations between the sites. It should be stressed that chronology is not the simplistic hunt for who or which region was 'the first': if one is interested in local pride, each region has in fact quite a lot to offer; and if one is interested in understanding human histories, then there are plenty of questions more relevant than who was the first: 'what exactly?', 'how fast?', 'together with what or who?' and 'why now?' are just some that are of far more consequence. Understanding the prehistoric chronology well is a prerequisite for answering most of these.

Yet gaining precise chronological knowledge is not easy. The natural-scientific method of choice for the Neolithic is radiocarbon dating. But while beautiful in its principle of tracking a uniformly decaying radioactive element, in practice radiocarbon dating is not simple. As with any physical experiment, plenty of things can go wrong, sometimes at no fault of the experimenter; thus a single measurement is never an unquestionably reliable datum. The experimental techniques of radiocarbon dating continue to be developed and further refined (to appreciate this constant process of improvement, see, for instance, Bird et al. 1999; Brock et al. 2010). So are the data and algorithms needed for 'calibrating' radiocarbon measurements: turning physical measurements into calendar years based on a calibration curve, with a new set of curves published just recently (Reimer et al. 2020).

Further aspects of modelling can also be complicated. Wood samples may come from older wood that stopped carbon exchange with the outside much be-

1 As far as radiocarbon chronology goes, the case for occupation in the first half of the 7th millennium basically rests on one date from Bademağacı level 8; though such early occupation is quite possible given the excavated evidence at this and other 7th millennium Lake District sites, future research will hopefully be able to add more to our knowledge.

2 Earlier layers of Neolithic sites are often only investigated in small exposures; but in these two cases, the relevant exposures of the earlier layers have been on the order of 100m² at Bademağacı (deduced from Duru, Umurtak 2019.162–163), and c. 135m² at Ulucak (Çevik, Vuruskan 2020.102), and thus the absence of stratified stamp finds in these cases may well be due to their genuine absence.

fore the tree was cut and used. Animals, including humans, may have drawn through their diet carbon from different sources with different radiocarbon concentrations. This is often labelled 'reservoir effects', where the reservoir refers to the carbon reservoir from which the carbon comes. Unfortunately, local reservoirs may have rather different qualities, and even the measurements of present-day marine reservoir properties can be rather scarce. For instance, in the whole of the Aegean Sea we only have three point measurements, at Nafplio, Piraeus and the Dardanelles/Çanakkale strait. The latter two are closer to each other in numerical value than to the Piraeus measurement, even though Piraeus is much closer to Nafplio than Dardanelles/Çanakkale is, <http://calib.org/marine/>. This all underscores just how non-trivial the issue is.

Finally, the dated sample may contain contaminants with a different carbon age, which in some cases just cannot be eliminated by any known procedure, and – what is even worse – with possibly no indication that something went wrong other than an unrealistic measurement (*van Klinken, Hedges 1998*), so if we are not lucky enough recognize it as unrealistic, we will just happily accept the wrong date.

In practice, difficult though these problems are, they can be largely counteracted by well-designed dating programs, generating not just single measurements, but longer series of dates sampled through the stratigraphy. The sheer number of dates in large series makes outliers, whatever the ultimate reason for their appearance, much easier to see and thus allows them to be weeded out by analysts. Perhaps even more importantly, when the dates are modelled jointly in a Bayesian framework, the stratigraphic information about dated samples can constrain the results in non-trivial and useful ways.

Bayesian modelling of archaeologically relevant radiocarbon measurements, pioneered by John C. Naylor and Adrian F. M. Smith (*1988*), has in the last few years become a nearly-standard method among prehistorians. Within the subfield of Aegean prehistory specifically, the importance of such statistical modelling is frequently acknowledged (*e.g., Reingruber 2020*) and practiced (*e.g., Maniatis 2014*). The point of Bayesian analysis is to incorporate the meaningful information gained by archaeological research into the process of obtaining calendar-age

dates from ¹⁴C measurements. This often allows time estimates to become much more precise, but also, importantly, more correct than if we ignored the actually known information and only relied on 'agnostic' calibration of single dates and their mechanistic and/or highly subjective combination (*Bayliss et al. 2007*).

However, it is common that in practice not all of the actually known information gets incorporated in the results. The purpose of the current contribution is to explain how to include one particularly common type of information we can obtain from interpreting excavation results: the rough duration of a particular deposition phase of the site to be dated. I discuss the issue with the help of two case studies, of basal Neolithic levels at Knossos on Crete (often labelled 'Aceramic' levels), and of the Early Neolithic settlement of Nea Nikomedea in Greek Macedonia. Douka *et al.* (*2017*) and Maniatis (*2014*) are the most recent dating analyses for these two, but neither includes the available prior knowledge about the apparent duration of the relevant deposition phase.

There may be different reasons for choosing not to specify the likely duration of a deposition phase in advance. In fact, for many common applications this duration would be among the main variables of interest: the fundamental work of introducing good Bayesian dating practice to prehistorians (*Bayliss et al. 2007*) is concerned exactly with gaining inferences about phase duration.³ But for the two case studies I report, there are arguably good grounds for making very specific assumptions about the duration of deposition.

In the current literature, basal Knossos gets assigned to anywhere from the later 8th to the middle of the 7th millennium BCE. But when properly modelled we obtain a fairly precise estimate of the 66th century BCE, which allows us to see how this short-lived occupation fits into the developments in the broader region. For Nea Nikomedea, existing estimates are equally discordant and wide: from 6600/6400 BCE to the end of the 7th millennium. In this case, the reported radiocarbon measurements clearly contain anomalies that cannot be explained without a new dating program for the site. Still, on present evidence we can place this site's existence as a 50–150-yearly period somewhere roughly between

³ Similarly, the purpose of the Gaussian Monte Carlo wiggle-matching (GMCWG) method (see, for example, *Benz et al. 2012.299–300*) is to get duration and date inferences in the case when we cannot independently estimate the length of a phase.

6300 and 6050 BCE, excluding both the highest and the lowest opinions in the literature. Both re-evaluations have consequences for our picture of the Neolithisation of the Aegean. For Nea Nikomedeia, I also discuss the consequences of the re-evaluation for the temporal distribution of stamps in the Aegean and Anatolia.

Accepting the specific proposals below for basal Knossos and Nea Nikomedeia will crucially depend on accepting the estimates of the phase duration that I accepted, as well as on the available radiocarbon measurements and on my choices regarding which ones to use. This is as it should be: if our respective understandings of the archaeological evidence differ; if our sets of data differ; or if we make a different choice of which data to discard as erroneous – this all may result in different date estimates as well. The key here is to first incorporate as much of our actual firm beliefs about the site into our dating analysis as possible; and second, to be explicit about our assumptions, so that they can be subsequently challenged or adjusted, as future evidence or future analysis may demand. To simplify future re-evaluation of my results, the original analysis files for OxCal (*Bronk Ramsey 2009*), as well as the result files, are all provided as online supplementary material. The analysis files include the uncalibrated dates discussed and used, coded in the OxCal format.⁴

Re-evaluating basal Knossos dates conditional on a very short occupation

The basal, and for all we know initial, occupation of Knossos, directly overlaying the bedrock, has been claimed to exist in three small areas AC (11 by 5m), X and ZE (*Evans 1994*), where it was labelled Stratum X; and in Trench II in the 1997 rescue excavations on the area of 1.5 by 1.5m, where it was labelled levels 38–39 (*Efstratiou et al. 2013*). Small areas X and ZE of Arthur Evans’s excavations are relatively far from the AC area, and contain architectural remains; I follow Agathe Reingruber (*2008*) in rejecting Evans’s identification of the basal layer in AC with those at X and ZE, given that no dates are available from X and ZE, and that the 1997 excavators did not find similarities with ZE either (*Efstratiou 2013.27*). Note that Evans himself connected the architectural remains in ZE and X to Stratum IX rather than X (*Evans 2008.19–20*). Judging from

Stratum IX ¹⁴C dates, it represents a much later occupation. In contrast to X and ZE, trench II is at most 10m away from Evans’s area AC (*Efstratiou et al. 2013.2, Fig. 1.1*), and I accept the 1997 excavators’ identification of their levels 38–39 with Evans’s Stratum X. The cited excavators label these basal layers ‘Aceramic’; I will refer to them as ‘basal Knossos’ to avoid using potentially theoretically charged terminology (see, for example, *Reingruber 2017* for a review).

The early radiocarbon dates were compiled by Evans (*1994*), and re-published with added information on their context by Yorgos Facorellis and Yannis Maniatis (*2013*), who also published further dates from the 1997 excavations. Finally, Katerina Douka *et al.* (*2017*) added still more dates on samples from both the 1997 and Evans’s excavations, and modelled them statistically using OxCal.

The apparently very early dates from basal Knossos have deservedly received much attention in the literature, but their exact interpretation remains contested. Evans (*1994.1*) writes of “*some time near the end of the 8th, or in the earlier part of the 7th millennium BC*”; Nikos Efstratiou (*2013.29*) of “*the first settlers of Knossos around 7000 BC*” for the initial Knossos occupation; Liora Kolska Horwitz (*2013.173*) says the dates “*place the Stratum X occupation [=basal Knossos – Author] at the end of the eight millennium calBC*”; Facorellis and Maniatis (*2013*) say that “*radiocarbon dating has established absolute dates for the beginning of the Neolithic in Crete at 7030–6780 BC*”; Maniatis (*2014.209*) writes that Knossos was established “*around 7000 BC*”; Çiler Çilingiroğlu (*2016.Tab. 1*) places Knossos X among a set of sites within “*7000–6600 calBC*”; Reingruber (*2008.121*) discusses the earlier radiocarbon dates and placed Knossos “*X and the upper [obviously “lower” is meant – Author] border of IX during the middle of the 7th mill. BC*”.

In its turn, the latest Bayesian modelling in Douka’s *et al.* (*2017*) study does not discuss the authors’ interpretation of their analyses explicitly, despite the fact that the estimates obtained differ between each other. The dates on the map in Douka *et al.* (*2017. Fig. 6*) give for Knossos ‘6910–6480/6970–6590’, which are called in the caption “*the numerical age estimates for the earliest Neolithic occupation (95.4% probability)*”. An examination of the plot in

⁴ All results in this paper were obtained using OxCal 4.4 (*Bronk Ramsey 2009*), run on the Oxford servers made available to the archaeological project, for which I am very grateful. IntCal20 (*Reimer et al. 2020*) was used as the default calibration curve, and the results were selectively checked against IntCal13 (*Reimer et al. 2013*), as reported in the text.

this figure and of supplementary Tables S2 and S3 (available at <http://dx.doi.org/10.4312/dp.48.3>) shows that this should be read as the estimates for the beginning of the earliest occupation, rather than for its whole length, as could be erroneously inferred. In the main text, we read: “*Knossos was first occupied at the beginning of the seventh millennium BC (6900–6600 BC at 95.4% probability)*” (O.c. 317). Finally, regarding the modelled duration of occupation, Douka *et al.* (O.c. 315) state: “*the life-span of the Knossos founder village was short; it seems to have lasted from a few years up to a maximum of 400 calendar years*”. This must refer to explicit measurement of the phase’s duration in OxCal, not directly shown in the paper.

Before we turn to modelling ourselves, it is useful to review the findings for basal Knossos from area AC’s Stratum X and Trench II’s levels 38–39. In area AC, we have numerous “*grain from a field of bread-wheat*” (Evans 1994.4), *i.e.* *Triticum aestivum* (Sarpaki 2013) (still surprising today at this early time and this place); and “*a row of stake-holes, and the carbonised remains of some of the actual stakes were found to be still in the holes in which they had been set*” (Evans 1994.5). There were child burials dug into this layer, but their simultaneity is not as secure (Reingruber 2008). Bone tools, a figurine, beads and shell pendants are reported by Evans (1994.5). Animal bones from Evans’s excavations were studied by Valasia Isaakidou (2004), divided by excavation area, and include cattle, pig and sheep/goat (with counts in her Fig. 6.1) for basal Knossos in AC. The lithic industry is described in James Conolly (2008), apparently for the combined sample from AC, ZE and X, which is unfortunate.⁵ Conolly reports signs of resource stress in the assemblage, while Evans (1994.5) reports the obsidian to be Melian.

The small 1.5 x 1.5m area of Trench II from the 1997 excavations added to Evans’s earlier finds “*some pieces of obsidian and dissolved unbaked mud-brick*” (Efstratiou *et al.* 2013.19); more concretely, “*four pieces of obsidian – small flakes and broken blades – and one flint blade*”, with the obsidian presumed to be Melian (Efstratiou 2013.28). The 1997 archaeobotanical sample presents multiple other ce-

reals and pulses (Sarpaki 2013.69–73). Summing up, there is considerable evidence of human activity at basal Knossos, including harvesting grain and various other forms of work with animal and stone tools. However, the overall layer is thin, and is compatible with a short-lived occupation of several years (perhaps a single harvest season!), as defended by Reingruber (2008.127) and accepted as a real possibility by Douka *et al.* (2017).

The radiocarbon dates for basal Knossos include five measurements from grain and five from charcoal, which includes two dates from the same stake from Evans’s Stratum X. Below I report four possible models for those dates, generated by two factors: (i) whether to include only dates from grain (a short-lived, and therefore more reliable material for dating associated events), or dates from both grain and charcoal; and (ii) whether to leave the length of basal Knossos with an implicit prior (similarly to Douka *et al.* 2017), or impose on it an informative prior corresponding to the hypothesis of a short occupation of just several years; specifically, I defined a log-normal prior with the mean below two years, but allowing, in principle, much longer spans, albeit with low probability. Figure 2 illustrates the analyses made only on grain dates, and shows considerably different inferences about both the duration and timing of basal Knossos.

The first thing to note is that the two analyses in Figure 2 provide very similar posterior estimates for the five grain samples. The choice of prior on the phase length thus did not have a dramatic effect on individual date inferences. However, that choice had just such an effect on the inferences about the phase’s length and overall timing. If we use the implicit prior, also used by Douka *et al.* (2017), the phase’s start ranges from 6704 to 6491 cal BC at the 95% HPD (that is, the highest posterior density), but with a restricted phase length this becomes a shorter 6598 to 6484 cal BC. The length of the phase, Figure 3, is anywhere between zero and 250 years (95% HPD) with the implicit prior, but is below five years with my informative prior at the same HPD. The inferred durations (black) on the right in Figure 3 closely follow the prior’s shape (light shaded).⁶ This means that it is ultimately the prior, and not the data,

⁵ In the light of this, the suggestion of continuity between basal Knossos and much later overlying Neolithic layers (Conolly 2008. 87) is unfortunately suspect.

⁶ It is not clear to me why negative durations are reported at the lower end, as the OxCal construction of a phase with two boundaries should ensure a non-negative phase length. Perhaps this is due to a difference in default resolutions used by the program when running and checking constraints on the one hand, and when reporting on the other; in this case, “-2” should really be read “0”.

which effectively drives the phase-duration inferences. Thus the seemingly harmless implicit prior in fact represents non-trivial beliefs about the phase length that we incorporated into Bayesian analysis. It is instructive to explain how this happens. The assumptions we made for the implicit prior, similar to those in Douka *et al.* (2017), but also in most Bayesian analyses of Aegean prehistoric chronology known to me, are (i) that our measured grains belong to one phase, and (ii) that their deposition was at a uniform rate. It is this uniform rate assumption that keeps the boundaries of the interval from going to infinity, while still allowing them considerable freedom, as we effectively allow a rather long time to pass before the first of the grains was grown and charred.

Now that we see the effects of choosing between the two priors on phase length, let us go back to the archaeological interpretation. I introduced the log-normal prior favouring a very short phase length on the basis of a hypothesis of very-short occupation, which may prove to be wrong in the future. Remaining agnostic about that specific hypothesis, do we have other reasons to choose between the two priors? I would argue yes. Note that the first three dates in Figure 2 stem from three grains of the same cache studied by Halbaek from AC Stratum X (Douka *et al.* 2017). The other two dates are from seeds from level 39 of Trench II, which in principle may or may not belong to the same season's crop. Thus whatever our beliefs about basal Knossos as a whole, we should accept almost simultaneous actual deposition for the three dated grains from Stratum X, and perhaps for all five, as Trench II was at most 10m away from area AC and the seeds from it could well belong to the same deposition event. To see if choosing three or five seeds makes a difference, I checked whether a

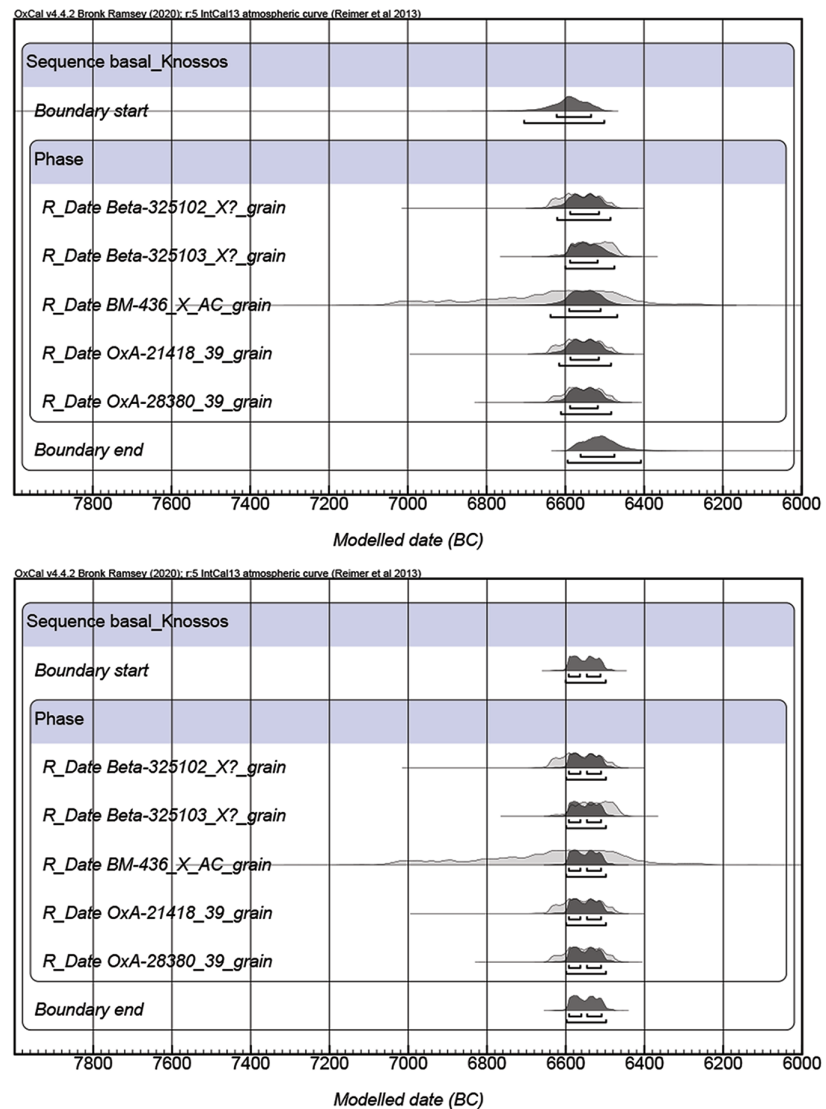


Fig. 2. Basal Knossos analysed with dates from grain only. Above: no additional prior on phase length. Below: log-normal prior on phase length with $\mu = 0.5$, $\sigma = 0.5$ (thus with the mean below two years, but a long thin tail allowing much longer durations). Here and in all subsequent analyses: (i) in plots, the lower interval lines correspond to 95% HPD (highest posterior density), upper lines, to 68% HPD; (ii) the corresponding OxCal scripts and result tables can be found in the online supplementary material at <http://dx.doi.org/10.4312/dp.48.3>

model featuring just the first three dates from Figure 2 with the short-length prior provided different inferences from those with five grain dates. The smaller three-date model (see the supplementary material at <http://dx.doi.org/10.4312/dp.48.3>) infers similarly prior-driven phase durations, but is less specific about when the short occupation occurred: roughly 6590 to 6500 cal BC at the 68% HPD, and 6630 to 6470 cal BC at the 95% HPD.

Let us spell out the substantive consequences of accepting either prior. If we choose the informative short-occupation prior for the grains, it is clear what

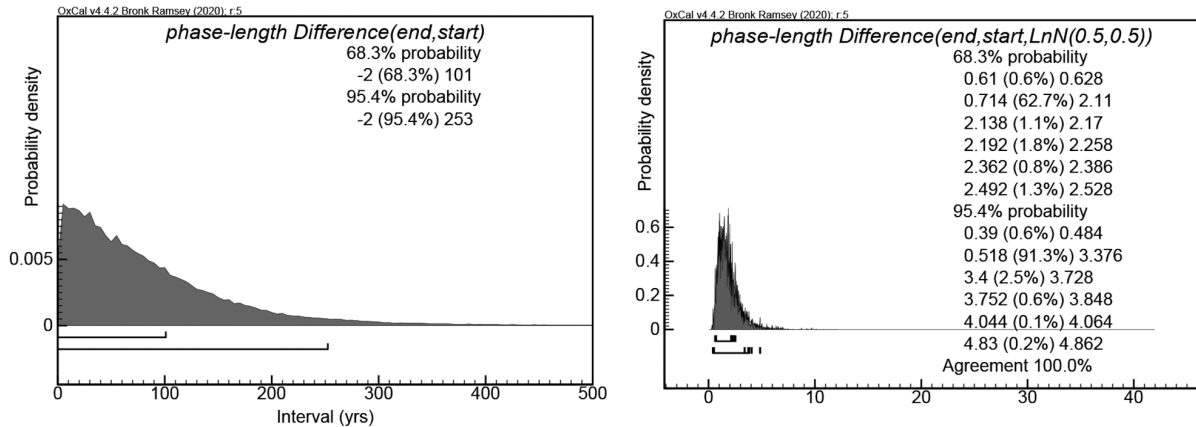


Fig. 3. The duration of basal Knossos from grain-only analyses in Figure 2. Left: no additional prior on phase length. Right: with log-normal prior on phase length with $\mu = 0.5$, $\sigma = 0.5$; the shaded area illustrates the shape of the prior, the solid black line, inferences; it is clear from the comparison that the inferences closely follow the prior. Note the difference in scale on the x-axis between left and right.

we are trying to date: the event of handling that crop, which may or may not coincide in duration with the overall basal Knossos occupation. If we choose the implicit prior that does not restrict the phase length, then we get inferences compatible with the Knossos occupation existing for decades, if not centuries, before the three/five grains were grown, and similarly after that event. Archaeologically speaking, it is not at all clear what we are actually measuring with a phase defined in this way.

While it is reasonable to disagree which prior is more appropriate for inferring the dates for the whole of basal Knossos, only the short prior is appropriate for dating the deposition of the grains. So even if we choose to believe the occupation could last a long time, we should still, on present evidence, place the event of growing the crop into the 66th century BCE (if we assume all five grains to be from one crop) or into the roughly one and a half century between 6630 and 6470 BCE (if we only accept the grains from AC).

Let us now consider what happens when we also include dates from charcoal, as seen in Figure 4. As we could now expect, the two models provide very different estimates for the phase date and duration. On the implicit prior on the left, basal Knossos ranges between roughly 6850 and 6450 cal BC at 95% HPD, with a duration anywhere between zero and 370 years. On the short-occupation prior, we infer a 95% HPD of about 6650 to 6600 cal BC for the phase, and a short duration, strongly induced by the prior.

Given the higher apparent precision of the model with the short-duration prior, one might wish to prefer the all-dates model with the short prior over the

grains-only one. The satisfaction of using all available data might tempt one to accept one of the models in Figure 4, whichever accords better with one's beliefs. But I argue that closer examination of the quality speaks against those choices. Even the visual inspection of Figure 4 shows that the combined (BM-124)+(BM-278) and the OxA-9215 charcoal dates show poor agreement between the individual measurement (light shaded and outlined) and the inferred distribution (dark shaded). Indeed, the agreement indices A for the two resulting calibrated dates are low in both models (see the results in the table form in the supplementary material at <http://dx.doi.org/10.4312/dp.48.3>). Furthermore, on the seemingly more precise short-duration-prior model on the right in Figure 4, two of the grain dates show very poor agreement, namely Beta-325103 and OxA-28380. In other words, some data is not in very good agreement with the models. I conclude from this that it is preferable to use the grain-only models for basal Knossos.

There are several possible reasons for the problem. First, it could be that the charcoal samples do not actually come from the same deposition event that affected the grains. This is perhaps unlikely for the stake from which the old dates BM-124 and BM-278 came from, as one of the dated grains is reported to be associated with that stake (*Facorellis, Maniatis 2013.Tab. 10.2*). For the other charcoal samples, theoretically they may have been produced by different fires. Second, the old-wood effect may well be in play; the two charcoal samples from the burned stake were considered by Evans to be unlikely come from an old tree, as “the oak was probably only 15–20cm in diameter” (*Evans 1994.5, fn. 11*), but its old date, when calibrated in isolation (*i.e.* the out-

line in Figure 4), is rather imprecise, and similarly for OxA-9215. The three other charcoal dates are measured considerably younger (over a century younger in uncalibrated BP), but even those measurements at face value appear to predate those from the grains. This is consistent with the dated wood having been old, and the whole basal occupation being very short; but we cannot on present evidence exclude the hypothesis of a longer light occupation, either. Finally, we cannot exclude the possibility that some of the measurements, especially from early dating, are objectively in error.

To conclude this case study: I argue that it is more appropriate to model the date of basal Knossos using only the measurements from grain; that the radiocarbon evidence is compatible with basal Knossos being a short-lived occupation of just several years, perhaps one season, though our radiocarbon data in themselves do not support this over alternatives; and finally, that this basal occupation happened specifically in the 66th century BCE. On presently available evidence, the reader may accept or reject this proposal judging for herself the merits of my reasoning. The advantage here is that this reasoning was made explicit above and is thus easy to evaluate independently.

Needless to say, it is also quite possible that in the future we will obtain more hard evidence about the basal occupation of Knossos, which can then significantly affect our inferences. But at least for the present evidence we applied some important model-checking steps: we checked sensitivity to the phase-length prior as recommended for priors in general, e.g., by Christopher Bronk Ramsey (2009.347),⁷ and performed an informal check of agreement of in-

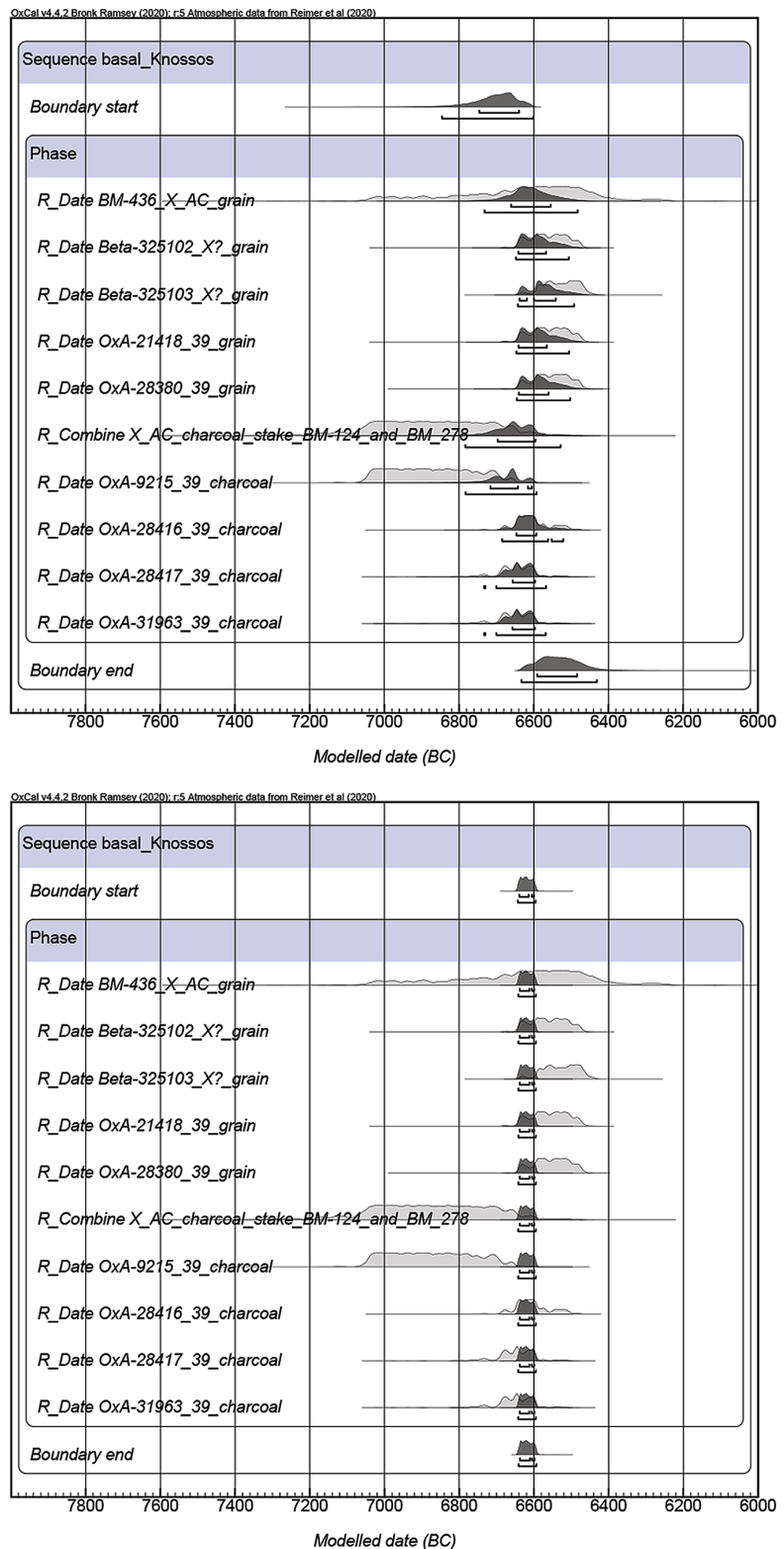


Fig. 4. Basal Knossos analysed with dates from grain and charcoal. Above: no additional prior on phase length. Below: log-normal prior on phase length with $\mu = 0.5$, $\sigma = 0.5$. See the online supplementary material at <http://dx.doi.org/10.4312/dp.48.3> for analysis scripts and tables.

⁷ For the proposed preferred analysis, that is the one incorporating only dates from grains and restricting the length of the deposition event, I also checked the effect of the calibration curve. Using IntCal13 (Reimer et al. 2013) instead of the current IntCal20 did not change the results significantly, resulting in slightly shorter HPD intervals for the start and end dates of the phase.

dividual radiocarbon measurements with the model (*cf. Bronk Ramsey 2009.356*).

Re-evaluating Nea Nikomedeia dates conditional on an occupation length of several generations

Until the last decade, it was a contentious issue whether Greek Macedonia featured any Neolithic sites before the last two centuries of the 7th millennium BCE. The site of Nea Nikomedeia, in the south-western corner of the Plain of Macedon, has been central to the debate. The site was excavated in 1961–64, but has not yet received a full final publication: Gillian Pyke and Paraskevi Yiouni (1996) is the final presentation of the stratigraphy, architecture and the pottery, but for example lithics or small finds, including among others the stamps that played a role in the chronological discussions of Nea Nikomedeia, have not yet been definitively published.

The set of radiocarbon dates for Nea Nikomedeia includes four dates on charcoal or on unknown material made in the 1960s. The two earliest of which have huge laboratory-reported standard deviations and after individual-date calibration reach far into the 8th millennium BCE – much earlier than the very early, for Neolithic Greece, charcoal dates from basal Knossos. However, further dates on grain and animal bone were obtained in the 1980s and 1990s (Pyke, Yiouni 1996.195), and fall into the second half of the 7th or even into the 6th millennium BCE, and do not all agree well (see, for example, the discussion in Perlès 2001.108–109).

Different interpretations have been expressed in the literature regarding the ordering of Nea Nikomedeia. Representative examples include the following. Maniatis (2014.Fig. 6) lists Nea Nikomedeia among sites already existing between 6600 and 6400 cal BC, while Perlès (2001) broadly orders the site to roughly 6400–6000 cal BC (that is, to her definition of the Early Neolithic in Greece). Urem-Kotsou and Kotsos (2020) provide the range 6400–6200 cal BC for the site. Reingruber (2008.394–396), considering the apparently temporally advanced elements of

the material culture, their similarity to early 6th millennium BCE sites in the neighbouring Republic of North Macedonia, and the then-lack of clearly comparable early sites in Greek Macedonia, orders the start of Nea Nikomedeia at between 6150 and 6100 cal BC. Significantly, when discussing the radiocarbon evidence Reingruber and Laurens Thissen (2017. *Region IId*) note the apparent inconsistency in our data about this site (see http://www.14sea.org/3_IId.html#site1), with several alternative interpretations of the evidence arguably remaining possible.

In recent years, the research context of Nea Nikomedeia has changed due to an enormous expansion of knowledge about the initial phases of the Neolithic in Greek Macedonia and bordering regions. While research is still ongoing and we lack final reports, it seems now beyond doubt that Greek Macedonia featured Neolithic settlements in the second half of the 7th millennium BCE, including most likely that millennium's third quarter and not just its end. Most preliminary information so far has been published from the site of Mavropigi-Filotsairi in the Kozani prefecture, less than 100km east from Nea Nikomedeia (Karamitrou-Mentessidi et al. 2015). The extensively excavated site of Paliambela Kolindrou, roughly 30km southeast of Nea Nikomedeia, features early dates (see Maniatis 2014) and shows evidence for rather complex landscaping behaviour at the initial settlement episode; importantly, Nea Nikomedeia-like houses succeed the small pit dwellings of the initial phase of the site (see Kotsakis 2019 for a preliminary report). Rescue excavations at Revenia in the early 2000s uncovered another early pit-dwelling site, presented with an extensive catalogue of finds by Foteini Adaktylou (2017). Besides pit structures, there appears to be a later, but poorly preserved phase of above-ground dwellings at Revenia (Adaktylou 2017).⁸ Taken together, the recently obtained evidence suggests an early presence of Neolithic settlements in Macedonia, and against that background Nea Nikomedeia is no longer exceptional.⁹

Still further inland from Greek Macedonia, we arrive to the Albanian Korçë basin, where the early Neoli-

8 Numerous dates for different pits – on charcoal, animal and human bone, and seeds – are reported by Adaktylou (2017. *Appendices 12, 22, 36, 42, 55, 72, 74, 102, 160, 163, 165, 168, 187, 195, 197, 242*). The dates show some spread, but mostly appear to point towards the third quarter of the 7th millennium BCE. Interestingly, stamps are present in several pits (Adaktylou 2017. *Appendices 378–379*), and also 'earplugs', with the lion's share of the latter in only two pits, Pit 44 (15 objects) and Pit 7 (seven objects) (Adaktylou 2017. *Section 6.5.5.6, Appendices 375–377*).

9 Urem-Kotsou and Kotsos (2020) is an up-to-date review of the sites in Central Macedonia, including the Early Neolithic ones; Maniatis (2014) published modelled dates from several of these, including Paliambela and Mavropigi; see also Bonga (2019.162–163), discussing the archaeological associations of some of the Mavropigi dates, and mentioning a possibly early date OxA-31863 from charred grain that seems not to have been formally published yet.

thic sites of Vashtëmi and Podgori (*Korkuti 1995.32–57*) show some decorated-ceramic affinities with Mavropigi, some 100–150km southeast (*Bonga 2017*). These Albanian sites might also be early (*Allen, Gjipali 2014*), though the radiocarbon dates stem from cores and are not in direct association with archaeological finds, and in any event remain isolated dates rather than series (see *Ruka 2018* for a critical overview). The chronological and spatial resolution of the ceramic associations also remain to be clarified, as Lily Bonga (*2017*) also discusses. In particular, a tradition appearing very similar to such polychrome decoration is a distinct part of the ceramic repertoire at Tell Čavdar in Western Bulgarian Thrace, almost 500km to the northeast of Mavropigi; *cf.* a polychrome ochre-on-red sherd in (*Bush 1984.81, Fig. 80c*), and several sherds described generally as “dark-brown or red” outlined by “thin white bands or thickly placed white dots” (*Georgiev 1981.87–88*), and represented at least in the V (*Georgiev’s Fig. 46*) and VI (*Fig. 47 middle right, 48 bottom left*) horizons, and possibly later (the preliminary report does not specify the exact duration of this variety’s appearance). The motifs appear, at least at first sight, rather similar to those at Mavropigi (*Bonga 2017.Fig. 5*). Unmodelled calibrated dates from horizons V and VI comfortably span the 62nd–57th centuries BCE at 68%, (*Reingruber, Thissen 2017*), while Mavropigi’s fall exclusively into the 7th millennium (*Maniatis 2014. Fig. 3*).¹⁰

Summing up, earlier dates for Nea Nikomedeia around the middle of the 7th millennium BCE as sug-

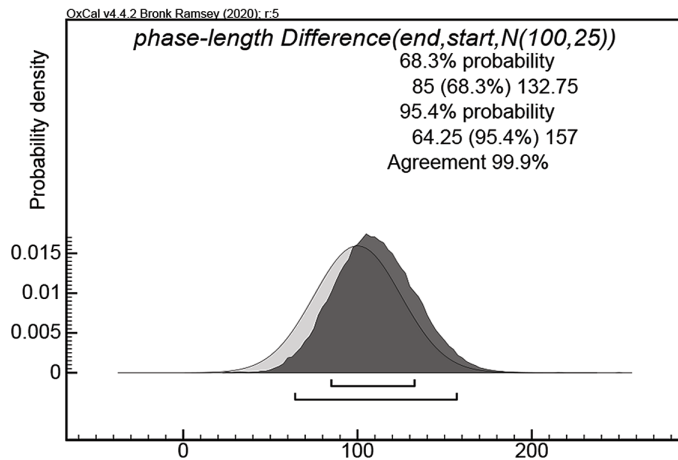
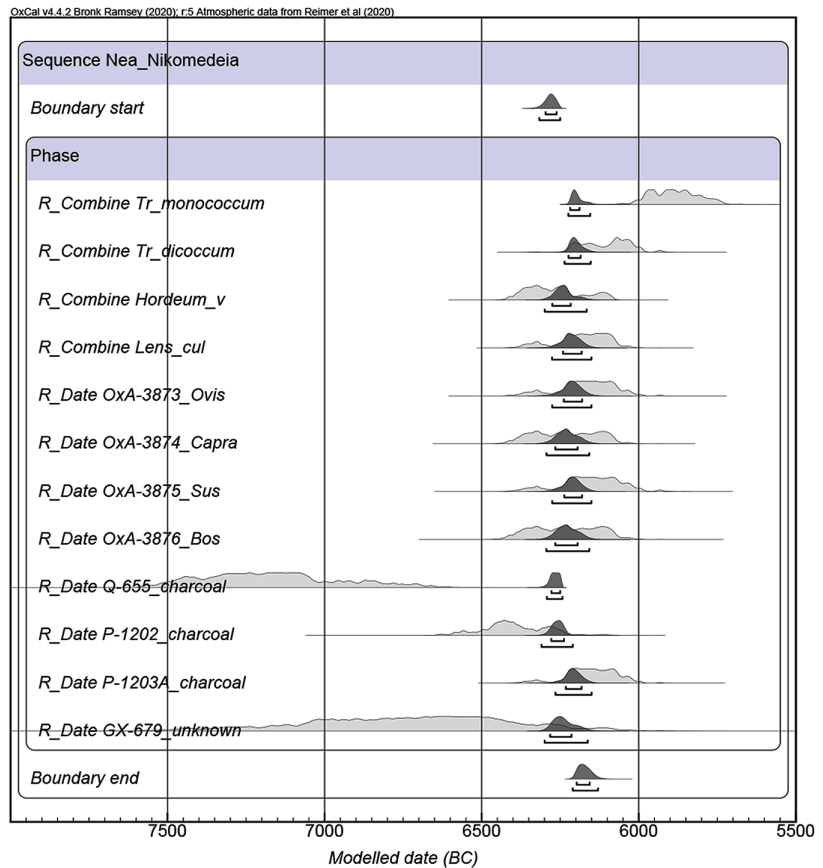


Fig. 5. Nea Nikomedeia: all dates reported in Pyke and Yiouni (1996); prior on the phase’s duration: Normal(100,25).

gested by Maniatis (*2014*) would not look as isolated in the broader region today. It is thus all the more important to revisit the Nea Nikomedeia dates and model them jointly. Catherine Perlès (*2001*) and Reingruber (*2008*) discuss which Nea Nikomedeia dates can or should be treated as outliers, and thus

¹⁰ For further context, in the Korçë-basin site Vashtëmi from the older excavations there are just two pieces featuring red and ochre together (*Korkuti 1995.49*), and they have no white outline in contrast to the pieces found in Podgori. Thus this specific ‘polychrome’ tradition is only observed in Podgori (*Korkuti 1995.37, Pl. 7.6; also Andoni 2017*). For Čavdar, Georgiev (*1981.87–88*) writes that such polychrome decoration similarly appears in other settlements of the Karanovo I-Kremikovci I geographical group, and was also excavated at Gradešnica in Northwestern Bulgaria.

ignored. Maniatis (2014) reports dates after apparent individual calibration (as opposed to joint modelling), and does not analyse the most suspicious outliers; This-sen and Reingruber (2017.134) report the dates together with their individual calibrations at the 68% HPD, but unlike Maniatis combine the dates from grain and corresponding humic acid, which apparently correspond to the same samples. I am not aware of an actual joint modelling of the Nea Nikomedeia dates.

To model the dates appropriately, we now need to discuss the site's archaeological evidence. Nea Nikomedeia is a tell site, possibly with a long occupation history, but cleared for taking earth for road-fill down to its early Neolithic occupation (Rodden 1996.5–7). The remaining cultural layer was at most 20cm at a large portion of the site, but up to 70cm closer to the centre of the mound. The architectural remains have been tentatively evaluated by Pyke to correspond to three stratigraphic phases, which “appear to follow in swift succession” (Pyke 1996.48). She also reports that there was no apparent change in small finds. Yiouni (1996.103–104) studies the pottery of the site, and concludes that it is remarkably uniform across the stratigraphy, also suggesting “only a short time span”. While Pyke and Yiouni (1996) refrain from voicing a calendar-years estimate for the duration of the studied (period of the) village, I accept here the agreeing estimates of 50–150 years by Stelios Andreou *et al.* (2001.323) and around 100 years (Reingruber 2008.395).

We now turn to defining a Bayesian dating model. I will go through the analyses I performed tutorial-style, in the order I did them, with the aim to demonstrate how one might proceed in practice. Considering the apparent short span of the occupation and its internal homogeneity, I model all dates as coming from a single deposition phase. Given that

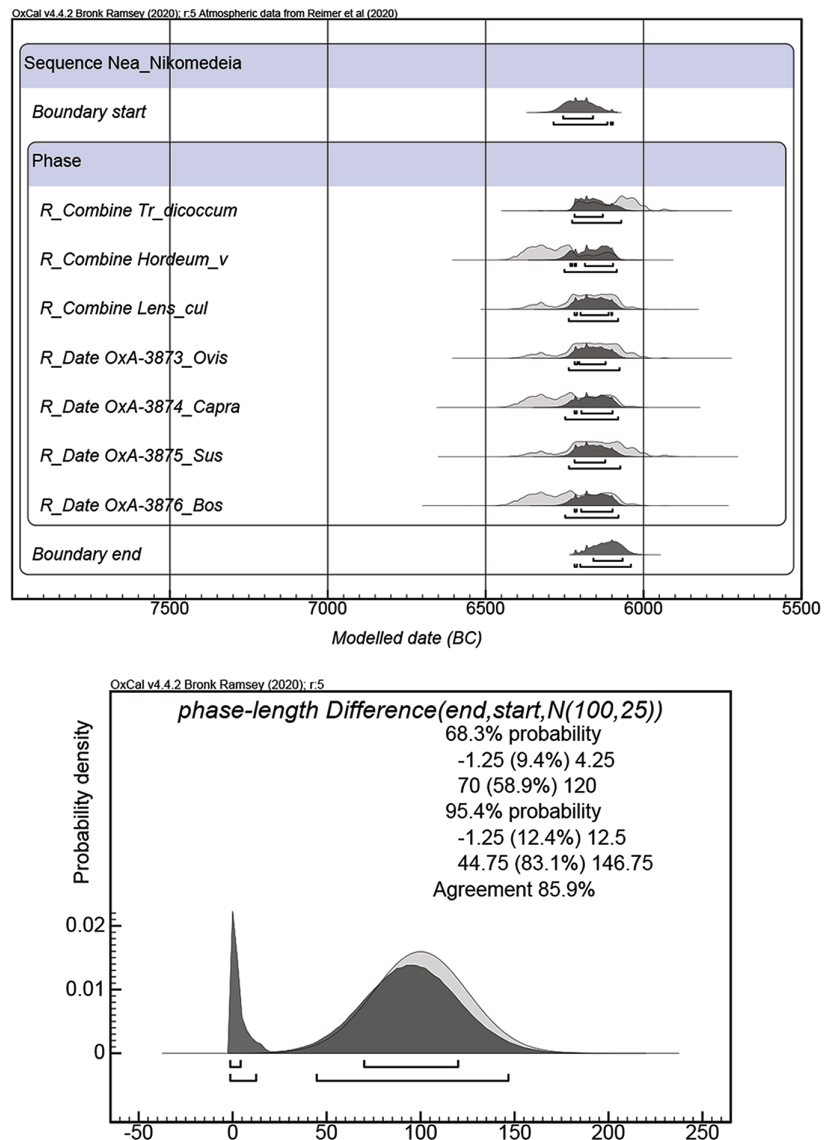


Fig. 6. Preferred model for Nea Nikomedeia: dates reported in Pyke and Yiouni (1996) without dates on charcoal and on unknown material, without the outlier combined date on grain, Triticum monococcum (OxA-1603)+(OxA-4280); prior on the phase's duration: Normal(100,25).

we do not have additional stratigraphical information on the relative relationships between the samples, I did not place any internal order on them. Finally, in agreement with the chosen prior duration estimate, I set an informative prior on the phase's duration, namely, Normal(100,25), which results in the 95% probability assigned to the duration(s) between 50 and 150 years, with a peak at 100 years. The results of such an analysis, taking into account all available dates including the likely outliers, are visualised in Figure 5 (see the online supplementary material at <http://dx.doi.org/10.4312/dp.48.3> for results in the table format and the analysis file). This served as an exploratory analysis to see how all the different dates fit together.

What is obvious already from a visual inspection of Figure 5 is that the two dates accepted in the literature as outliers, Q-655 and GX-679, clearly look as such. This is no surprise: the plot on the right in Figure 5 shows that this set of dates drives the inferred length of the phase (dark shaded) in the direction of longer compared to the prior Normal (100,25) (light shaded), but not by much. There is no way to fit those implausibly early dates Q-655 and GX-679 well into such a short time span.

Another clear outlier is the combined date from *Triticum monococcum*: it is too young to fit in. Without knowing the archaeological context of the original sample, it is hard to say what exactly went wrong, but given that the mound seems to have originally had layers overlaying the studied early Neolithic occupation, an intrusion remains a possibility, as do all other reasons that can lead to outlying measurements. To my mind, it is clearly justified to exclude these *Triticum monococcum* samples as well as the two old charcoal dates if our goal is to date Nea Nikomedeia's studied occupation phase. It is not that those dates are necessarily 'wrong', but I believe it safe to conclude that if they are technically right, they are dating something else than the occupation phase of interest.

In addition to those exclusions, I subjectively prefer to exclude the two remaining charcoal dates P-1202 and P-1203A. It is not that they are obviously out of range of the rest of the dates on potentially shorter-lived material, and another analyst might prefer to include them as well (and we will see below what happens if we do).

The results are visualised in Figure 6. We can see from the plot on the left that our prior assumption about the length of the deposition in effect excludes considerable probability mass for most measure-

ments, both on the older and younger sides. Agreement indices A, however, are high except for the two combined dates from *Triticum dicoccum* (A=88%) and *Hordeum vulgare* (A=66%) (see the table with the results in the supplementary material at <http://dx.doi.org/10.4312/dp.48.3>). For comparison, the grain-only model for basal Knossos with a short-deposition prior (on the right in Figure 2) featured agreement indices all over 100%. Alone, the level of agreement seen in the analysis in Figure 6 would be a moderate cause for concern.

However, when we consider the phase-duration diagram on the right in Figure 6, we can see that there is indeed a serious problem. The prior we put on the phase's duration is the same as it was in Figure 5, and is again light-shaded in this plot. But now we can see that it is bi-modal rather than uni-modal: in addition to the expected peak around 100 years, there is also a high peak close to 0. Note that this new peak strongly disagrees with our prior: our prior puts 95% of all probability into the interval of 50 to 150 years! Bayesian inference needs to see really strong reasons to override this. At the same time, we see that it has not shifted all the posterior probability mass to this unexpected peak: if it did, this would be a reason to consider if our prior could be in error, in which case we would need to adjust our analysis of the site accordingly. However, there is still a clear peak agreeing with the prior, so it is not that our assumptions of 50–150 years are fully incompatible with the data at hand. But of course only one of the two alternatives can be right: either Nea Nikomedeia had only a very short deposition phase, close to 0 years, or the deposition continued for several generations. Since there are good archaeological reasons to believe the latter option (after all, we are dealing with three building phases!), it is the unexpected peak that must be in error. But that peak is there for a reason in our analysis: there

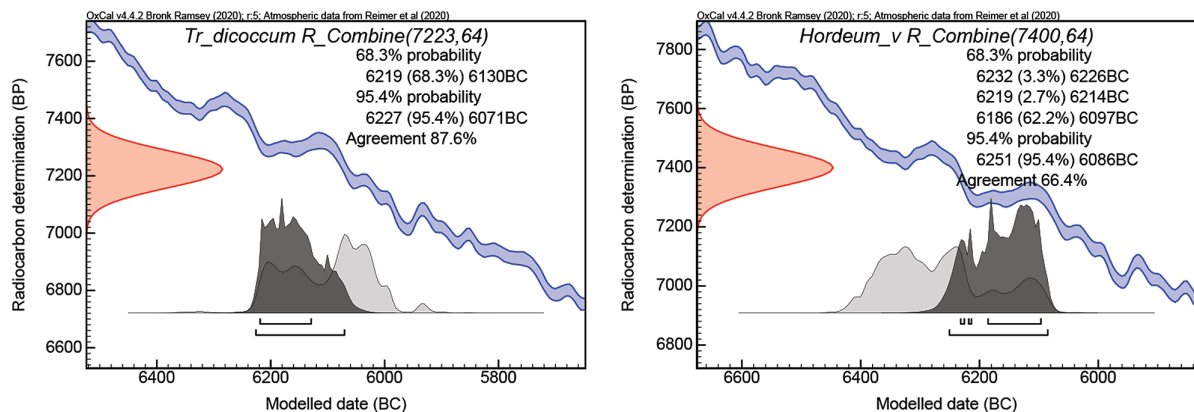


Fig. 7. Enlarged plots for combined dates from *Triticum dicoccum* and *Hordeum vulgare* from Figure 6.

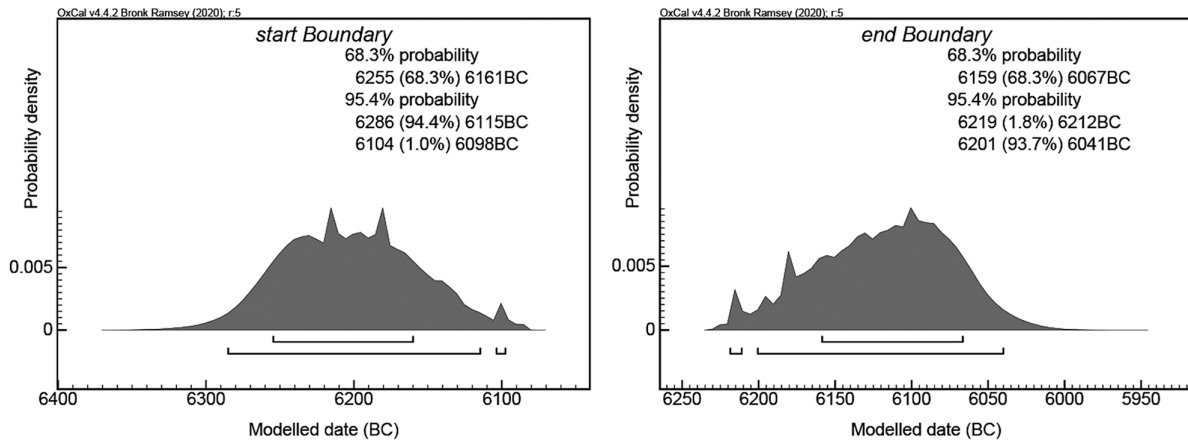


Fig. 8. Enlarged plots for the start and end boundaries from Figure 6.

must be strong enough 'pressure' from the data to force its existence. The only conclusion left is that there is a problem with our data in this analysis. It cannot all be quite correct.

What could have gone wrong? Visual inspection of the left plot in Figure 6 suggests that the main problem might be caused by the *Triticum dicoccum* and *Hordeum vulgare* dates. However, checking their independent calibrations (light shaded) and posterior calibrations (dark shaded), Figure 7, we can see that the problem is very subtle: it looks like the two dates are well compatible with each other. Just by looking at them, it is hard to predict there would be a problem.

Yet further close inspection of the analysis results shows the problem is actually very serious. Consider the posteriors for the start and end boundaries of our deposition phase, as shown in Figure 8. Note three spikes on each of the plots. They are clearly in the same temporal positions for the two phases. This shows that they correspond to the unexpected peak for the phase's duration close to 0 years: indeed, if the start and end boundaries are both selected from, say, the first spike, the resulting duration would be very short. This is really a 'wait a minute' moment for our analysis. Suppose for a moment that a very short phase really makes sense, given the data. But how could the data then favour three distinct, very specific datings for that very short phase? Why these dates? Examining the independent calibrations, choosing these particular three

time points does not make sense. And indeed, it is nothing more than an artefact of our analysis, unfortunately. In reality, the true mathematical posterior in its short-phase part must be 'smooth', without noticeable spikes. It is just that our run fails to explore this true posterior properly. We can check that this diagnosis is correct by running the model again: the prediction is that the spikes will appear in different places on each run. This is, indeed, the case.¹¹

In fact, the first time when I ran the analysis in Figure 6, OxCal completely failed to notice the unexpected peak, and I – mistakenly – believed the analysis was just fine. It was only when I ran it for the second time that the short-phase peak was discovered. MCMC is among the best options we have for performing Bayesian inference in complex models, but it faces various difficulties with posteriors of particular shapes. These difficulties are not absolute, and would have been properly dealt with if we could run MCMC for literally infinite time. As this is not really an option, we have to live with the fact that our convergence diagnostics sometimes think we are fine while in fact we have not yet obtained a good approximation of the true posterior. In particular, when there are several regions of the model space divided by an area of very low probability – as the true posterior of our model apparently is – it can sometimes lead to problems.¹²

Let us check if going with a different set of data or a different prior might convince us to prefer a different model. This will also serve as a sensitivity

¹¹ To check this, one can examine the files with suffixes "start1.pdf" and "end1.pdf" in the supplementary material available at <http://dx.doi.org/10.4312/dp.48.3>, or run the script on OxCal to produce new, and different, results.

¹² As a technical note, this particular case is probably so hard for OxCal because the short-phase area of the probability space is a very thin crest, but moving along it is somehow difficult for the sampler. Rather than exploring this crest in full, the sampler appears to jump off it into the other, prior-compliant, area of the posterior instead. It would appear that on the technical level OxCal's engine has a difficulty changing two highly correlated variables at the same time.

check: we need to know how robust the inferences of the model in Figure 6 are to the assumptions we put into it. I tested two such models: (i) the same as in Figure 5, but with two non-obvious outlier charcoal dates included, as seen in Figure 9; and (ii) the same as in Figure 5, but with an implicit prior on the phase's length, similar to the Knossos case study above, with results shown in Figure 10.

The model in Figure 9 stems from reasonable assumptions; its only difference from my preferred model is that it uses two dates on charcoal that are not obvious outliers. But the problem of the unexpected short-phase peak remains the same. This is not surprising if the problem was induced by the combination of date estimates we used in Figure 6: they are a subset of the data in Figure 9. Still, the results could have been otherwise: for example, by including the older charcoal dates P-1202 and P-1203A, that I chose to leave out, we could have been able to identify some other dates as probable outliers. Furthermore, having performed this analysis, we can check how much our results for inferring the time of Nea Nikomedeia deposition depends on those charcoal dates.

Figure 10 shows what happens if we modify the model in Figure 6 by lifting our explicit prior imposing the duration of 50–150 years at 95% probability, and use instead the implicit prior induced by the assumption of a uniform rate of individual deposition events. As expected, under this implicit prior some durations very different from 50–150 years are judged possible: both short durations below 50 years, but also long durations over two centuries. The 95% HPD interval for the phase duration is from 0 to 350 years (see the table-format result in the supplementary materials at <http://dx.doi.org/10.4312/dp.48.3>). It thus includes both durations that are too short and too long, given what we know about the site.

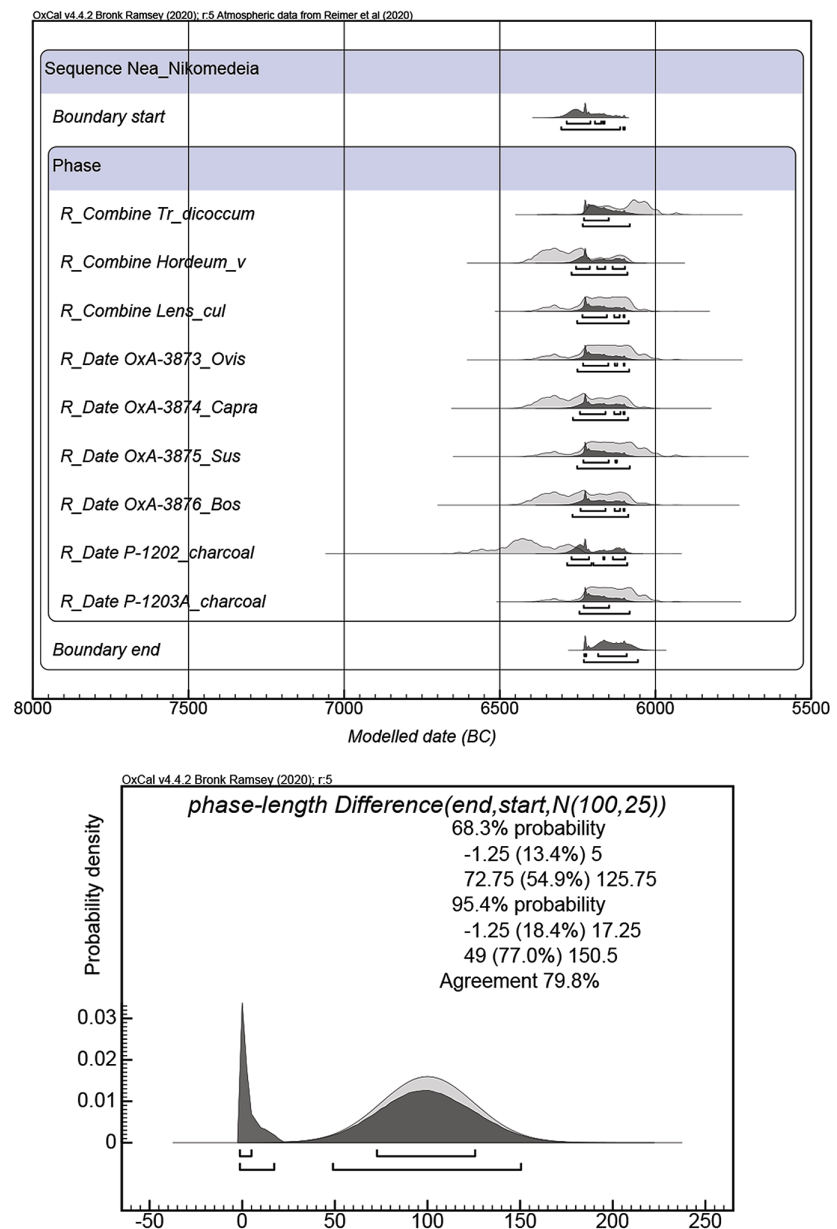


Fig. 9. Nea Nikomedeia: dates reported in Pyke and Yiouni (1996) without two outlier dates Q-655 and GX-679 and the outlier combined date on grain, *Triticum monococcum* (OxA-1603)+(OxA-4280); prior on the phase's duration: $\text{Normal}(100,25)$.

It is also useful to rephrase this result in the following way: our radiocarbon data do not by themselves suggest a length of roughly 50–150 years; the explicit prior on this duration genuinely adds information to the Bayesian analysis that could not be recovered from the ^{14}C measurements themselves. In fact, the right plot in Figure 10 demonstrates the radiocarbon measurements that we have are compatible with a wide range of possible durations. Since we can be confident that Nea Nikomedeia existed roughly 50–150 years, it is crucial to include this as prior information. The model in Figure 10 is to be rejected, just as certainly as the model in Figure 5 that features obvious outliers.

Table 1 summarizes how the choice of model affects our estimates of the chronological position of Nea Nikomedeia. Comparing our preferred model, Figure 6, with the others, we note the following. All models result in wide 95% HPD intervals, which is partly due to the high standard deviations of the measurements themselves (see the scripts in the supplementary material for those at <http://dx.doi.org/10.4312/dp.48.3>), partly to a small plateau in the 62nd century BCE (see the calibration curve in Figure 8), and, quite likely, partly also due to problems with the measurements themselves. The model with an implicit prior on phase duration, seen in Figure 10, differs from the others by providing the widest, four-century-long interval into which it orders Nea Nikomedeia. This model is to be rejected as it is inconsistent with our knowledge about the site. Further, the model in Figure 5 infers a shorter interval than our preferred model. It thus seemingly offers better precision. But as discussed above, it includes obviously problematic measurements, and is therefore also to be rejected. Finally, our preferred model and the model in Figure 9, which keeps the reasonable looking charcoal dates in, largely agree: they both place Nea Nikomedeia within a *c.* 250-year-long interval, and position their intervals very close to each other, roughly between 6300 and 6050 cal BC. Our inferences are thus not strongly sensitive to whether we keep or discard the old dates from charcoal P-1202 and P-1203A. Such robustness is, generally speaking, a welcome result: good inferences should not depend

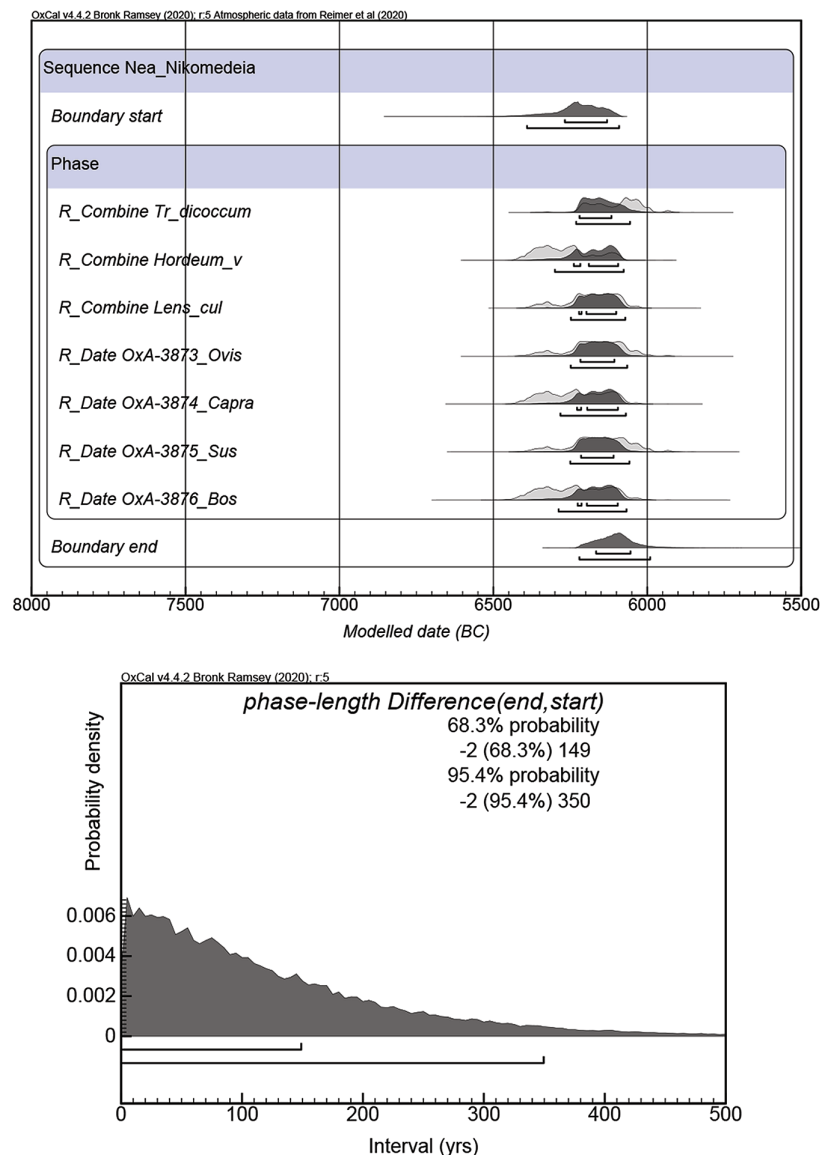


Fig. 10. Nea Nikomedeia: the same as in Figure 6, but with an implicit prior on the phase's duration.

too much on leaving out this or that specific observation. However, this does not cancel the problem inherent to our data that led to the short-phase-duration peak in both Figures 6 and 9. In other words, we have to reiterate the concern about the inconsistency of the dates and the analysis of archaeological evidence voiced by Reingruber and Thissen (2017: *Region IId*).

	95% HPD
Fig. 3, all data	6317 to 6130 cal BC
Fig. 6, outliers and all charcoal out	6286 to 6041 cal BC
Fig. 9, outliers out, some charcoal in	6303 to 6057 cal BC
Fig. 10, as Fig. 6 but with implicit prior on length	6391 to 5991 cal BC

Tab. 1. The interval within which the 50–150-year occupation of Nea Nikomedeia should fall, according to four different models.

To conclude, on currently available evidence the occupation of Nea Nikomedeia, of length 50–150 years, should be placed between roughly 6300 and 6050 BCE at 95% HPD. This implies that in Thessalian terminology (Reingruber et al. 2017), Nea Nikomedeia falls into EN II, pos-

sibly touching the transitional EN III/ MN I. The early dates in Maniatis (2014.Fig. 6) are then unwarranted, but the estimate of a 6150–6100 cal BC proposed by Reingruber (2008) may well be too late. The occupation does not appear to be particularly early in the Thessalian EN, but does not have to be at the very end of the 7th millennium either.

Discussion: Aegean Neolithisation and the chronology of stamps

More precise dating is not a goal in itself, and it can be helpful for archaeological interpretation. In this section, I describe the consequences we can draw from the dating re-evaluations above for two topics: the broader picture of Neolithisation in the Aegean region, and the spatio-temporal distribution of stamps in the Aegean and Anatolia.

The dates for basal Knossos previously given in the literature allowed one to place it very broadly: it could have been contemporaneous with the very earliest pottery sites in northern Mesopotamia (late 8th/very early 7th millennium BCE), or with the transformations of the Central Anatolian Neolithic around and after 6500 BCE. Our re-evaluation has placed basal Knossos firmly into the 66th century BCE, and this has many implications. First, it appears that the people who planted *Triticum aestivum* and created the Knossos basal layer were operating after agriculturalist sites such as Ulucak and Çukurici had been founded near the Western Anatolian coast. It follows that there was a non-negligible diversity in the Aegean agricultural practices towards the end of the first half of the 7th millennium, with different sets of crops exploited at different sites. At the same time, the movements of the basal-Knossos group also predate the significant changes that the Central Anatolian Neolithic undergoes in the third quarter of the millennium (cf. Brami 2017). The Aegean of the second quarter of the 7th millennium must have already been a dynamic and interesting place, before the appearance of Neolithic communities in North-western Turkey or the significant changes at Çatalhöyük.

For Nea Nikomedeia, our re-evaluation implies that this community was not a particularly early one in the region, and in particular it appears later than some other sites in Greek Macedonia such as Mavropigi or Paliambela (Maniatis 2014). However, some aspects of Nea Nikomedeia's material culture make a more precise determination very interesting: it is not only important who, or which site, was 'the

first'. One such aspect is the use of stamps, with numerous examples preserved in Nea Nikomedeia (e.g., Rodden 1965.86). At the large and materially advanced site of Çatalhöyük in Central Anatolia, the earliest stamps appear in Level VII (Türkcan 2013.240), dated to the 66th century BCE (Cessford et al. 2005), but the majority of the corpus (see Türkcan 2005; 2013) comes from the higher levels. In Western Anatolia, in contrast, we only have stratified instances of stamps later in the 7th millennium: in the third quarter in the Lake District's Bademağacı (Duru, Umurtak 2019.207, Pl. 123), and in the fourth quarter at Ulucak (Çevik, Erdoğan 2020). In Greek Macedonia, Mavropigi features at least six stamps, but they have only been preliminarily published, and we thus cannot determine which period of this apparently long-lived site they come from (Karamitrou-Mentessidi et al. 2015.62, Fig. 42). In Revenia Kolinou, several seals were found in a pit that has been radiocarbon dated by several measurements into the third quarter of the 7th millennium (Pit 7; Adaktylou 2017.42–46). To this picture, we can now add the rich use of stamps at Nea Nikomedeia as ordered into the late third or earlier fourth quarter of the 7th millennium BCE. This timing is similar, on present evidence, with that of the stamps of the Turkish Lake District, and might predate their use on the Western Anatolian coast. The study of seal motives and their exchange between areas would further benefit from better temporal resolution for individual examples.

Conclusion

My purpose in this paper has been to show how we can incorporate substantive assumptions about phase duration, stemming from archaeological work, into Bayesian modelling of radiocarbon dates. Using already available information about basal Knossos and Nea Nikomedeia, we were able to reach the following chronological conclusions, based on 95% HPD:

- The event of the deposition of charred grain in the basal Knossos levels occurred within the 66th century BCE (Fig. 2, right).
- The (studied part of the) village of Nea Nikomedeia probably existed between 6300 cal BC and 6050 cal BC, thus falling mainly into Thessalian EN II, and possibly also the beginning of the transitional EN III/MN I (Fig. 6). However, caution is in order because the available measurements were clearly demonstrated to be problematic when considered together.

The present re-evaluations of the dates for basal Knossos and Nea Nikomedeia may have to be adjusted in the future – in fact, I hope we will eventually get more data that would allow that, especially for Nea Nikomedeia. They are also conditional on particular modelling choices that I made and described. While I consider them reasonable, you are free to disagree and consequently to accept results from a different model instead. It is important to bear in mind that in statistical analysis there are modelling choices that are obviously wrong, and then there are legitimate, but incompatible alternatives.

As we discussed above, both basal Knossos and Nea Nikomedeia received very different dating interpretations in the previous literature. Those interpretations, in turn, played an important role in the discussions about the earliest Neolithic in the Aegean. Radiocarbon dating has the appeal of supposed objectivity. But its results in fact depend, often crucially, on the assumptions we put into our models. We could observe this in our two case studies. Moreover, even if we do not explicitly build a Bayesian model, but interpret dates individually, this also amounts to adopting very particular – and frequently very wrong! – assumptions about the archaeological reality from which our samples came.¹³

What Bayesian modelling of dates forces us to do is to make our assumptions explicit, so that we can compare, discuss, and crucially, improve them when needed. However, in order for future research to be able to do this, we also need to publish all the details of our models, and not just their results. This is why I provide all OxCal analysis files as an online supplement, so that they can be re-run (with newer calibration curves, for example) or modified (for instance, with new data). I suggest every archaeological paper engaging in statistical modelling of dates does the same. Such sharing is of considerable importance, because as we start modifying priors our figures no longer straightforwardly summarize the model. I suggest that our standards of reporting the model itself should be as strict as for reporting the radiocarbon data (*Bayliss 2015*).

I would like to end by noting that even though designing and interpreting models requires effort (just as noted already by *Bayliss et al. 2007*), the techni-

cal overhead on implementing them is really not large. Specifically, in OxCal it only requires adding one line to the analysis script to put a prior on one phase's length: “*phase-length*”, “*end*”, “*start*”, $N(100, 25)$.

This line, from my Nea Nikomedeia model, orders a new variable “*phase-length*”: to be created, which (i) records, in the OxCal output, the interval between “*end*” and “*start*”, which are just my names for the two boundaries of the single phase in the model; and (ii) puts the $N(100,25)$ prior onto this quantity. To record the length, but not restrict it implicitly, as in Figure 10, we simply omit the last argument $N(100,25)$. Needless to say, other priors can be mentioned in this argument, to appropriately capture the substantive knowledge won through archaeological analysis. I hope that the ease with which the technical side can be conquered will lead to more radiocarbon modelling employing this possibility in future research.

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¹³ It is also worth noting that the reasonable statistical-philosophical alternatives to being a careful Bayesian (*Buck, Meson 2015*), is certainly not doing nothing, that is, only looking at one's data informally. It may be being a convinced and careful frequentist, but that would require no less care in designing and performing the needed statistical tests. There is, unfortunately, no escape from the complexity of doing careful science!

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