ChronoLog: A Tool for Computer-Assisted Chronological Modelling

Eythan Levy (Universities of Zurich and Bern) < eythan.levy@gmail.com>
Gilles Geeraerts (Université libre de Bruxelles) < gilles.geeraerts@ulb.be>
Frédéric Pluquet (Haute École Louvain en Hainaut) <fredericpluquet@gmail.com>

Abstract

Archaeologists and historians are often confronted with the problem of extracting the most meaningful and precise conclusion from a set of chronological data (e.g., stratigraphic data, historical records, radiocarbon dating). The amount of available data can be very large, thus there is a stringent need for rigorous techniques to manipulate and analyse this information. In this paper, we present a methodology to this end, which relies on two elements. First, we present the notion of 'chronological networks', a rigorous model to represent chronological units and relations between them. Our model can represent successive periods in time, punctual events, and a wide range of synchronisms (such as: 'period A starts after the end of period B'). Second, we introduce the latest version of the ChronoLog software, which allows users to encode, manipulate, and analyse chronological networks. ChronoLog has an intuitive interface, in which the user can edit chronological networks with a simple click of the mouse. ChronoLog can also automatically and interactively extract the most precise dates that can be inferred from the input data. We also present guidelines to model classical archaeological situations, in order to help users exploit the ChronoLog data model to its full potential. Finally, we illustrate these guidelines through a practical case study.

1. Introduction

Our understanding of ancient chronology is usually deduced from a mass of data collected by archaeologists and historians. This data stems from ancient texts, archaeological strata, ceramic analysis and radiocarbon samples, among others. Hence, archaeologists are often confronted with a dauting amount of material, that must be linked and analysed to build comprehensive chronologies. This raises two main questions: 1) How to express all the available data in a synthetic and rigorous fashion? 2) How to infer the most precise conclusions regarding chronology from this data?

In standard archaeological literature, available chronological data is traditionally expressed using natural language. The inference of new dates is also performed using step-by-step reasoning, using a natural language. However, this `handcrafted' method has its limits and cannot be extended to the massive amounts of data which are available nowadays. In fact, this paper shows that extracting optimal chronological knowledge from even small chronological datasets is not at all straightforward.

In this paper, we address the two questions stated above, by discussing techniques which are amenable to implementation as a computer program. This program can then assist archaeologists and historians in their task of analysing chronological data. We first present (section 2) our model of 'chronological networks', which can express the data on which chronological reasoning is based in a rigorous and intuitive way. We then present the latest

version of the ChronoLog software, which has been designed to manipulate and analyse such chronological networks. ChronoLog allows users to edit chronological networks through an intuitive graphical user interface (in the same fashion as a usual drawing program that one could use to typeset diagrams). ChronoLog then checks for the existence of inconsistencies in the chronological network. More importantly, ChronoLog also computes the most precise bounds (on the start dates, end dates and durations of all periods in the model) that can be inferred from the available data. This computation is very fast (a couple of seconds at most, even on large models with hundreds of elements). The speed of ChronoLog is, in our view, an important feature, because it allows the user to test chronological hypotheses in an interactive way, by immediately witnessing the effect of changing constraints in the model.

In section 3, we discuss a series of guidelines for properly modelling different common archaeological situations (e.g., tombs, strata, radiocarbon dates) in ChronoLog. This should help archaeologists to properly exploit the full power of our modelling techniques and to extract the most useful and accurate conclusions from the available data.

Next, in section 4, we present an extensive case study that illustrates many features of chronological networks and of ChronoLog. We show the kind of experiments that can be performed thanks to ChronoLog, as well as the conclusions that can be drawn from them. Finally, section 5 draws a short conclusion.

As far as we know, ChronoLog is the only publicly available tool that allows one to perform the kind of analysis we have just sketched. The closest related work is the Groundhog software (Falk 2016, 2017, 2020). However, it is not yet available for download as general-purpose software and it relies on slow exhaustive search algorithms, which renders its impractical for large models. In the field of stratigraphy, the classical Harris matrix approach (Harris 1989), was originally used only for relative chronology, but has now also been augmented with absolute dating capabilities. This enables users to build models containing several types of constraints similar to ours (Desachy 2016). However, the ChronoLog model presented here is more general, allowing a more diverse set of chronological constraints to be expressed. Finally, chronological models featuring data similar to ours can also be created using Bayesian tools for radiocarbon analysis, such as OxCal (Bronk Ramsey 2009) and ChronoModel (Lanos and Philippe 2015a, 2015b). Their use is specific to radiocarbon calibration, while ChronoLog is a general-purpose tool, not relying on radiocarbon *per se*. Another important difference is that radiocarbon Bayesian tools are probabilistic, while ChronoLog uses only deterministic algorithms. Hence, the dating results provided by these radiocarbon tools are expressed as confidence intervals, with an associated probability (typically 68 or 95%), while the ChronoLog results are deterministic ranges, not associated with a probability (for more details on ChronoLog and radiocarbon, see Levy, Fantalkin and Finkelstein, as well as the discussion in Levy et al. 2022, p. 11-12).

2. ChronoLog

In this section, we describe ChronoLog, our software tool for analysing chronological data. It runs on PCs (Windows, Linux) and Apple Macintosh computers. ChronoLog is a Java application, distributed in *.jar* format (Java executable). It requires prior installation of the Java Runtime Environment, available for free at https://www.java.com/en/download/. ChronoLog can be downloaded free of charge from https://chrono.ulb.be/.[1] ChronoLog allows one to design and manipulate so-called chronological networks (see Levy et al. 2021 for full details), and to analyse those models, as shown below. The latest version of ChronoLog is version 2.1, released in April 2023.

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[1] Note that some browsers block the download of .jar files. This issue can be resolved by adjusting the browser's security settings.

Data model

The chronological networks model allows one to represent both absolute and relative chronologies. It is based on three types of objects: time-periods, sequences and synchronisms.

Time-periods. The basic modelling unit is called a 'time-period' (often abbreviated to 'period'). It represents any type of continuous timespan (e.g., stratum, reign, ceramic type, historical period, cultural phase). A period contains three variables: 'start', 'end' and 'duration'. The start or end of a period can be 'known' (e.g., 1200 CE), 'lower bounded' (e.g., after 1200 CE), 'upper bounded' (i.e., before 1300 CE), 'in a range' (e.g., between 1200 and 1300 CE), or 'unknown'. The same holds for durations (five years, at least five years, at most five years, between five and 10 years, or unknown). The granularity used by ChronoLog is the year (no months or days). Figure 1 presents examples of time-periods, using the following graphical conventions: the start date appears in the lower left corner, the end date in the lower right corner, and the duration in the centre.
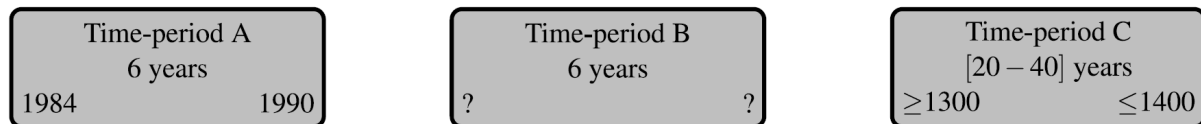
Time-period A 6 years	Time-period B 6 years	Time-period C $[20-40]$ years
1984 1990	? ?	≥ 1300 ≤ 1400

Figure 1. Examples of ChronoLog time-periods. Period A lasts exactly six years, from 1984 to 1960. Period B lasts exactly six years, at an unknown absolute time. Period C starts no earlier than 1300 CE, ends no later than 1400 CE, and lasts 20 to 40 years.
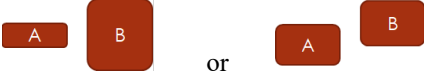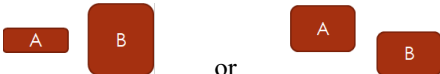
Sequences. Time-periods can be grouped into a 'sequence', meaning they follow each other without gaps. In other words, the end of a period equals the start of the next period in the same sequence. Sequences are drawn as periods stacked on top of each other, with time flowing from above to below.

Synchronisms. Finally, time-periods are related to each other through 'synchronisms'. A synchronism is a chronological relation between two periods. There are several types of synchronisms. The most common one is 'contemporaneity', meaning two periods that have at least one unit of time in common (without any other knowledge on their relative order). Some types of synchronisms (e.g., 'starts during', 'ends during', 'includes') are stronger than contemporaneity (i.e., they imply contemporaneity). Some others are weaker than contemporaneity (i.e., they are implied by contemporaneity), such as 'starts before end of'. Others do not bear direct relation to contemporaneity (e.g., 'starts after start of'). We draw synchronisms as arrows connecting two time-periods. Table 1 presents some examples of synchronisms (32 different types of synchronisms are currently defined in ChronoLog). Note that most synchronisms have an inverse version, say 'A includes B' is the inverse of 'A is included in B'. Inverse synchronisms have been omitted from Table 1, for the sake of conciseness. For more details on ChronoLog synchronisms (including formal definitions) and their strengths and limitations, see Levy et al. 2021.

Figure 2(a) presents an example of a ChronoLog model bearing two sequences: a fictional dynasty with two kings and a stratigraphic sequence with two strata. The first king, King Albert, reigned at most 10 years, and the second king, King Baldwin, reigned at least 35 years. The dynasty starts no earlier than 1200 CE and ends no later than 1300 CE. Each stratum has an assumed duration of at least 20 years. Stratum 2 (the oldest stratum) was built by Albert, while Stratum 1 (the youngest stratum) was destroyed during the reign of Baldwin. This short

description should be sufficient to allow the reader to understand the ChronoLog data model. A more in-depth coverage can be found in Levy et al. 2021.

Table 1. Some examples of possible synchronisms in the ChronoLog data model (time flows from above to below). Many more synchronisms are available in the software, including (among others) the symmetric versions of inclusion ('A includes B'), overlap ('A overlaps with the preceding period'), 'starts during' ('A includes the start of B'), and 'ends during' ('A includes the end of B').

Name	Image
Contemporaneity (A contemporary with B)	A B or A B or A B or A B
Inclusion (A included in B)	A B
Overlap (A overlaps with next period B)	A B
Starts during (A starts during B)	A B or A B
Ends during (A ends during B)	A B or A B
Synchronised start	A B
Synchronised end	A B
Equality	A B
Ordered boundaries	$\text{A} \begin{cases} \text{starts} \\ \text{ends} \end{cases} \begin{cases} \text{before} \\ \text{after} \end{cases} \begin{cases} \text{start of} \\ \text{end of} \end{cases} \text{B}$
Delay synchronism	$\text{A} \begin{cases} \text{starts} \\ \text{ends} \end{cases} \begin{cases} \text{exactly} \\ \text{at least} \\ \text{at most} \end{cases} \text{X years} \begin{cases} \text{before} \\ \text{after} \end{cases} \begin{cases} \text{start of} \\ \text{end of} \end{cases} \text{B}$

(a)

Time

Strata

Stratum 2
≥ 20
? ?

Stratum 1
≥ 20
? ?

Starts during →

Ends during →

Kings

Albert
≤ 10
≥ 1200 ?

Baldwin
≥ 35
? ≤ 1300

(b)

Time

Strata

Stratum 2
$[20, \mathbf{80}]$
$[\mathbf{1200}, \mathbf{1260}]$ $[\mathbf{1220}, \mathbf{1280}]$

Stratum 1
$[20, \mathbf{80}]$
$[\mathbf{1220}, \mathbf{1280}]$ $[\mathbf{1240}, 1300]$

Starts during →

Ends during →

Kings

Albert
≤ 10
$[1200, \mathbf{1260}]$ $[1200, \mathbf{1265}]$

Baldwin
$[35, \mathbf{100}]$
$[1200, \mathbf{1265}]$ $[\mathbf{1240}, 1300]$

(c)

Time

Strata

Stratum 2
≥ 20
? ?

Stratum 1
≥ 20
? ?

Starts during →

Ends during →

Kings

Albert
≤ 10
≥ 1200 ?
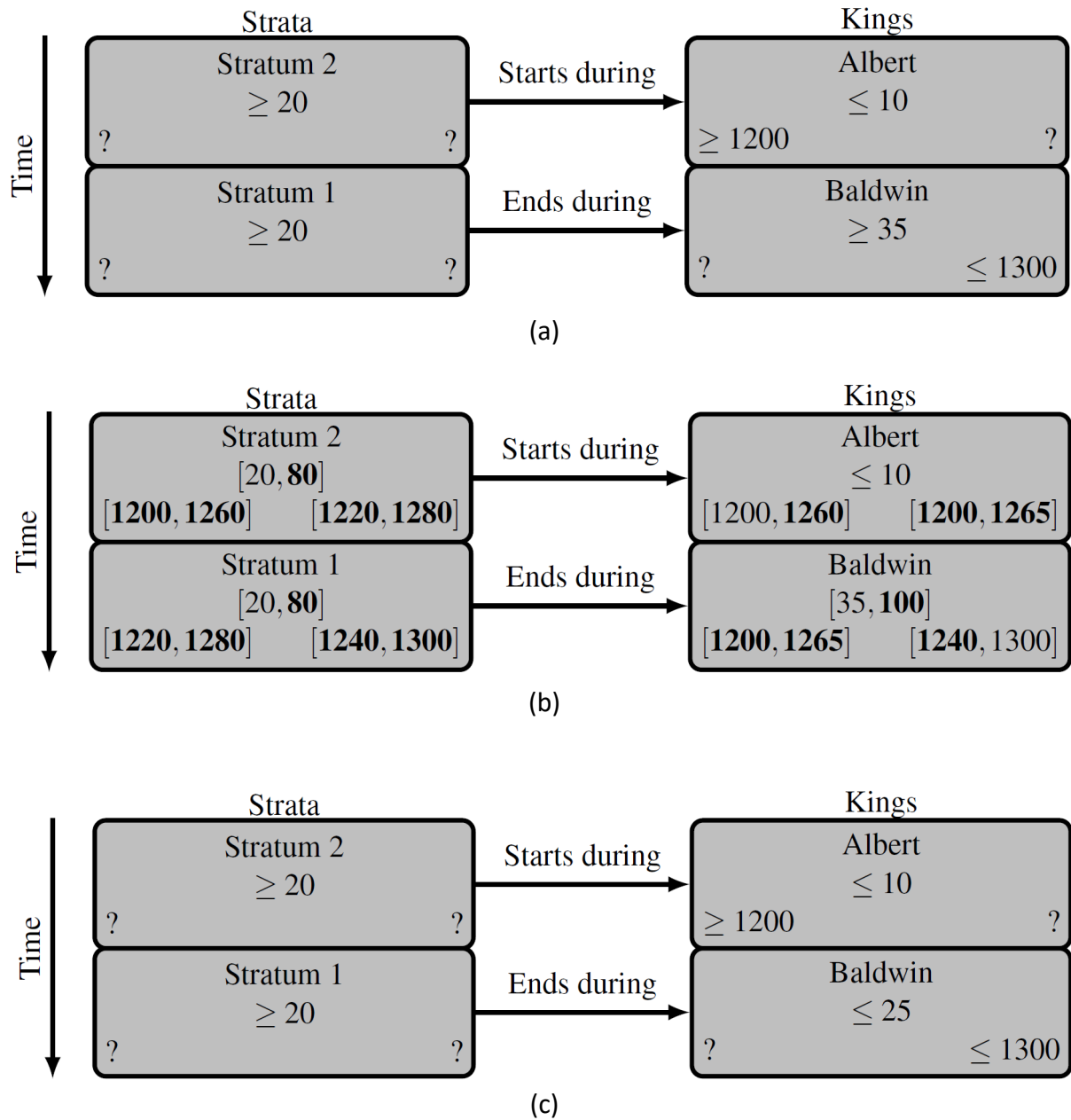
Baldwin
≤ 25
? ≤ 1300

Figure 2. Example of a complete chronological model. (a) Input data of the model, (b) result of the tightening procedure (bounds improved through tightening are shown in bold), (c) inconsistent model. Model (c) is inconsistent because the dynasty has at most 35 years (10+25), while the two strata have a combined duration of at least 40 years. This yields a contradiction since the strata are supposedly included in the timespan of the dynasty (by the 'starts during' and 'ends during' synchronisms).

Use cases

Let us now discuss the kind of questions that one can automatically answer on this data model, using ChronoLog:

1. **Tightening**. Our main goal is to compute the most precise date and duration bounds that can be assigned to all periods, while still respecting all the constraints. In other words, this allows one to deduce the most precise information from the available data. An example is shown in Figure 2(b), where the newly computed data is shown in bold. Here, again one can see that deducing this information is not a trivial task and can greatly benefit from the help offered by a computerised tool.

2. **Consistency check**. In certain cases, a model can be 'inconsistent', in the sense that there is no way to find values for all start and end dates that satisfies all the constraints.

An example of an inconsistent model is shown in Figure 2(c), where King Baldwin has a maximum duration of 25 years, instead of a minimum duration of 35 years. The model is inconsistent because the total duration of the dynasty (at most 35 years) is too short to contain the whole duration of the strata (at least 40 years). We want to automatically detect such inconsistent models. Observe that even in our small model, finding such inconsistencies 'by hand' is a hard and error prone task, which prompts for an automatic approach.

3. **Tracing.** Finally, for each tight bound, we want to compute the complete chain of information that leads to the computed result. This allows the user to understand the impact of each piece of data on the final result. Such chains are called 'traces' in computer science. In ChronoLog, these traces contain *termini post/ante quem*, duration estimates and synchronisms. An example of a trace is shown in Figure 3.

Practical use

A comprehensive user manual to ChronoLog can be found at https://chrono.ulb.be/download/. Here, we will describe its most saliant features. First, ChronoLog allows users to encode chronological networks according to the data model specified above. Figure 3(a) presents a screenshot of a ChronoLog model representing the theoretical example of Figure 2. Furthermore, ChronoLog automatically performs the computations described above. Each time new data is inserted, modified or deleted in a model, a **consistency check** is performed to make sure that the new model is still consistent. If so, the **most precise bounds** for all periods are automatically re-computed and displayed (tightening). Finally, **traces** can be displayed to witness each computed bound. Figure 3 displays the model's input bounds (Figure 3(a)), its tightened bounds (Figure 3(b)), and a trace (Figure 3(c)).

In addition, ChronoLog implements several other features that make the tool more practical:

1. ChronoLog allows one to **tag** the different sequences. Tags can represent any type of information, such as 'stratigraphic', 'ceramic', 'radiocarbon', etc. This enables users to check/uncheck given tags in order to immediately assess the impact of specific types of data on the chronology. For example, one could uncheck the 'radiocarbon' tag, to see what the (tightened) chronology becomes without any radiocarbon data.

2. ChronoLog boasts a series of ready-made libraries of sequences, including dynastic lists from ancient Egypt and Mesopotamia.

3. ChronoLog has several convenient import and export features. One can import/export input data and computed results to and from CSV files. The whole model can also be exported as an image file.
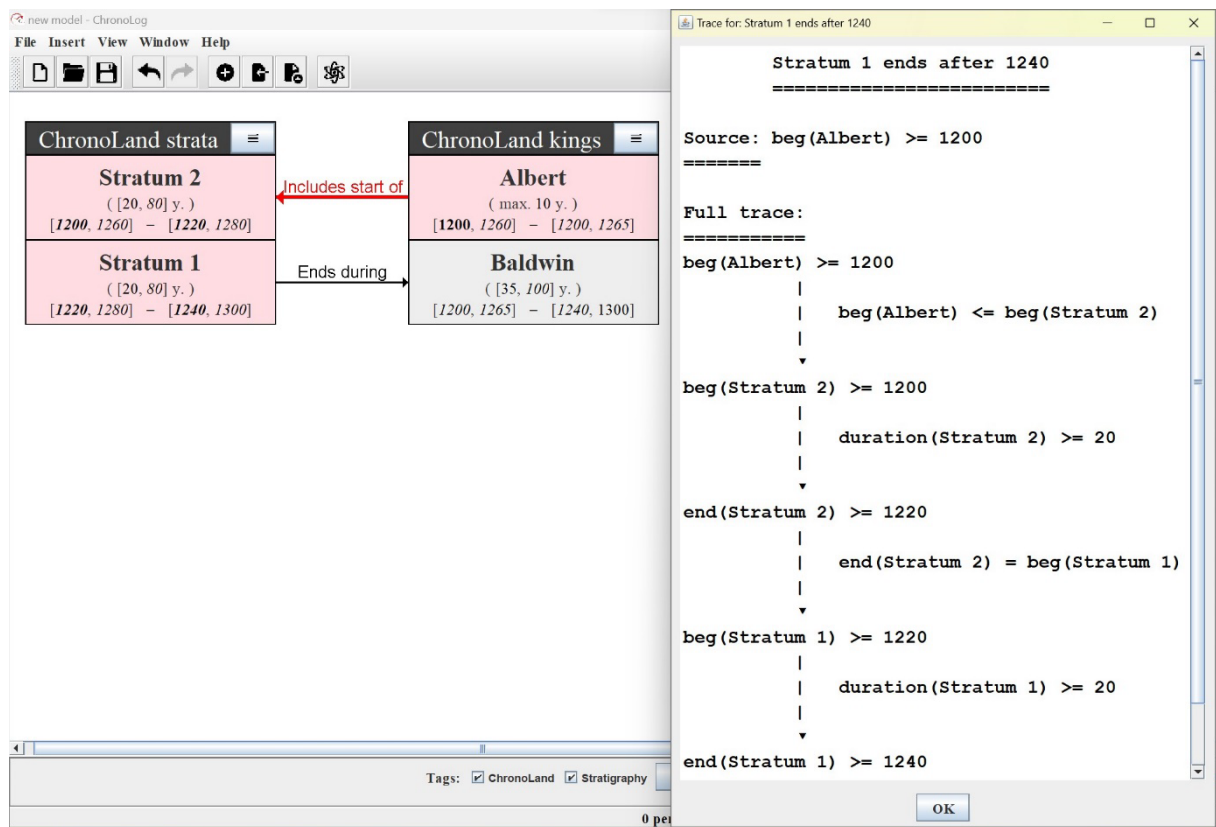
The algorithms underlying ChronoLog have been thoroughly described elsewhere (Geeraerts, Levy and Pluquet 2017; Levy et al. 2021). If you are publishing results obtained with the help of ChronoLog, please cite this paper, as well as Levy et al. 2021, and the tool's web page (https://chrono.ulb.be/).
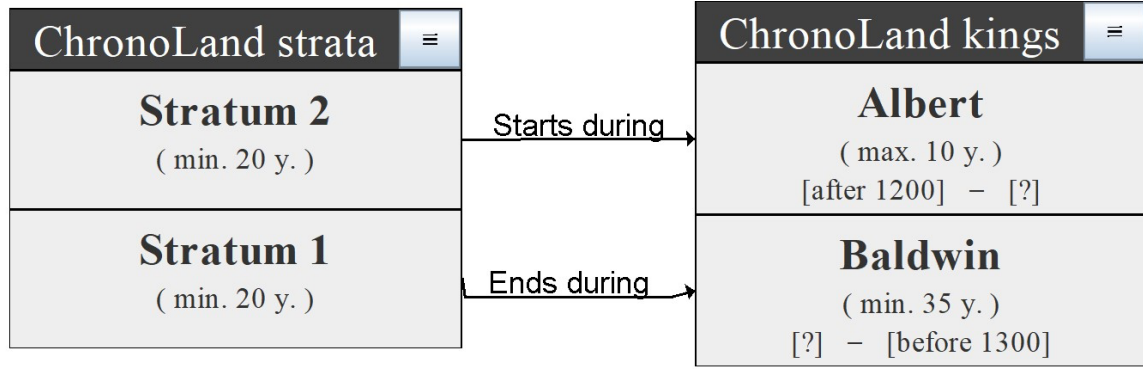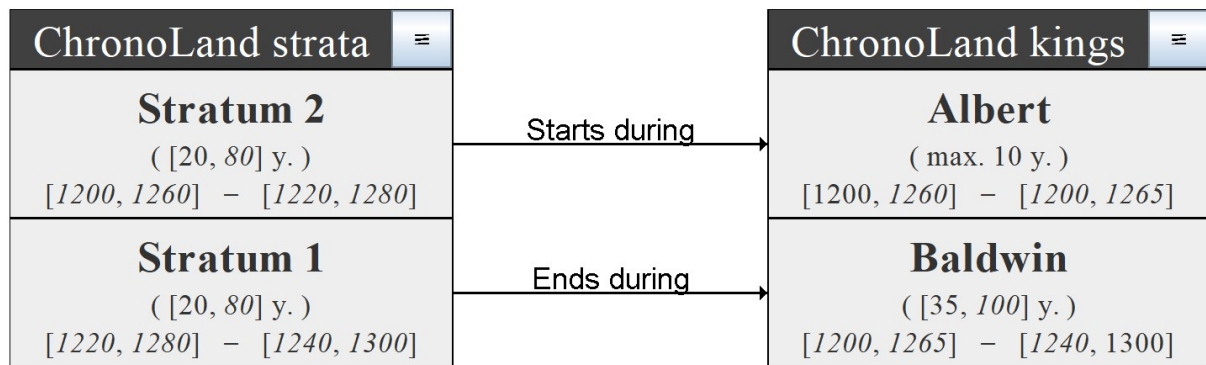
Figure 3. Selected screenshots of ChronoLog. (a) ChronoLog model for the example of section 2, showing inputs only. (b) Same model, showing the results of the tightening operation (tightened results are shown in italics, and inputs in straight font). (c) Example of a trace: the periods and synchronisms intervening in the trace are shown in pink and the involved bounds in bold.

3. Modelling guidelines

This section provides practical guidelines for modelling archaeological data with ChronoLog. As is often the case in scientific modelling, a given archaeological case lends itself to different modelling choices. For example, ChronoLog offers 32 different types of synchronisms. Hence the choice of the most relevant one for a given situation is not straightforward. Some choices might be more cautious, others less. It is important that the modeller be informed of the exact interpretation and implication of each possible modelling choice. Hence, the following are guidelines for helping ChronoLog users in their practice of chronological modelling:

1. **Discrete events.** Discrete events happen at a precise point in time, such as the fall of a city, a shipwreck, or the coronation of a king. They are characterised by equal start and end dates (say 1453 CE for the Fall of Constantinople). When the exact date of the event is not known, a discrete event is represented in ChronoLog by setting the period's duration to zero.[2] Figure 4(a) and 4(b) provide examples of discrete events.

2. **Tombs**. An undisturbed single-burial tomb can be seen as a discrete event, and hence be modelled as a period with zero duration. A multiple-burial tomb has a non-zero duration, representing the time span between the first and the last burial.

3. **Reigns**. The ChronoLog data model allows for the encoding of both well-dated reigns (known start and end dates) and partially dated reigns (partial knowledge on the start date, end date and/or duration). Coregencies can be modelled either with three periods (two 'sole reigns' periods and one coregency period), or with two periods connected by a 'delay synchronism'. Figure 4(c) and (d) provide examples of a 10-year long coregency.

4. **Strata.** Archaeological strata can be directly represented as ChronoLog periods and stratigraphic sequences as ChronoLog sequences. Gaps between successive strata are represented by additional 'gap periods'. Strata of different sequences (e.g., different excavation areas of a site) can be synchronised using synchronisms such as 'simultaneous end' (e.g., synchronous destruction/abandonment events) or 'simultaneous start' (e.g., synchronous foundation). Figure 5(a) provides an example of two stratigraphic sequences, starting and ending at the same time and featuring optional gaps of a maximum duration of 40 years.[3]

5. **Datable artifacts.** Archaeological contexts (e.g., strata, tombs) are often dated thanks to the presence of historically datable artifacts, such as imported royal Egyptian scarabs. In such cases, cautious modelling imposes the use of a *terminus post quem*, expressed by the following synchronism: 'the stratum ends after the start of the reign'. This synchronism holds even in cases of heirlooms, scarabs manufactured after the king's death, or intrusions from deeper strata (so-called 'residual artifacts'), but not in cases of intrusions from later strata (so-called 'infiltrated artifacts') (Levy, Piasetzky and Finkelstein 2020). An alternative is to use explicit modelling of the scarab, using a period of its own, representing the span of time between the scarab's manufacture and its demise. Figure 5(b) and (c) provide examples of both types of modelling.

6. **Genealogies.** When periods represent the lifetime of an individual (rather than only a reign), a father-son relationship cannot be represented by a ChronoLog sequence, since such modelling would mean that the father died at the birth of his son. One simple way

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[2] The zero duration is important, as it strongly affects the propagation behaviour of chronological information when synchronisms are added to the model (periods with zero duration propagate more information than periods with unknown duration).

[3] The optional aspect of the gap is represented by a minimum duration of 0 years.

to model a parent-child relationship, is to use the 'starts during' synchronism, meaning that a child is born during the lifetime of his parent. A more precise alternative it to use a custom macro synchronism introduced in ChronoLog version 2, named 'Parent of'. It includes a modified version of 'starts during', where a father is allowed to die even the year preceding his son's birth (which is possible if the father dies soon after conception) and also allows the user to specify a minimum and maximum age for the parent at childbirth. A symmetrical relation 'Child of' is also provided.

7. **Artifact types.** Types of artifact (e.g., pottery, lithics) are often considered as periods of their own, representing the time span between the start and end of their common use. Such types, say 'Philistine Bichrome Pottery', can be represented by a ChronoLog period. When types are considered as sequential, like the Philistine Monochrome (considered as preceding the Bichrome), a ChronoLog sequence can be used. Such a modelling, with a strict sequence, is often used in archaeological publications but is, of course, a simplified representation of reality. More detailed modelling would involve a certain overlap between successive types. In that case, the two types should not be inserted in the same ChronoLog sequence, but rather should be linked with an overlap synchronism.

8. **Archaeological periods.** Archaeological/cultural periods (e.g., Late Bronze I, Late Bronze II) are often modelled sequentially in archaeological charts, but sometimes also with overlaps. They can thus be modelled either as ChronoLog sequences or using overlap synchronisms. Furthermore, since archaeological periods are often related to specific artifact types, the relation between these types and archaeological periods can also be modelled in ChronoLog. For example, in the southern Levant, Philistine Monochrome and Bichrome pottery are considered typical types of the Iron I period. This relation can be represented using an 'inclusion' synchronism, e.g., 'the Bichrome is included in Iron I' (Figure 6(b)).

9. **Radiocarbon dating (single sample, short-lived)**. We examine the case of inserting a single calibrated short-lived sample found inside a stratum.[4] If the calibrated radiocarbon result is the range [*a,b*], the constraints on the stratum should be: 'the stratum starts before *b*, and ends after *a*', and **not** 'the stratum starts before a, and ends after *b*'. Alternatively, we could explicitly model the sample itself as a ChronoLog period with zero duration (representing the date of death of the organism), add the range [*a,b*] to the end of that period, and use a synchronism 'sample is included in the stratum' to model the fact that the sample originated anywhere within the stratum's lifetime. This yields the same result as above, but in a more explicit way, as in Figure 6(c). In other cases, say short-lived samples from a destruction layer, if we assume that the sample (say, seeds) were harvested during the same year as the stratum's demise, a 'synchronised end' synchronism might be used instead of the inclusion synchronism mentioned above.

10. **Radiocarbon dating (single sample, long-lived).** In case of long-lived material (say wood, charcoal), the modelling rules should be more cautious, if we want to allow the possibility that the sample is actually older than the stratum it was found in. If the calibrated radiocarbon range is [*a,b*], all we can say for sure is that the stratum ends after *a*. Alternatively, we can use explicit modelling, with the synchronism 'sample ends before the end of the stratum', yielding the same result (Figure 6(d)).

11. **Radiocarbon dating (modelled boundary date).** When using Bayesian modelling for radiocarbon (Bronk Ramsey 2009), one does not only obtain a dating for each sample,

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[4] The modelling method described here can also apply to an average of several short-lived samples, if they are assumed to reflect the same radiocarbon age, for example seeds assumed to have been harvested at the same time.

but also a dating for boundaries of interest, say the end of a given stratum. Like sample dates, these boundary dates consist of confidence intervals and can therefore be directly inserted as ranges on the start or end of a ChronoLog period (for an alternative approach, using ChronoLog as a front-end to automatically generate OxCal Bayesian models, see Levy, Fantalkin and Finkelstein 2022).
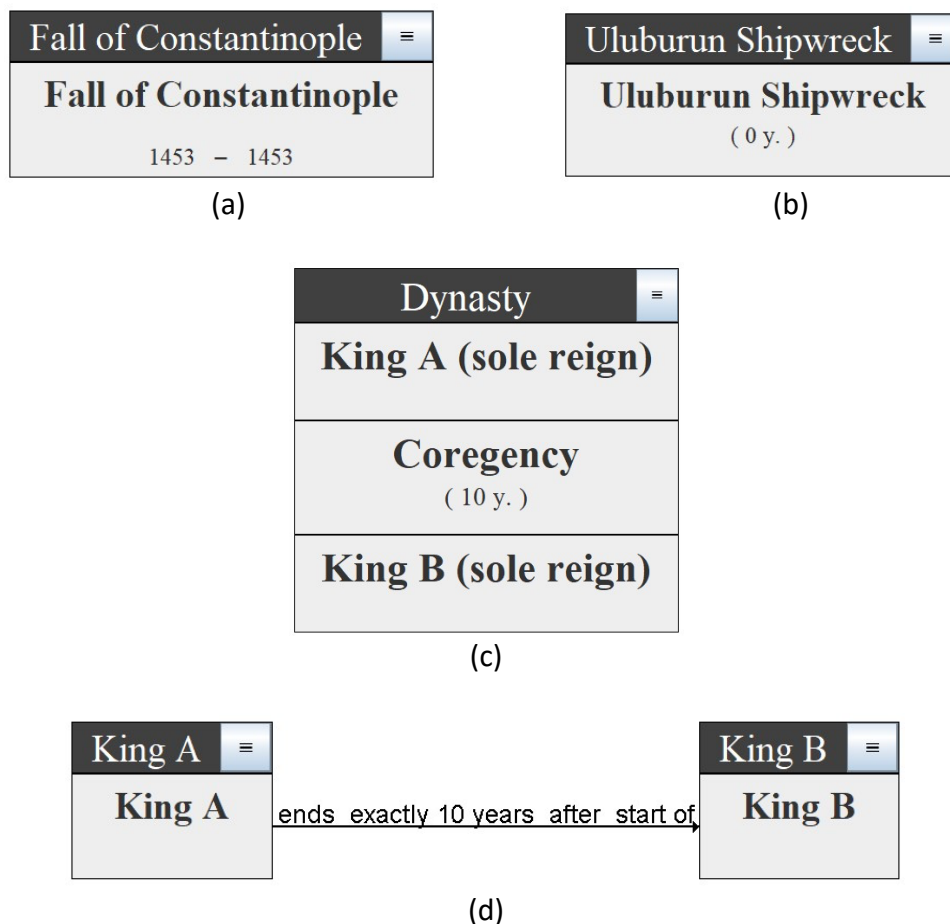

Figure 4 Modelling guidelines. (a) Discrete event with known dates. (b) Discrete event with unknown dates (duration=0). (c) Two succeeding kings with a coregency of 10 years (using a single sequence). (d) Two succeeding kings with a coregency of 10 years (using a delay synchronism). These figures show only the input data, hiding the tightened ranges, for the sake of clarity.
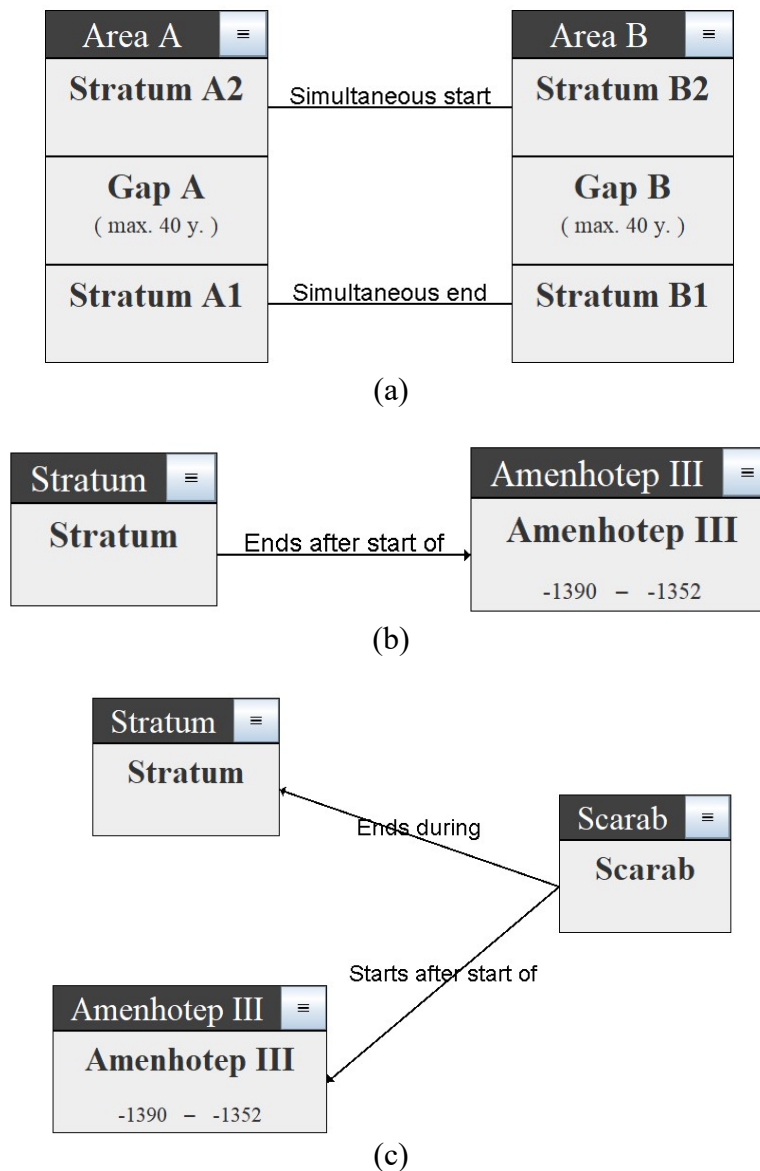
(a)

(b)

(c)

Figure 5 Modelling guidelines (cont'd). (a) Two correlated stratigraphic sequences, featuring a 40-year maximum duration optional gap. (b) Stratum bearing a scarab of Pharaoh Amenhotep III (concise modelling). (c) Stratum bearing a scarab of Pharaoh Amenhotep III (explicit modelling of the scarab). The scarab is only assumed to have been manufactured after the start of the reign and to have been demised before the end of the stratum. These figures show only the input data, hiding the tightened ranges, for the sake of clarity.
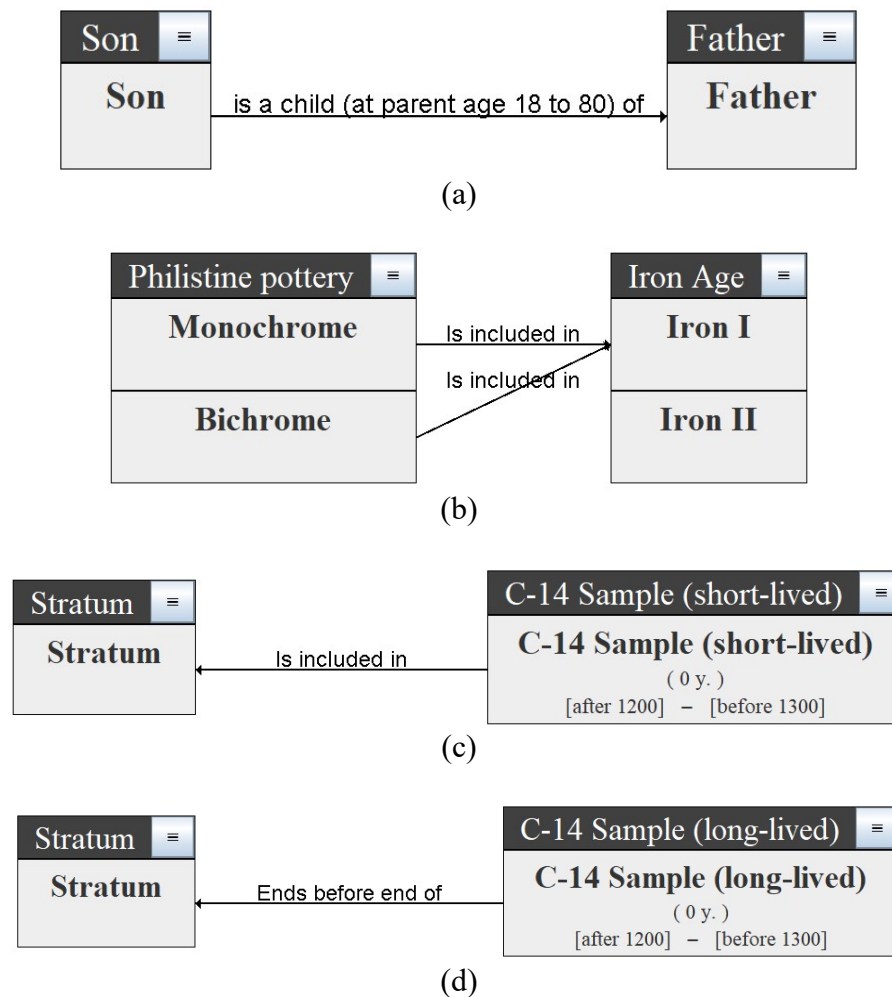
Figure 6 Modelling guidelines (cont'd). (a) A father-son relationship, with the son's birth occurring between the father's 18th and 80th year. (b) Two ceramic types included in the same archaeological period. (c) Stratum bearing a short-lived C-14 sample. (d) Stratum bearing a long-lived C-14 sample. In both C-14 cases, the duration is set to zero, because the dated event represents the death of the living organism from which the sample originates. These figures show only the input data, hiding the tightened ranges, for the sake of clarity.

4. Case study

We present a short case study related to the Mediterranean Late Bronze Age (Figure 7). The model highlights some relations between Egypt, the Aegean and the southern Levant. Our goal is to compute an estimate for the end of the Late Helladic (LH) and Late Minoan (LM) III A1 periods, based on Egyptian and Aegean synchronisms, as well as radiocarbon dates. The ChronoLog input file of the case study is available on the ChronoLog web page, at https://chrono.ulb.be/download/.
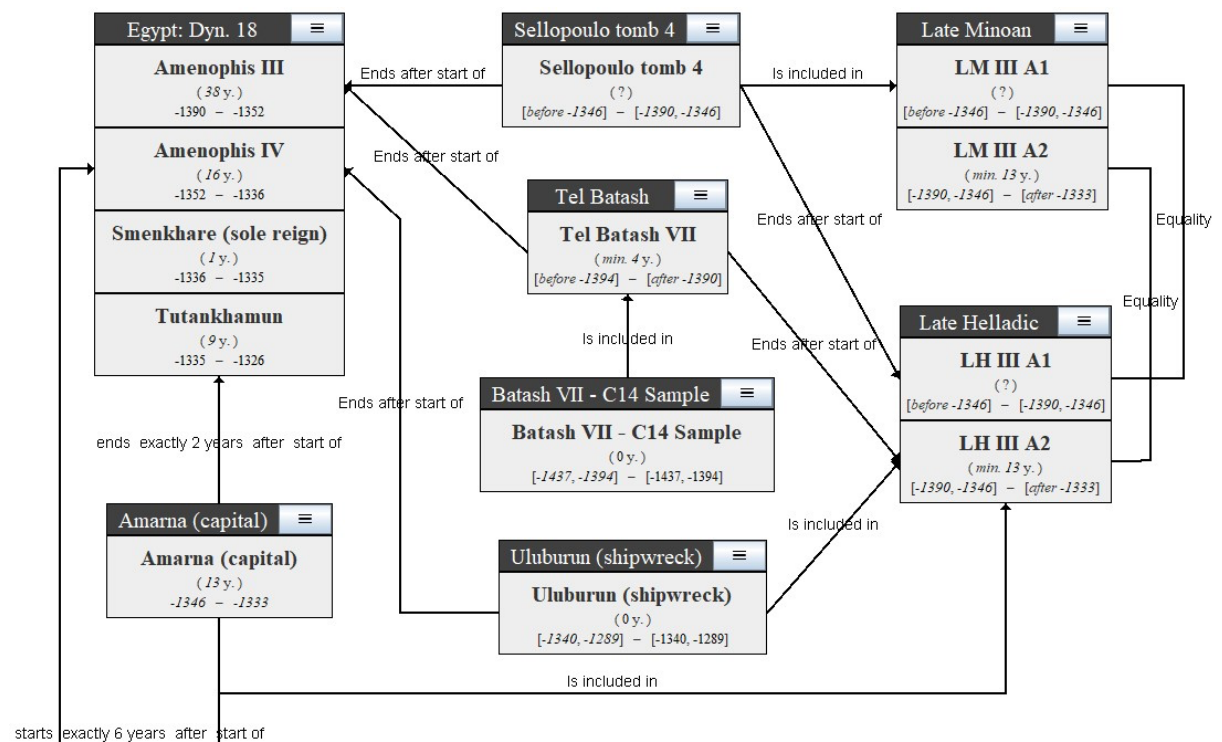
Figure 7. Case study: ChronoLog model for Late Minoan & Late Helladic III A1 chronology. The model shows both the input data (straight font) and the computer bounds (italics).

Data

The model comprises the following data:

1. **Pharaohs Amenhotep III to Tutankhamun.** The model includes the dates of four Dynasty 18 pharaohs (adapted from Kitchen 2000).
2. **Tell El-Amarna.** The city of Tell El-Amarna served as Egypt's capital for 13 years, between Year 7 of Amenhotep IV and Year 3 of Tutankhamun. Over 1,300 sherds of LH III A2 pottery were found in the city (Wiener 1998, p. 312). The short duration of Tell El-Amarna as a capital city strengthens the value of its synchronism with LH III A2.[5]
3. **Sellopoulo Tomb 4.** Late Minoan Tomb 4 at Sellopoulo, near Knossos, contained three burials bearing local LM III A1 pottery (Popham et al. 1974). The earliest burial also contained a LH III A1 jug and the latest burial contained a scarab of Amenhotep III.
4. **Tel Batash Stratum VII.** Stratum VII at Tel Batash (southern Levant) contained a palace with rich finds, which ended in a violent destruction (Mazar and Panitz-Cohen 2019). The palace contained a scarab of Amenhotep III and an imported LH III A2 vessel. Four seeds found inside a jar were radiocarbon dated, yielding an average calibrated date of 1437-1394, at 95% confidence level.
5. **Uluburun shipwreck.** The famous Uluburun shipwreck, with its rich cargo of commercial jars, ingots, and other luxury items, contained LH III A2 pottery and a scarab of Queen Nefertiti, wife of Amenhotep IV (Pulak 1998). A Bayesian radiocarbon

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[5] For the possible presence of few LH III B1 sherds at Tell El-Amarna, see Warren and Hankey 1989, p. 149–151. For a defense of the traditional identification of the whole assemblage as LH III A2, see Wiener 1998, p. 312.

model established a date of 1340-1289 (at 95% confidence level) for the wreck (Manning et al. 2009).

6. **Late Minoan/Late Helladic III A.** The LH/LM III A1 and III A2 periods are modelled using sequences, without overlaps. Furthermore, as a common approximation, the LH III A1 is equated with LM IIIA1 and LH III A2 with LM III A2 (for example, see Warren and Hankey 1989, p. 169, table 3.1).

Table 2 lists all the data in chronological model.

Table 2. Input data in our model.

Period	Dates	Duration	Synchronisms
Egyptian pharaohs	Amenhotep III (1390-1352) Amenhotep IV (1352-1336) Smenkhkare (1336-1335) Tutankhamun (1335-1326)	Deduced from the dates	See below
Amarna	None	None	Starts 6 years after the start of Amenhotep IV Ends 2 years after the start of Tutankhamun Is included in LH III A2
Sellopoulo Tomb 4	None	None	Ends after the start of Amenhotep III Is included in LM III A1 Ends after the start of LH III A1
Tel Batash VII	None	None	Ends after the start of Amenhotep III Ends after the start of LH III A2
Batash VII radiocarbon sample	[-1437, -1494]	0	Is included in Tel Batash VII
Uluburun	[-1340, -1289]	0	Ends after the start of Amenhotep IV Ends during LH III A2
LM/LH III A1	None	None	LM III A1 = LH III A1
LM/LH III A2	None	None	LM III A2 = LH III A2

Modelling choices

Our model is small and far from including all the available chronological data. Rather, it is given as an illustration of the ChronoLog modelling philosophy. Here are some comments on our modelling choices:

1. **Scarabs.** Scarabs bearing royal names have been modelled according to the cautious rule defined above (Section 3): the start of the reign is a *terminus post quem* for the end of the stratum.

2. **Pottery.** Pottery was modelled using different types of synchronisms, according to the context in which it was found. The local LM III A1 pottery from Sellopoulo Tomb 4 was modelled with an inclusion synchronism (cf. Popham et al.: 'all three burials in Tomb 4 occurred within the short span of the IIIAI stage' [Popham et al. 1974, p. 206]). In the same way, Tell El-Amarna and the Uluburun shipwreck were also modelled using inclusions (in LH III A2), because of the large quantity of wares, making their interpretation as heirlooms less likely. In cases of few imported pieces found in an archaeological context (the Helladic pottery from Tel Batash and Sellopoulo), a more cautious approach was used, using the same type of *terminus post quem* as we did above for scarabs.

3. **Radiocarbon.** The dates for the Uluburun shipwreck, resulting from a Bayesian model, were encoded directly as a range on the end of the Uluburun period (Guideline 11 in

Section 3). For Batash VII, we created a separate period representing the samples and connected it to Batash VII using an inclusion synchronism. In other words, the harvest date of these seeds is assumed to be included in the stratum's lifetime (Guideline 9 in Section 3).

Results

ChronoLog computed a range of [-1390, -1346] for the end of LM/LH III A1. Querying the traces of these two bounds shows that -1390 derives from the Sellopoulo scarab, and -1346 from the Tell El-Amarna date. Hence, at this stage, the radiocarbon dates did not provide tighter ranges than the historically derived dates. In the previous sections, we have stressed that one of the strengths of our method is that it allows the user to interactively test the impact of the different hypothesis on the result. Let us now illustrate this methodology by answering a series of questions on the model (Table 3).

Since the tightened range of [-1390, -1346] derives from Sellopoulo and Tell El-Amarna, a natural question is what happens if these data are removed from the model. Removing Sellopoulo deprives us of any *terminus post quem* (TPQ) for the end of LH/LM III A1 (Table 3, row 2). Removing Tell El-Amarna widens the range to [-1390, -1289] instead of [-1390, -1346] (Table 3, row 3), with 1289 deriving from the Uluburun shipwreck.

We could also alter (rather than remove) some of the hypotheses in the model, as not all of them are universally accepted. For example, the traditional inclusion of the Amarna period within LH III A2 has been challenged by Warren and Hankey, who believe that Tell El-Amarna was rather abandoned by the royal court during the succeeding period, LH III B1 (see note 5 above). Modelling this alternative scenario does not alter the result for the end of LM/LH III A1. However, it does provide an interesting narrow range of [-1340, -1333] for the end of LM/LH III A2 and a duration of 6 to 57 years for that period (Table 3, row 4).

Regarding the Sellopoulo scarab of Amenhotep III, Brandl et al. (2013) proposed to date it not earlier than Year 25 of the reign. We model this hypothesis using a 'delay synchronism' between Sellopoulo and Amenhotep III[6]. This yields a narrow range of [-1366, -1346] for the end of LH/LM III A1 (Table 3, row 5).

We could also alter the simplified equation of LH III A1 = LM III A2 and LH III A2 = LM III A2. Authors have indeed noted that LH III A2 seems to start slightly earlier than LM III A2, towards the end of LM III A1 (Warren and Hankey 1989, p. 84). We model this hypothesis by keeping a synchronised start between LH III A1 and LM III A1 and a synchronised end between LH III A2 and LM III A2 but adding the synchronism 'LH III A2 starts during LM III A1'. This yields different results for the end of LH III A1 and LM III A1: the former ends before 1346, the latter after 1390. Thus, we have a single bound for each period, rather than a range (Table 3, row 6).

We could also make the A1 and A2 periods as overlapping rather than sequential. In that case, we obtain that LH/LM III A1 ends after 1390 and LH/LM III A2 starts before 1346 (Table 3, row 7).

Regarding Uluburun, some authors have suggested that the shipwreck took place during the LH III B period despite the ship's cargo of LH III A2 pottery. This suggestion is based on the idea that this pottery was probably produced in a peripheral region still producing III A2 shapes, while the master ceramic sequence in the Argolid (the main centre of production and creation of Late Helladic pottery) had already transited to III B shapes (Wiener 2003, p. 246). In that case, the end of LH/LM III A1 is unchanged, but the end of LH/LM III A2 now becomes

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[6] More precisely, we use the following synchronism: 'Sellopoulo Tomb 4 ends at least 24 years after the start of Amenhotep III'. Note that we use 24 years instead of 25 years because pharaonic regnal years start at Year 1, rather than Year 0.

included within [1333, 1289] (Table 3, row 8). Note that the lower bound (1333) comes from the dating of Tell El-Amarna, and the upper bound from the radiocarbon dating of the Uluburun shipwreck.

Finally, the Tel Batash samples, because they are short-lived (seeds), could be interpreted as dating to the last year of Stratum VII, rather than being included anywhere in the stratum's lifetime. This can be modelled with an 'equal ending' synchronism rather than an inclusion synchronism. This results in an inconsistent model, because it would require that Amenhotep III started reigning before 1394, instead of in 1390 (Table 3, row 9).

All the above results were obtained automatically by ChronoLog, by directly altering the model using the graphical user interface. Every such alteration takes no more than a few seconds and provides an immediate – and traceable – answer. Doing such experiments by hand is more cumbersome, and error prone. Note that these experiments also involved altering only one hypothesis at a time. More complex experiments could combine several of the above hypotheses, in order to obtain tighter bounds, or to discover new inconsistency results.

Table 3. Outcome of selected alterations to the model (all dates are BCE).

	Data	Result
1.	Original model	LM/LH III A1 ends within [1390, 1346]
2.	Removal of Sellopoulo	LM/LH III A1 ends before 1346 (no more TPQ)
3.	Removal of Tell El-Amarna	LM/LH III A1 ends within [1390, 1289]
4.	Tell El-Amarna starts during LH III A2 and ends during LH III B1 (Warren and Hankey 1989)	No change for the end of LM/LH III A1 LM/LH III A2 ends within [1340, 1333] LM/LH III A2 lasts between 6 and 57 years
5.	Sellopoulo scarab dating not earlier than Year 25 of Amenhotep III (Brandl et al. 2013)	LM/LH III A1 ends within [1366, 1346]
6.	LH III A2 starts during LM III A1 (start of LH/LM III A1 and end of LH/LM III A2 are still synchronised)	LM III A1 ends after 1390 (no more TAQ) LH III A1 ends before 1346 (no more TPQ)
7.	The LH/LM III A1 and A2 periods are overlapping rather than sequential	LH/LM III A1 ends after 1390 LH/LM III A2 starts before 1346
8.	The Uluburun shipwreck happened during LH III B	LM/LH III A1 unchanged LM/LH III A2 ends within [1333, 1289]
9.	Batash VII samples end at the same time as Batash VII	Model is inconsistent. The dating of the samples would imply that Amenhotep III started reigning before 1394, instead of in 1390.

5. Conclusion

In this paper, we have presented the ChronoLog tool for chronological research in archaeology. We have shown how it can be used to efficiently build, test and analyse chronological models. The main interest of this approach is that it fully automates the propagation of chronological information and helps prevent human errors (Levy, Piasetzky and Fantalkin 2021). Another advantage of our approach is that it forces users to explicitly lay down all their working hypotheses. No chronological assumption lies hidden. We have full disclosure of all prior knowledge encoded in the model and every computed result is fully traceable as a chain of evidence (called a *trace*) involving these prior assumptions.

The difficulty in this modelling approach lies in making the right decision for each piece of available data. Modelling choices can be more or less cautious and are entirely left at the user's discretion. ChronoLog features a wide set of synchronisms (32 different types), thus allowing very fine tuning of a model, but potentially also making the work of the modeller more difficult. Thus, we presented ChronoLog users with a set of practical modelling guidelines for helping them build their own models (Section 3). As guidelines (rather than rules), they can and should be adapted to each practical situation. Finally, we encourage users to build several models for each case study, in order to test the effect of different chronological assumptions and to discover potential inconsistencies. To the best of our knowledge, ChronoLog and its associated methodologies are the first to offer researchers in chronology a fast, practical and rigorous tool to perform such experiments. Moreover, ChronoLog enables scholars to widely share their models (as ChronoLog input files), along with the papers discussing these models, in order to enhance reproducibility of results and encourage other researchers to reuse and expand these models.

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