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A study of the scribal hands of Knossos based on phylogenetic methods and find-place analysis

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Part III: Dating the Knossos tablets using Phylogenetic Methods*

1. Introduction

Thus far, we have demonstrated that the Knossos tablets can be divided into three groups which can potentially be dated to three different time periods. In Part I, we used the phylogenetic analysis as a guide for categorizing the Knossos tablets into these three groups on the basis of paleography. Each of these styles is also associated with particular find-places: the Early Knossian style is found in the RCT; the Middle Knossian style is found in the NEP, Room of the Column Bases, Arsenal, and Corridor of the Sword Tablets; and the Late Knossian style is found on the tablets from the East-West Corridor and most of the tablets from the West Wing. In Part II, we have shown that there are no strong archaeological and textual reasons why these groups of tablets must be contemporaneous. On the contrary, there are good reasons to place the tablets of the RCT in LM IIIA1, those of the NEP and the Arsenal in LM IIIA2, and most of those from the East and West Wings in LM IIIB1.

Here, in Part III, we will use phylogenetic methods to assign dates to each of these groups of Knossos tablets. It will be shown that the dates favored by the phylogenetic analysis strongly support the archaeological interpretation in Part II.

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2. Design of the analysis

2.1. *Estimating dates using phylogenetic methods*

Up to this stage we have only used our phylogenetic analysis to make statements about relative dates. We know, for instance, that the Early Knossian style must have developed earlier than the Middle Knossian style because the Early Knossian scribal hands diverged earlier on the phylogenetic tree (that is, closer to the root). In the initial phylogenetic tree shown in Skelton (2008, fig. 4), the LH IIIA2 tablet Ui 2 from Petsas House, Mycenae is close to scribal hands of the Middle Knossian style, and the LM IIIB1 scribal hand Khania 115 appears in the clade consisting of the Late Knossian scribes. The branch lengths in those areas of the tree are short, which implies that very little time has passed between the divergence of our two dated taxa and their nearest neighbors. If we assume that the short branches mean that the Middle Knossian scribes were contemporaneous with Ui 2, and the Late Knossian scribes were contemporaneous with KH 115, we can conclude that the Middle Knossian style dates to LH/LM IIIA2, while the Late Knossian style dates to LM IIIB1.

However, a better approach to dating the tablets would be to quantify the passage of time on the phylogenetic tree. In principle, the amount of time represented by a given branch can be calculated if the branch length and rate of character state change along that branch are known. The branch length is defined as the number of character state changes which occurred along that branch. In our phylogenetic analysis of Linear B, each character state change represents a single shift from the use of one stylistic variation to another (Skelton 2008, p. 166). If we know the rate at which stylistic changes occurred, we can readily compute the amount of time represented by a given branch, by the equation (Sanderson 1997, p. 1220):

$$\text{Time} = \frac{\textit{Branch length (i.e., number of character state changes)}}{\textit{Rate of character state change}}$$

Unfortunately, quantifying this rate is not a straightforward task. In our case, in which we are studying a writing system which was used over a period of two to three centuries more than three millennia ago, we cannot measure the rate directly. Instead, we will try to infer a rate of evolution from our phylogenetic tree using the phylogenetics program, r8s, as described below.

2.2. *Selecting an appropriate date estimation method*

The simplest method for estimating dates uses a clock-like model of evolution, which assumes a constant rate of evolution over the whole tree. In order to apply

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clock-like methods to our Linear B dataset, we must assume that the rate of stylistic evolution did not change over the entire history of Linear B. Clearly, this is a very strong assumption, and it is untenable in the case of Linear B because we do not know *a priori* the rate of Linear B evolution, much less whether it remained constant.

We have chosen instead to use another standard method known as Non-Parametric Rate Smoothing (NPRS), which relaxes the assumptions of a constant rate. NPRS assumes that rates of evolution are not constant but do not vary wildly from branch to branch. The NPRS algorithm seeks the joint set of rates and times that minimizes variation in the rates of evolution within the bounds on times set by the user. The NPRS penalty function attempts to equalize the rates across the whole tree, but does not constrain them to be equal. But, if equal rates fit within the time bounds set by the user, NPRS will choose that answer. A detailed description of NPRS is given in Sanderson (1997), and a discussion of its implementation in the program r8s can be found in the r8s manual (Sanderson 2004).[1]

2.3. *The phylogenetic tree*

The phylogenetic tree we have used for our dating experiment is essentially the same as the trees given in Part I, but includes far fewer scribal hands. The tree was obtained by running the same Linear B dataset that was used in Part I,[2] with the full complement of phylogenetic characters. However, we included only the taxa used in Skelton's earlier study, because many of the extra taxa are difficult to place conclusively and lead to multiple equally acceptable trees.[3] The phylogenetic analysis was run in PAUP* 4.0b (Swofford 1998) using the same methods as described by Skelton (2008).

We then took the phylogenetic tree produced by this run and pruned a number of terminal taxa. We retained as many taxa as we judged necessary to define each of the major groups of taxa, as well as Khania Hand 115 and tablet Ui 2 from Petsas House, Mycenae, which can be dated archaeologically to LM IIIB1 and LH IIIA2, respectively. We included Hagia Triada and Zakros to represent Linear A; Hands 124-B, 124-R, and 124-S to represent the Early Knossian style; Knossos Hands 102a, 104, 111, and 118 to represent the Middle Knossian style; Knossos Hands 101, 103, 115, and 117 to represent the Late Knossian style. Mycenae Hand 51 and Thebes

[1] We have chosen to use NPRS instead of later and more sophisticated methods like Penalized Likelihood (Sanderson 2002) because, in practice, NPRS is computationally less burdensome (Jeremy Brown, personal communication 10/2007).

[2] This data set is available from http://www.utexas.edu/research/pasp/phylo/.

[3] However, we omitted the Kafkania pebble here because it is probably a forgery (Palaima 2002-3) and would add nothing to our attempt to reconstruct the tree.

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Hand 304 were included to represent the central Mainland, and Pylos Hands 1, 21, 32, and 41 to represent Pylos. We also included Pylos Hand 13 because the earlier phylogenetic analysis, as well as oddities in its archaeological context, suggest that it probably dates earlier than the Pylos main archive (Skelton 2008, 163, 171-172).

We limited the number of taxa in the tree that we are attempting to date because estimating dates is computationally difficult, and reducing the number of taxa increases the chances of finding a good solution using the program r8s. Sanderson, the originator of r8s, does not have confidence that r8s works on datasets of more than 35 taxa (Sanderson 2004, 27). In our case, we have 22 taxa (i.e. 20 Linear B scribal hands plus two Linear A examples). We aim only to establish dates for the major deposits of Knossos tablets, so including more scribal hands in the tree to be dated would not necessarily accomplish our objective any better. We included more taxa when running the phylogenetic analysis (using the program PAUP*) than we would be able to use in dating the tree (using the program r8s) because including those extra taxa improves the accuracy and resolution of the tree that we wish to date.

2.4. *Selecting dates to input*

NPRS requires that some taxa are given dates (or date ranges) in order to estimate rates of evolution and assign dates to nodes. We have chosen to provide constraints for a minimum of taxa in order to show that the dating scheme proposed by r8s arises from the structure of the data itself and is not created by imposing dates on a large number of taxa. We have only constrained the two earliest dated taxa, the two Linear A taxa; one taxon from the end of each major LM/LH IIIB branch, Khania 115, Thebes 304, and Pylos 1; and one taxon from roughly the middle of the tree, Mycenae Petsas House.[4]

However, assigning absolute dates to the relative chronology of these Linear A and Linear B taxa is problematic on several levels. First, the assignment of absolute dates to the Aegean relative chronology is controversial because two different dating methods, scientific methods such as radiocarbon dating and archaeological synchronisms with Egypt and the Near East, may give different dates, particularly

4 In practice, this scheme for dating taxa produces broadly the same archaeological dates as a scheme in which we constrained all taxa whose archaeological relative dates are well established on the basis of archaeological evidence: the two Linear A taxa; the taxa from LH IIIB Mycenae, Thebes and Pylos; the LH IIIA2 taxa from Mycenae Petsas House; and the LM IIIB1 taxa from Khania 115, as well as the RCT taxa, which probably date to LM IIIA1. The most appreciable difference between the tightly constrained and loosely constrained runs is the difference in the fluctuation of the rates of evolution across the tree. However, we choose to present the results of the loosely constrained calculation because they demonstrate that the results are not dependent on tightly constraining the taxa.

in the seventeenth and sixteenth centuries BCE (Shelmerdine 2008, 3-7). For this study, we have chosen to run the analysis twice, once using the "high chronology" based on radiocarbon dates, and once using the "low chronology" based on archaeological synchronisms. The absolute dates used here (given in Table 1) come from Shelmerdine (2008, 3-5 and personal communication 31 May 2008).

Table 1: *Aegean relative and absolute chronology*

Ceramic Period	High Chronology	Low Chronology
LM IB	1600-1490	1490-1440
LM II	1490-1430	1440-1380
LM IIIA1	1430-1380	1380-1360
LM IIIA2	1380-1300	1360-1300
LM IIIB	1300-1200	1300-1200
LH IIA	1610-1500	1500-1430
LH IIB	1500-1440	1430-1390
LH IIIA1	1440-1390	1390-1370
LH IIIA2	1390-1300	1370-1300
LH IIIB	1300-1200	1300-1200

Second, Linear B tablets may be said to date to the "beginning", "middle", or "end" of a period. There is not enough information to translate these rough estimations into absolute lengths of time. Therefore, dates have been arbitrarily set so that the "beginning" represents roughly the first third of a period, the "middle" represents the roughly the second third of the period, and the "end" represents the last third of the period. The late LH IIIA2 Petsas House tablet was constrained in this way. In the case of LM/LH IIIB1 and LM/LH IIIB2, in which LM/LH IIIB1 is estimated to have lasted longer than LM/LH IIIB2 (Shelmerdine personal communication 31 May 2008), LM/LH IIIB1 is arbitrarily set to represent roughly the first 2/3 of the period, and LM/LH IIIB2 roughly the last 1/3. The three taxa from LM/LH IIIB which were given constraints were constrained in this way. The two Linear A taxa were only constrained to LM IB because the r8s analysis placed them in late LM IB without any need for additional constraints.

Input dates are given below in Table 2.

2.5. *Running the analysis*

The NPRS analysis was run in the software package r8s 1.71 (Sanderson 2006) using the Powell algorithm, the only choice of algorithm available for NPRS (Sanderson 2004, 15).

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Six terminal taxa were given constraints, as described above. In addition, r8s generally requires that at least one internal node be fixed or several internal nodes constrained in order to keep r8s within reasonable parameter space (Sanderson 2004, 11, 28). Therefore, we constrained the node representing the divergence of Linear B from Linear A to LM IB-LM II[5].

The exponent in the NPRS penalty, which determines how heavily changes in rate from branch to branch will be discouraged, was set to the default value of 2 (a value of 0 would result in no penalty) (Sanderson 2004, 32). In other words, the analysis was set to discourage changes in rate according to the square of the difference in rate from one branch to another (Sanderson 2004, 13). In one run, which used only the high dates, we experimented with decreasing the exponent in the NPRS penalty function to 1.5. Phylogenetic absolute dating methods can be sensitive to the prior assumptions about the degree of penalties for changes in rates, and we wanted to see to what extent this was the case for our analysis. We found that changing the NPRS penalty function from 2 to 1.5 only affected the dates estimated by r8s by five years at most, and in most cases only affected the dates by one or two years or did not affect the dates at all. Therefore, we decided to continue using the default setting of 2 for the NPRS penalty.

An NPRS analysis poses an optimization problem for which it is impossible to obtain an exact solution[6]; how thoroughly the algorithm should explore the solution space is at the discretion of the investigator. In one run we experimented with increasing the number of initial random starts and the number perturbed restarts after an initial solution was found. We found that these results did not appreciably differ from the results from using the default settings of one random start and one perturbed restart (Sanderson 2004, 32-33), so we continued to use the default settings, which had a much faster run time.

The program was otherwise run using the default settings.

5 For a discussion on the date of the origin of Linear B, see Driessen (2000, pp. 106-107). Failure to include a constrained internal node resulted in one set of runs which, although no doubt mathematically correct, were for practical purposes total nonsense.

6 "Exact solution" here means that the calculation has trawled through all of solution space so that we could say with certainty that the resulting solution is literally the best. In practice, for this type of calculation, exact solutions are not attainable because the analysis would take an unreasonable length of time. With a "non-exact solution" strictly all you can say is that it is the best solution in the solution space that the calculation has trawled through. However, search algorithms are designed to ensure that the analysis trawls through the amount of solution space that is necessary to be likely that it generates the best answer that is possible within a reasonable time; this may not be literally "the best" solution, just a very good one. The impossibility of finding an exact solution is true of most phylogenetics problems; however, the problems handled by r8s are typically more difficult than most (Sanderson 2004, 27).

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We would like to emphasize that one of the main advantages of a computer analysis is that it is easy to change the input parameters and run the analysis again to see how these changes affect the results. We recognize that the archaeological dates we have chosen are somewhat controversial, and that our choice of parameters for the r8s analysis is somewhat arbitrary. Therefore, we welcome additional suggestions or scenarios for running our analysis.

3. Results

Table 2a: *Results of r8s runs using high dates*

Taxon	Constraints[7]	r8s-assigned date	Local rate of evolution[8] (x 10^{-3})
Hagia Triada	1600-1490 LM IB	1490 LM IB	4.5
Zakros	1600-1490 LM IB[9]	1510 LM IB	4.1
First Linear B	1600-1430 LM IB-II[10]	1452 LM/LH II	3.8
Pylos 13		1435 LH IIIA1	3.8
RCT 124-B		1387 LM IIIA1	4.1
RCT 124-R		1359 LM IIIA2	4.4
RCT 124-S		1415 LM IIIA1	3.9
Knossos 102a		1319 LM IIIA2	5.6
Knossos 104		1296 LM IIIB	4.7
Knossos 111		1306 LM IIIA2	4.7
Knossos 118		1307 LM IIIA2	6.1
Mycenae Petsas House	1330-1300 LH IIIA2[11]	1330 LH IIIA2	4.9
Knossos 101		1242 LM IIIB	7.6
Knossos 103		1232 LM IIIB	7.9
Knossos 115		1228 LM IIIB	8.1
Knossos 117		1247 LM IIIB	7.1

7 For taxa which are not constrained these cells have been left blank.

8 The program r8s presents these results to 5 significant figures; however, we have given them to two significant figures for clarity of presentation and to avoid spurious implications of accuracy.

9 The archaeological dates for the Linear A taxa come from Godart and Olivier (1985).

10 This range of dates corresponds to the range of estimates given for the origin of Linear B surveyed in Driessen (2000, pp. 106-107).

11 The late LH IIIA2 date for the Petsas House tablet comes from Shelton (2002-2003).

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Table 2a (cont.)

Taxon	Constraints	r8s-assigned date	Local rate of evolution (x 10^{-3})
Khania 115	1300-1230 LM IIIB1	1230 LM IIIB	8.1
First Mainland *koiné*		1275 LM IIIB	5.53
Mycenae 51		1225 LH IIIB	3.3
Thebes 304	1230-1200 LH IIIB	1230 LH IIIB	1.8
Pylos 1	1230-1200 LH IIIB[12]	1200 LH IIIB	8.9
Pylos 21		1214 LH IIIB	8.4
Pylos 32		1258 LH IIIB	6.8
Pylos 41		1230 LH IIIB	7.8

Table 2b: *Results of r8s runs using low dates*

Taxon	Constraints	r8s-assigned date	Local rate of evolution (x 10^{-3})
Hagia Triada	1490-1440 LM IB	1440 LM IB	6.1
Zakros	1490-1440 LM IB	1456 LM IB	6.0
First Linear B	1490-1370 LM IB-II	1419 LH/LM II	5.8
Pylos 13		1409 LH II	5.8
RCT 124-B		1375 LM IIIA1	5.9
RCT 124-R		1354 LM IIIA1	6.0
RCT 124-S		1394 LM II	5.9
Knossos 102a		1319 LM IIIA2	6.4
Knossos 104		1305 LM IIIA2	6.1
Knossos 111		1312 LM IIIA2	6.1
Knossos 118		1308 LM IIIA2	6.5
Mycenae Petsas House	1330-1300 LH IIIA2	1330 LH IIIA2	6.1
Knossos 101		1242 LM IIIB	7.5

12 For the LM IIIB1 period for Khania 115 and the late LH IIIB period for Pylos 1 and Thebes 304 see Shelmerdine (1998) and the references quoted therein.

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Taxon	Constraints	r8s-assigned date	Local rate of evolution (x 10^{-3})
Knossos 103		1233 LM IIIB	7.8
Knossos 115		1228 LM IIIB	7.9
Knossos 117		1248 LM IIIB	7.2
Khania 115	1300-1230 LM IIIB1	1230 LM IIIB	8.0
First Mainland *koiné*		1276 LH IIIB	5.6
Mycenae 51		1226 LH IIIB	3.3
Thebes 304	1230-1200 LH IIIB	1230 LH IIIB	1.8
Pylos 1	1230-1200 LH IIIB	1200 LH IIIB	8.8
Pylos 21		1214 LH IIIB	8.4
Pylos 32		1258 LH IIIB	6.8
Pylos 41		1230 LH IIIB	7.7

3.1. *Discussion of results*

The r8s analysis produces dates which are largely consistent with the dates of the Linear B tablets known from archaeological work, and confirm the dates for the Knossos taxa proposed in Part II. For the most part, using high dates or low dates made no difference to which archaeological period, or portion of an archaeological period, r8s dated the taxa. Therefore, results of both runs will be discussed together, noting instances where high and low dates yield different results.

3.1.1. Linear A, the invention of Linear B, and Pylos Hand 13

The Linear A taxa fall in the last 20 years of LM IB. This result is consistent with the view that the Linear A tablets were preserved in the destructions of the Minoan palaces at the end of the LM IB period (Younger and Rehak 2008). r8s dates the invention of Linear B to LH/LM II: 1452 for the high dates, or 1419 for the low dates. While Skelton (2008) proposes that Pylos Hand 13 represents some of the earliest known examples of Linear B, the r8s analysis suggests that Pylos Hand 13 in fact comes less than a generation after the invention of Linear B. The high dates place Pylos Hand 13 at 1435, or seventeen years after the invention of Linear B; the low dates place Pylos Hand 13 only ten years after the invention of Linear B, in 1409. The high dates place Pylos Hand 13 at the very beginning of LH IIIA1, while the low dates place it in LH II.

For comparison, the r8s analysis places the writing style of the earliest RCT scribe 37 years (high dates) or 25 years (low dates) after the invention of Linear B. The r8s analysis suggests that writing style of RCT Hand 124-S is 15 to 20 years later than that of Pylos Hand 13. The implication is that Linear B spread throughout the Mycenaean world quite rapidly.

Essentially, the r8s analysis supports the scenario for the invention of Linear B proposed by Palaima (1988, 339-340), with the Mycenaeans adapting the Linear A script to Linear B in LM II driven by the impetus arising "from the complex activities of an expanding economic and political center".[13]

3.1.2. Early, middle and late Knossos

The r8s analysis proposes essentially the same dating scheme for the Knossos taxa as the one which was proposed in Part II on the basis of archaeological and internal textual evidence. The Early Knossian writing style of the RCT dates to LM IIIA1, the Middle Knossian style dates to late LM IIIA2, and the Late Knossian style dates to mid LM IIIB.

r8s dates the RCT scribes to slightly different archaeological periods depending on whether the high dates or the low dates are used. Using the high dates, two RCT scribes, 124-B and 124-S, date to LM IIIA1, while the third, 124-R, dates to very early LM IIIA2. Using the low dates, one scribe, 124-S, dates to LM II, while the others, 124-B and 124-R, date to LM IIIA1. In short, the high dates imply a slightly later ceramic period for the RCT than the low dates. The range of dates for the RCT taxa, 56 (high) or 40 (low), is surprisingly wide, which might suggest that the r8s analysis is pushing RCT 124-R a little later than expected. In any case, either interpretation is generally consistent with the LM IIIA1 date favored in Part II of this paper.

The r8s analysis places the Middle Knossian hands in late LM IIIA2. The run with the high dates gives a range of dates of 1319-1296, actually pushing the latest Middle Knossian hand, Knossos 104, a few years into LM IIIB. The run with the high dates gives a date range of 1319-1305. These dates are consistent with the archaeological interpretation proposed in Part II. The range of dates is narrow, 23 years for the high dates and 14 years for the low dates.

[13] Palaima (1988, 339) states that he is unable to determine whether Linear B was invented on Crete or on the mainland (in particular, at Knossos or Mycenae). The present analysis suggests that Pylos Hand 13 pre-dates the writing style on the earliest Linear B scribal hands on Crete by 15-20 years. However, this should not be taken to imply that Linear B was invented at Pylos, simply that, according to the present study, the earliest preserved Linear B tablet currently known was found at Pylos.

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The r8s analysis dates the Late Knossian hands to mid-late LM IIIB. The results for the runs using the high dates and the low dates are nearly identical, 1247-1228 and 1248-1228, respectively.[14] As with the dates for the Middle Knossian hands, these dates are consistent with the dates proposed in Part II and have a narrow spread, 19 or 20 years.

3.1.3. Mainland

As expected, all Mainland taxa which have been assigned LH IIIB dates on the basis of archaeological evidence are also dated to LH IIIB by the r8s analysis. The r8s analysis also dates the birth of the common graphical style found across the Mainland during LH IIIB, known as the Mainland *koiné*, to early LH IIIB: 1276 by the high dates, or 1275 by the low dates. Early LH IIIB is somewhat later than the date commonly proposed for the development of the Mainland *koiné*, late LH IIIA2 (Skelton 2008). However, an early LH IIIB date is entirely reasonable within the dating scheme proposed by the r8s analysis, in which the Middle Knossian hands, which predate the Mainland *koiné*, are dated to late LM IIIA2.

Both Mycenae 51 and Thebes 304 present minor problems with regard to the r8s analysis. First, the date which r8s assigns to Mycenae 51 is higher than the archaeological evidence suggests. r8s dates Mycenae 51 to 1225 (high dates) or 1226 (low dates), or LH IIIB2. However, Mycenae 51 comes from the Oil Merchant group of tablets, which is dated to LH IIIB1. According to the absolute dating scheme proposed for this paper, LM IIIB1 should end in 1230, four or five years before the date r8s gave to Mycenae 51. Thebes 304 also presents surprising results. This is not due to the date, which r8s gives as 1230, the lower bound of the constraints, for both the high and low runs. Instead, the rate of evolution is surprisingly slow, 1.8×10^{-3} in both high and low runs. The other LM/LH IIIB taxa, the Pylos taxa and the Late Knossian hands, have considerably higher local rates of evolution, ranging from $6.8\text{-}8.9 \times 10^{-3}$.

The large discrepancy in local rates of evolution, and the high date for Mycenae 51, arise from the topology of the starting phylogenetic tree, which shows Mycenae 51 as post-dating Thebes 304.[15] If we did not constrain Thebes

[14] Archaeologically speaking, the high and low dates have come into synch by LM/LH IIIB, so there is only one absolute dating scheme for this century. However, NPRS requires us to run and report two completely separate analyses, even though the date constraints differ only partially. Since NPRS minimizes rate variation across the whole tree, there is the possibility that the rates prior to the point at which the high and low dates come into synch will affect the NPRS calculation of the rates after that point. Therefore, it is necessary to continue to refer to the two runs separately.

[15] However, the arrangement of taxa within the Mycenae-Thebes branch of the tree may be inaccurate. Skelton (2008) observed that bootstrap support values in the Mycenae-Thebes branch of the tree

304 to LH IIIB2, it would appear in LH IIIB1. Thus, in the present analysis, the constraints on Thebes 304 result both in an anomalous local rate of evolution and also pushing Mycenae 51 into LH IIIB2. This analysis was designed to consider the Knossos hands and it is more appropriate for us to return to the issues raised by the phylogenetic analysis of the Mycenae and Thebes hands in future work.

The dates for the LM IIIB Pylos hands are the same for both the runs using both the high dates and the low dates: 1200-1258. This represents a relatively large range of dates, probably longer than would be reasonable without special pleading such as suggesting that Pylos Hand 32 either had a particularly conservative style or was very long-lived and retained his style through his life. Again, it is noted that this analysis was primarily intended to study the Knossos hands and we should return to consider the Pylos hands in more detail in a future study.

3.1.4. Rates

r8s reports the rate of evolution in terms of the substitutions per site per unit time that is, the average number of changes that would happen for a given paleographical variation in a year, the unit of time we have chosen for this analysis. To the best of our knowledge, no other publications have attempted to quantify the rate of handwriting evolution or how that rate changes over time. Thus, we have no basis for comparing the rates in this analysis with other epigraphical data. However, it is still possible to survey the differences in rate between the two runs, and derive certain conclusions from this internal evidence.

The run using the high dates had a lower rate of evolution, on average, than the run using the low dates. For the run which used the high dates, the mean rate of evolution was 5.8×10^{-3}, the minimum rate was 1.8×10^{-3}, the maximum rate was 8.9×10^{-3}, and the ratio of the highest rate to the lowest rate was 4.9. For the run which used the low dates, the mean rate of evolution was 6.5×10^{-3}, the minimum rate was 1.8×10^{-3}, the maximum rate was 8.8×10^{-3}, and the ratio of the highest rate to the lowest rate was 4.9. Therefore, the run using the high dates had rates of evolution which were slower, on average, than the run using the low dates. This result is exactly as to be expected. Given our equation above, that rate equals distance divided by time. Therefore, decreasing the amount of time from 400 years to 240 years should have the effect of increasing the average rate of evolution.

Otherwise, the rates of change for both runs are comparable. The range of rates was 7.0×10^{-3} for both runs, the ratio of the highest rate to the lowest rate was 4.9 for both runs, and the standard deviation varied slightly, 1.8×10^{-3} for the high dates and

were consistently low, and took the low bootstrap values as an indication that the topology of the Mycenae-Thebes branch of the tree may be unreliable.

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$1.4x10^{-3}$ for the low dates. The rate of evolution changes by the same pattern in both runs, gradually increasing from the root to the tips, with local drops in the rate of evolution around Pylos 13 and the invention of Linear B, and again at the beginning of the Mainland koiné, Mycenae 51, and Thebes 304. It would be interesting if these rates reflected a real increase in the rate of innovation in Linear B over time.

4. Conclusions

The r8s analysis is able to produce a very plausible set of archaeological dates for the Linear B tablets on the basis of a minimal set of imposed constraints. This result strongly implies that the structure of these dates results from the underlying form of the data, not because the investigators forced the results by tightly constraining the parameters within the analysis. This study confirms that phylogenetic methods are effective at reconstructing the evolutionary histories of writing systems.

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