Rates of change and phylogenetic signal in Mixtec tone

Sandra Auderset
University of Bern

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Abstract

Despite the abundance of tonal languages around the world, the diachrony of tone is still poorly understood, especially when compared to segmental sound change. This lacuna has contributed to the untested assumption that tones are inherently unstable and change unpredictably. This paper addresses the questions of whether tones change faster than segments and whether tones show less phylogenetic signal than segments in the Mixtec languages of southern Mexico. To this end, I created a database of tonal and segmental sound changes across a sample of 42 Mixtec languages. I calculated phylogenetic signal with the metric *D* and estimated rates of change with a hidden Markov model across a posterior sample of phylogenetic trees. The results show that the majority of tone changes show phylogenetic signal and that they generally do not change at a faster rate than segments.

Keywords: Mixtec, tone change, phylogenetic signal, evolutionary rate

1 Introduction

Historical linguistics as a field has expanded considerably in the past decade both with respect to methodology and data. The adoption of computational and quantitative methods, such as automatic sequence alignments (List et al., 2018) and Bayesian phylogenetics (Greenhill et al., 2020), has led to more explicit and testable hypotheses and exchange with other fields dealing with the human past, such as archaeology and population genetics. Language documentation efforts all over the world have made it possible to diversify the data used to study language change. There is, however, a gap in the field when it comes to tone. Tonal phenomena are conspicuously absent from studies on language change despite the abundance of tonal languages worldwide (Yip, 2002). Research on tonal correspondences (Dockum, 2019), tone reconstruction (Dimmendaal, 2011), and tone change (Janda and Joseph, 2003) is still relatively rare and often confined to the emergence of tonal contrasts from segmental changes (Campbell, 2021). The latter is reflected in a long tradition of work on tone correspondences in languages of Southeast Asia, which relies on relatively well established processes of tonogenesis (Gedney, 1972; Joseph and Burling, 2001; Ferlus, 2004; Dockum, 2019, among others). But for tone change apart from tonogenesis no such body of literature exists.

It has often been observed that tone realizations can vary drastically even in closely related languages (Cahill, 2011; Beam de Azcona, 2007; Morey, 2005; Dürr, 1987, among others), leading to the assumption that tones change faster than segments (Ratliff, 2015). This in turn has led to tone being omitted in studies on the history of a language family (Campbell, 2021). Further complications arise with respect to the comparison of tonal systems more broadly. Available typological studies are coarse-grained and based on highly analysis-dependent categories such as the number of tonal contrasts or wholesale classification of tonal systems as "simple" vs. "complex" (Lee, 2022; DiCanio and Bennett, 2020; Maddieson, 2013). To sum up, there are many challenges with respect to research on the historical dimensions of tone, and empirical studies on the rate of tone change and its contribution to subgrouping outside of tonogenesis are still lacking.

In this study, I take a first step at addressing this gap. I investigate tone change in Mixtec combining data analysis practices from typology and quantitative methods from historical linguistics. I compare phylogenetic signal and rates of change in tones vs. segments to empirically address the claims about tone volatility mentioned above and assess whether tones indeed change faster than segments and show less phylogenetic signal in this language family. The Mixtec languages of southern Mexico, which form part of the Mixtecan branch of the Otomanguean family, provide an ideal testing ground for such an investigation. These languages are all tonal and tone carries a high functional load both in lexicon and grammar. Tones in Mixtec are old and must be reconstructed to Proto-Mixtec and Proto-Mixtecan and most probably as far back as Proto-Otomanguean (Campbell, 2017; Rensch, 1976). Furthermore, there are previous historical linguistics studies on Mixtec including reconstructions of the Proto-Mixtec segmental inventory (Longacre, 1957; Mak and Longacre, 1960; Bradley and Josserand, 1982), identification of segmental sound changes (the aforementioned and Josserand, 1983; Swanton, 2021), but also tone reconstruction and tone change (Dürr, 1987; Swanton and Mendoza Ruiz, 2021). Due to recent intensification of documentation efforts in the Mixteca region and diaspora communities, we now have data for more varieties than the earlier sources were able to draw on and can extend or update previously collected data on a number of varieties. In addition, we have a recent, up-to-date family tree of Mixtecan based on Bayesian phylogenetic methods (Auderset et al., 2023a), which provides considerable detail concerning the lower-level relationships of these languages.

As mentioned above, comparison of tones in general is challenging even on a synchronic level. To address these challenges, I draw on data organization and analysis methods developed for multivariate typology (Bickel, 2010; Bickel et al., 2011; Bickel, 2015). Multivariate typology works with systems of fine-grained variables which are created bottom-up from the language data and thus aim at capturing all the variation present in the data without imposing preconceived definitions (Bickel, 2010). This approach is easily adaptable to diachronic data, such as sound changes, and has the added benefit of resulting in databases that can be reused and expanded upon for other research questions. I thus establish sound changes, both tonal and segmental, in Mixtec and code them in interlinked databases. The process is described in more detail in Section 2. To address the questions of whether tones change faster than segments and whether or not they can be used for subgrouping in an empirical way, I rely on computational methods established for exploring biological evolution but which are currently gaining traction in studies on linguistic change (Macklin-Cordes et al., 2021; Hübler, 2022; Phillips and Bowern, 2022, among others). Phylogenetic signal measured by the metric D is based on the sum of sister-clade differences across a family tree. It provides a measure for the tendency of related species (sisters in the tree) to be more similar to each other than to other species sampled randomly from the tree (Fritz and Purvis, 2010; Münkemüller et al., 2012). In linguistic terms, phylogenetic signal reflects the tendency of closely related languages to be more similar to each other with respect to a given variable than to more distantly related languages in a given language family tree. Comparing phylogenetic signal across segmental and tonal changes thus provides us with an explicit measure of how much these changes align with language relationships within Mixtec. This in turn will help answer the question of whether tones carry phylogenetic signal, or in other words, whether tone changes can (and should) be used for subgrouping alongside segmental changes. To investigate evolutionary rates of change in tones and segments, I use a hidden Markov model. This model estimates transition rates between two observed characters based on a tree. The "hidden" part of the term refers to the fact that in this type of model multiple processes can be invoked to describe the evolution of the observed characters (Beaulieu et al., 2013). Applied to linguistic evolution, this means that the model estimates the transition rates (rates of change, in other words) between the presence and absence of a variable across the languages of the family tree. As opposed to other models, it allows the transition rate to vary across the tree, such that a variable can change quickly near the root of the tree and then slow down in some branches, for example. This suits changes in linguistic structures well, as those are not assumed to proceed at a constant, unchanging rate (Nettle, 1999).

Given that the majority of the world's languages are tonal (Yip, 2002) and historical linguistics is one of the primary ways of accessing the past of an ethnolinguistic group, understanding whether or not tone can contribute to that is crucial. Earlier studies on tone correspondences suggest that it does, but to what extent remains unclear. Assumptions on the volatility and variability of tone suggest that it does not. If we can show that tone change proceeds at similar rates to segmental change and that tone changes carry just as much phylogenetic signal, this will make a strong case for no longer ignoring this aspect of language in historical studies.

2 Data collection and analysis

The data used for this study constitutes a revised subset of an existing database of annotated cognate sets across 130 Mixtecan languages (Auderset et al., 2023b). These cognate sets were established based on a word list tailored to the Mesoamerican cultural area. Verbal forms were excluded because they require aspect-mood inflection, which is not well understood on a comparative Mixtec level, and is not always provided or reliably identifiable in glosses in the source material. The entire list is provided in Auderset et al. (2023a) and described in more detail in Auderset et al. (2023b). The orthographic entries were converted to IPA and tone notation was standardized. I discuss only the standardization of the tone notation here; details regarding segments can be found in Auderset et al. (2023a,b).

IPA offers two principal ways of displaying tone: diacritics that are placed above the tone-bearing unit or tone bars, with the latter method suggested as the preferred one. Tone diacritics are useful in practical orthography but not well suited to alignment for comparative purposes or for computational processing. For such purposes, it is more useful to represent the tone after the tone-bearing unit as its own character (even if this does not reflect phonetic reality). Therefore, I use Chao's tone numbers (Chao, 1930), since they are widely known and easy to type and read. In this system, each distinctive pitch level is assigned a number from one to five, with one being the lowest and five the highest; see Table 1. The interval between the lowest and highest

Table 1: Overview of tone notation based on Chao (1930).

Chao's number	Musical comparison	Label
5	G#	high
4	F#	half-high
3	E	mid
2	D	half-low
1	C	low

Table 2: Tone levels and standardized tone notation with an overview of notations found in source materials.

Description	**5**=high	**4**=mid-high	**3**=mid	**2**=mid-low	**1**=low
all three marked	acute (á)		macron (ā)		grave (à)
mid-low grave, low underbar	acute (á)		unmarked (a)	grave (à)	underbar (a̱)
low unmarked, mid macron	acute (á)		macron (ā)		unmarked (a)
low unmarked, no mid	acute (á)				unmarked (a)
mid unmarked, low macron	acute (á)		unmarked (a)		macron (ā)
no mid, low macron	acute (á)				macron (ā)
mid unmarked, low grave	acute (á)		unmarked (a)		grave (à)
no mid, low grave	acute (á)				grave (à)
mid unmarked, low underbar	acute (á)		unmarked (a)		underbar (a̱)
Chao	5	4	3	2	1
Chao with 4	4		3	2	1
Chao with 3	3		2		1
inverse Chao	1	2	3	4	5
inverse Chao with 4	1	2	3		4
inverse Chao with 3	1		2		3

pitch is assumed to correspond roughly to an augmented fifth (Chao, 1930). Contour tones are represented as combinations of these levels. A high to low falling tone, for example, is noted as 51.

The source materials display a wide range of tone notations. Most descriptions of varieties with three tonemes denote them with diacritics, while those with more tonemes usually represent them with numbers. The mapping of a specific diacritic or number to toneme varies widely in the sources. The tone notations found for level tones in the sources and their standardization used in all the materials of this study are summarized in Table 2.

For the present study, I restricted the data to just those Mixtec varieties for which reliable information on tonal contrasts is available. Out of the 130 Mixtec varieties for which we were able to collect entries for the word list in Auderset et al. (2023a), only 46 have tones marked on more than a few entries.[1] Of these 46, Metlatonóc Mixtec had to be excluded because of low coverage,[2] and Cahuatache, Diuxi, and Abasolo del Valle Mixtec due to difficulties in the interpretation of the tone values (see the supplementary materials at "Data and explanations/tone_standardization" for details), resulting in a sample of 42 languages. These 42 languages belong to six of the seven larger subgroups identified in Auderset et al. (2023a) and to 10 out of the 12 dialect areas identified by Josserand (1983). Due to lack of documentation, I was not able to include any varieties of Linkage[3] 5 (roughly corresponding to the Tezoatlán area of Josserand, 1983, but including a few more varieties). A list with all varieties, subgroup and dialect area affiliations, abbreviations, and language codes is provided in the supplementary materials (at "Data and explanations/metadata"). Figure 1 provides a geographic overview of the sample with subgroup affiliation and Fig. 2 shows the maximum clade credibility tree from Auderset et al. (2023a) pruned to just the languages under discussion here, illustrating the genealogical relationships of the varieties in more detail.

Reconstructed segmental proto-forms were created using the comparative method and based on already established reconstructions provided in Josserand (1983) and Dürr (1987). Each reconstruction was then carefully checked and reconsidered in light of the newly available primary data and—if needed—updated to match the current data set and knowledge of the sound changes. I also added new lexical reconstructions not covered by previous sources. All the reconstructions, alternative proto-forms, and earlier proposals can be found in the supplementary materials (at "Data and explanations/protoforms_tones").

Mixtec languages have a strong tendency for lexical morphemes to be bimoraic, and this applies to reconstructed lexical Proto-Mixtec morphemes as well.[4] Each vowel counts as one mora and long vowels consist of two morae. There are no final consonants apart from the glottal stop, which is retained only in two varieties, and consonant clusters are very restricted or absent in all modern Mixtec varieties, which means that most bimoraic morphemes have a syllable structure of CVCV, CVV, VCV, or VV. Lexical entries can also have more than two morae (just not less). Most commonly these longer forms have three morae and historically consist of a one-mora (CV or V) "prefix" added to a bimoraic lexical base. I reconstruct both bimoraic and trimoraic forms, segmenting the latter into the "prefixal" element and the base morpheme. I removed duplicates[5] and all entries which are not tone marked, as well as cognate sets consisting of only one item. This results in a total of 5,255 entries spread over 258 cognate sets. Coverage per variety is between 42 and 198 cognate sets, with a mean of 125 and a median of 126 sets.

[1] Note that I do not distinguish between languages and dialects, since there is no solid basis nor necessary or sufficient criteria to do so in Mixtec. I use the terms "variety" and "language" interchangeably, but refrain from using the term "dialect" since it carries a negative connotation in Mexico and has been part of a long history of oppression of communities that speak Mixtecan and other indigenous languages (Cruz and Woodbury, 2014).

[2] Low coverage is defined here as having values for under half of the variables.

[3] I use the term "linkage" to refer to groups and varieties which are placed close together in the maximum clade credibility tree but do not have good support, i.e., low posteriors. In other words, these varieties show a wave-like structure (see Ross, 1988; François, 2015).

[4] This bimoraic unit is often referred to as the "couplet" in Mixtec literature (Pike, 1948), but in a recent study Swanton (2021: 35, n. 40) points out that there is little reason for using the term, as there is some confusion over whether it is supposed to describe a morphological or a phonological domain.

[5] Since the data was collected from multiple sources for one variety if available, the exact same form sometimes was collected from different sources. These true duplicates were removed for the analysis.

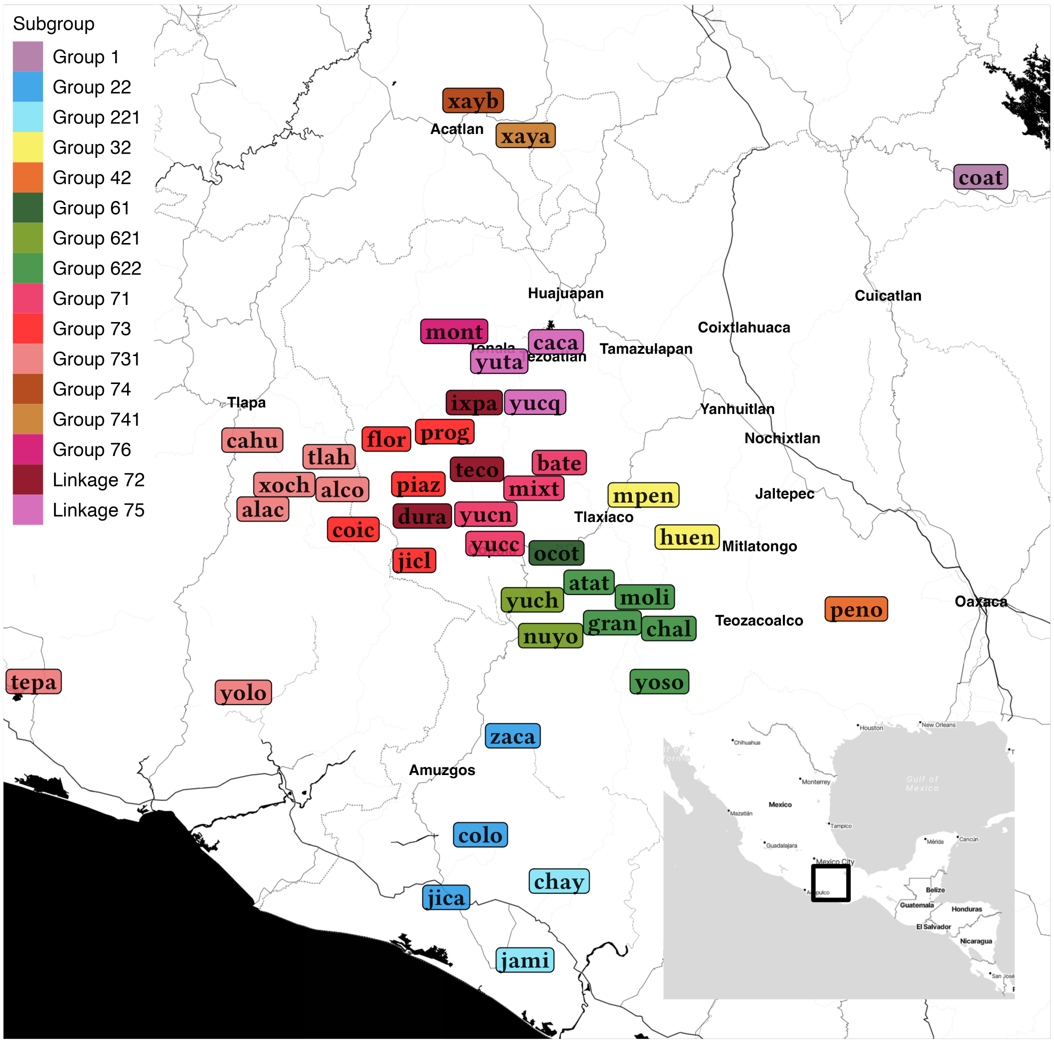

Figure 1: Languages sampled in the present study with their subgroup affiliation (according to Auderset et al., 2023a; for language codes see the supplementary materials at "Data and explanations/metadata"). The inset shows the location of the detailed map within Mesoamerica.

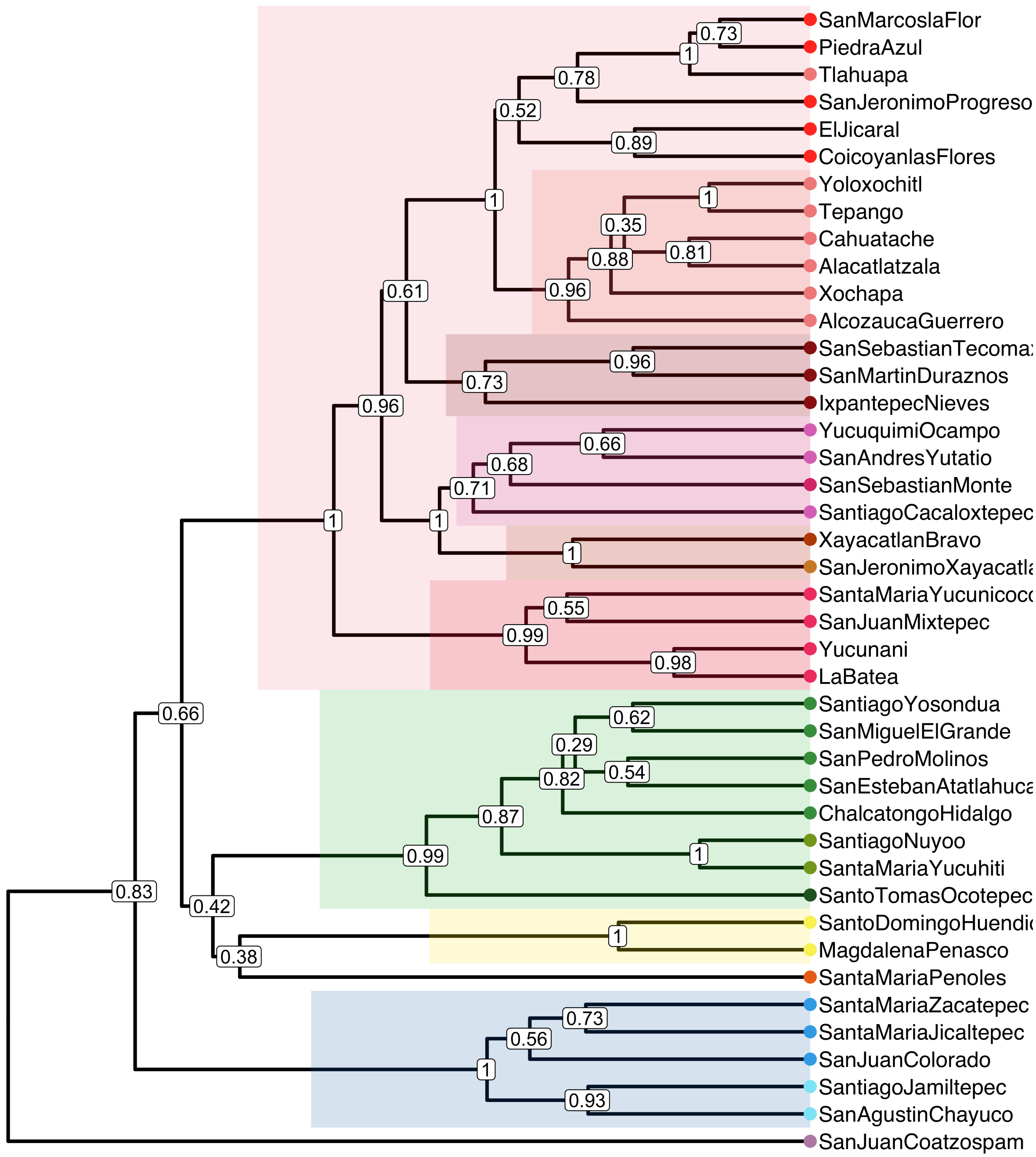

Figure 2: Maximum clade credibility tree of the sample colored by group (see map legend for details).

Table 3: Four example cognate sets across three Mixtec varieties and the reconstructed Proto-Mixtec form, with cognate IDs given in square brackets. A superscript L represents a reconstructed low tone (*low).

Mixtec variety	DISEASE [172]	TWO [811]	GRIDDLE [310]	TORTILLA [789]
Proto-Mixtec	*kʷ e^{L} ʔ j i^{L}	*u^{L} w i^{L}	*tʃ i^{L} j o^{L} ʔ	*s i^{L} t a^{L} ʔ
Santa María Peñoles	kʷ e^{5} ʔ e^{5}	u^{5} u^{5}	ʃ i^{5} o^{5}	ð i^{5} t a^{5}
San Esteban Atatlahuca	kʷ e^{3} ʔ j i^{1}	u^{3} u^{1}	x i^{3} ʒ o^{1}	s t a^{3} a^{1}
Xochapa	kʷ e^{1} ʔ e^{1}	u^{1} β i^{1}	ʃ i^{1} j o^{5}	ʃ i^{1} t a^{5}

2.1 Segmental correspondences and variables

In order to compare segmental and tonal change across the varieties of the data set, I identified segmental correspondences and derived segmental change variables based on the reconstructed proto-forms and the cognate sets. Segmental correspondences, changes, and reconstructions are better understood than tonal ones and have been studied in more detail (Bradley and Josserand, 1982; Josserand, 1983; Swanton, 2021). The database containing segmental proto-forms, cognate sets, and segmental change variables constitutes a subset of Auderset and Campbell (2024), where a more detailed explanation can be found.

I created multiple, interlinked databases following AUTOTYP principles such as modularity, autotypology, separation of definition and data files, and late aggregation (Witzlack-Makarevich et al., 2022). The AUTOTYP research project was developed to address problems that arose from the creation of more traditional typological databases. One of these issues is the use of fixed, a priori categories determined by theoretical considerations or simply traditional usage that often fail to capture a phenomenon across a large and diverse sample of languages. I adapted these principles and guidelines to ensure that the data set is expandable in the future, reusable for other research questions, and created in a bottom-up fashion that allows for maximal accuracy and transparency.

Based on the established cognates sets, I identified regular sound correspondences linked with a Proto-Mixtec reconstructed sound. From these correspondences, I derived binary segmental change variables and coded these variables for each variety of the sample. I illustrate the process and coding with a small example; in Table 3, I provide four cognate sets with Proto-Mixtec reconstructions and reflexes from three varieties. We can see changes in the final vowel of DISEASE and loss of the glide *j in the same set, as well as in GRIDDLE. Set TWO shows loss of the glide *w and a different set of final vowel changes. Finally, GRIDDLE and TORTILLA illustrate different reflexes of Proto-Mixtec fricatives and effects of palatalizations. Table 4 summarizes the sound changes and coding identified for the sample of three contemporary varieties. To make the coding maximally transparent and reproducible, changes are not ordered with respect to each other, but simply represent a correspondence of a proto-sound to a modern reflex. They are also all coded as applying to a single segment (instead of a syllable, for example) to ensure comparability.

Of the segmental change variables and coding established in this way, I took a subset of the data that includes only the 42 varieties used in this study. I excluded variables that have data for less than half of the varieties and those which show the same value across all languages of the sample (that is, they are either present or absent in all sampled languages, not taking into account

Table 4: Example segmental change variables derived from the cognate sets in Table 3 with their presence and absence coded for the three example varieties.

Mixtec variety	*j > ∅ / _i	*j > ∅/i_o	*j > ʒ / _o	*w > ∅ / _i	*tʃ > ʃ / _i
Santa María Peñoles	yes	yes	no	yes	yes
San Esteban Atatlahuca	no	no	yes	yes	no
Xochapa	yes	no	no	no	yes

	*i > e/j_	*i > u/w_	*i > ∅/s_t	*s > ʃ / _i	*s > ð
Santa María Peñoles	yes	yes	no	no	yes
San Esteban Atatlahuca	no	yes	yes	no	no
Xochapa	yes	no	no	yes	no

NA).[6] The latter is necessary because variables that have the same value across all languages do not contribute information about subgrouping, splits, and rates of change. This results in a total of 197 segmental change variables, of which 104 pertain to vowel correspondences and 93 to consonantal correspondences. The complete data set is provided in the supplementary materials (at "DefinitionFiles" and "VariableFiles") and a more detailed explanation of the coding method and process is provided in Auderset and Campbell (2024).

2.2 Establishing tone correspondences and deriving tonal change variables

There are many obstacles to comparing and reconstructing tones. First, there is often little reliable data, as it is still common in descriptive materials of tonal languages to either ignore tone completely or only note it in a few cases (Campbell, 2021; Beam de Azcona, 2007), such as when it is required for the disambiguation of segmentally identical forms. In materials that do mark tone consistently, the phonetic realization can be unclear due to variation in tone notation and analysis (see also above in Section 2). Descriptions of tone in Mixtec languages are often confined to a list of the inventory and how each identified tone is marked in the orthography. Only rarely are minimal pairs provided, and discussions of allotones or distribution of tones are even rarer, especially in older materials. Fortunately, this situation seems to be shifting, with some recent sources on Mixtec varieties providing rich discussions of tone (see McKendry, 2013; Mendoza Ruiz, 2016; Vázquez, 2017; Peters, 2018).

Furthermore, there is little cross-linguistic research to draw on. We simply do not know which tone changes are common or even possible. In this regard, we have not significantly progressed from the situation 50 years ago, summarized by Ballard (1969: 105, n. 10) as follows: "The two major obstacles to tone reconstruction to date have been a lack of knowledge of the phonetic

[6] The variables excluded due to low coverage are: A02, A03, A09, A10, A11, I09, I17, I19, J05, K01, K03, Q02, O06, U11, U12, U13, U27, U28, U33, W04, W14, W15, X07. The variables excluded because they were present in or absent from all sample languages are: A07, D10, E10, E21, I06, J03, K04, K05, K06, K07, O13, O17, O18, O19, O23, O28, Q04, S09, T04, U03, U29, W11, W16, X09, X10, X19, Y04.

nature of tones and a lack of experience in doing such reconstructions." The latter is certainly still true today. The former, I believe, does not constitute an obstacle to the reconstruction of tone per se. When comparing tones in a historical perspective, we need to make sure that what we compare and reconstruct is at the same level of abstraction—just as with segments. In the context of the current study, this means that we want to focus on contrasts (tonemes and phonemes) rather than the phonetic properties of the sounds in question. This focus on phonology, a quite abstract level, is necessary because phonetic studies on Mixtec languages are largely lacking and because it allows for better comparability between segmental and tonal changes. That proto-segments are also abstract to at least some degree is most obvious in cases like the laryngeals of Proto-Indo-European, numbered from one to three due to uncertainty regarding their articulatory and acoustic properties (Beekes, 1989). This is not to say that there are no proposals as to what phonemes the three laryngeals correspond to, but rather that this is a separate question which has not impeded reconstruction or the analysis of sound changes in this language family. An example from within Mixtec concerns the phonetic realization of the phoneme that Swanton (2021) reconstructed as Proto-Mixtec *tʃ. Earlier studies reconstructed a velar fricative *x (Longacre, 1957; Bradley and Josserand, 1982), or *h as the result of an unconditional lenition from *x (Mak and Longacre, 1960: 33). This is plausible as there are contemporary varieties which retain /x/, but either have an allophone [h] or the pronunciation is closer to [h] generally, as mentioned for example in Hollenbach (2013: 11) and Macaulay (1996: 20). However, Swanton (2021: 14) pointed out that the correspondence set (given by the author as ʃ:h:tʃ) is easier to explain and follows more natural changes if derived from Proto-Mixtec *tʃ. I follow this updated reconstruction, but it is possible that future work will lead to further changes regarding the reconstruction of this phoneme. Despite this open question, we can still establish the sound correspondences and reflexes of Proto-Mixtec *tʃ.

Before discussing the methodology of establishing tone change variables, I cover the basics of Mixtec tone systems and summarize two earlier studies of Mixtec tone reconstruction. The tone-bearing unit in Mixtec is the mora, which means that most lexical morphemes have two tones, due to their tendency to be bimoraic. These two tones can be level or contour tones, depending on the variety. In a historical perspective, there is a further distinction of "basic" vs. "modified" tone melodies already established in Longacre (1957). "Basic" tone melodies are reflexes that do not contain "modified" tones, which are interpreted as the result of tone sandhi processes. With respect to the basic sets, Dürr (1987: 23) pointed out that the glottal stop "seems to be restricted to tonemic couplets with identical tones." The modified sets are established based on the idea that tonal reflexes were not only affected by final glottal stops, but also by glottal stops or tones from preceding elements. For example, some modified tone melodies can be explained by analyzing forms as earlier but now reduced compounds whose initial stem—and its original tone and presence or absence of glottal stop—is identifiable or even attested in colonial era sources (e.g., DOOR from 'mouth of house', a widespread Mesoamerican calque; see Smith-Stark, 1994).

Dürr (1987) established tone correspondences across 17 Mixtec languages based on 110 cognate sets. He reconstructed two tones to Proto-Mixtec (*high and *low) from which the contemporary tone reflexes are derived. The loss of the final glottal stop in most varieties then led to a third tone, often realized as a floating tone or a high tone (see Pankratz and Pike, 1967), but in other varieties as a low tone (Campbell and Reyes Basurto, 2023). He focused on the reconstruction of the basic sets. These six sets arise from the combinations of reconstructed *low and *high tone and the interaction with final glottal stop, which is reconstructed only with melodies

Table 5: Overview of the six basic tone sets reconstructed by Dürr (1987) and the 10 modified tone sets reconstructed by Swanton and Mendoza Ruiz (2021: 338). Swanton and Mendoza Ruiz (2021: 337) use ʔ[1] and ʔ[2] to distinguish between two correspondence sets they assume came with a final glottal stop, but that result in different tone reflexes.

Basic		Modified	
1	*HH	7	*(ʔ^1)-HH
		8	*(ʔ^2)-HH
2	*HHʔ	9	*(ʔ)-HHʔ
3	*LL	10	*(ʔ)-LL (rare)
		11	*ʔ-LL (rare)
4	*LLʔ	12	*ʔ-LLʔ
5	*HL	13	*ʔ-HL
		14	*L-HL
		15	*(L)-HL
6	*LH	16	*Lʔ-LH

of the same tone: *high-high, *high-highʔ, *low-low, *low-lowʔ, *high-low, *low-high. These sets of basic tone melodies are said to be more regular than the modified ones (Dürr, 1987: 21). The tone reflexes of the 17 languages he analyzed fall into two groups with respect to the basic sets: area A, which covers the majority of languages, and area B, containing only Santa María Peñoles, San Juan Diuxi, Santa María Jicaltepec, and San Juan Coatzóspam Mixtec, with the latter showing divergent patterns altogether. Area A generally has a mid tone reflex for *high and a low tone reflex for *low, while area B exhibits low tone for *high and high tone for *low (see also the discussion in Daly and Hyman, 2007). The third (modified) tone is said to result in a high tone in area A, but has a lowering effect in area B (Dürr, 1987: 35). Dürr's (1987) study is explicitly preliminary and he pointed to several remaining issues that should be addressed with more data.

More recently, Swanton and Mendoza Ruiz (2021) take Dürr's (1987) reconstruction as the basis for investigating tones in Alcozauca Mixtec in a diachronic perspective. As opposed to most varieties included in the earlier study, Alcozauca Mixtec shows no tone alternations across word boundaries; in other words, there are no floating tones or tonal processes. The study also includes data from three other varieties: Santa María Zacatepec, Chalcatongo de Hidalgo, and Yucuquimi de Ocampo Mixtec. With respect to the "basic" sets, they confirm Dürr's (1987) correspondences and reconstructions. They are particularly interested in the "modified sets", which the previous study did not systematically address. They add 10 modified tone groups, in which the tone reflexes are influenced by the preceding constituent, or, in other words, which are the result of tone sandhi or the effects of final glottalization. I summarize all proposed tone reconstructions in Table 5.

One of the open questions concerns the two tone levels that should be reconstructed to Proto-Mixtec. Longacre (1957), who worked on Proto-Mixtecan including tone before Dürr (1987), reconstructed three tones (high, mid, and low), with *mid corresponding to Dürr's (1987) *high, *high to *modified, and *low to *low. The problem is best summarized with the help of Fig. 3: the reflexes are basically opposite in areas A and B, which means that whichever one chooses as the proto-form, one then has to explain the inversion in the other area. Unfortunately, we are not in a much better position to assess the issue today, since good tonal descriptions are still

Area A		Proto-Mixtec		Area B
MID		*high		LOW
LOW	←	*low	→	HIGH
HIGH		*ʔ# (modified)		lowering

Figure 3: Proto-Mixtec tones and reflexes in areas A and B (adapted from Dürr, 1987: 35, and Swanton and Mendoza Ruiz, 2021: 314).

largely lacking for varieties within Dürr's area B. I thus adopt Dürr's (1987) tone levels of high and low in my study. As mentioned above, the fact that these reconstructed Proto-Mixtec tones might not have been phonetically high and low does not preclude us from analyzing the tonal correspondences and deriving tone change variables, just as we do with segments.

Based on the cognate sets which were previously assigned a tonal reconstruction by Dürr (1987) and Swanton and Mendoza Ruiz (2021), I established tone correspondences across the 42 languages of the sample. I started with the basic sets, because there is ample data for each of those sets. The correspondences established in this way allowed me to identify other cognate sets belonging to the same tone group. I added seven cognates sets for *HH, seventeen for *HHʔ, eleven for *LL, twenty-one for *LLʔ, seven for *HL, and four for *LH, which in turn helped refine the correspondences. I then reviewed the new sets proposed by Swanton and Mendoza Ruiz (2021) in light of the data set used in this study. The tone groups I identified in the modified sets overlap but do not fully agree with those from Swanton and Mendoza Ruiz (2021). This is hardly surprising, given that their reconstructions are based on four languages, while this study takes into account 42 languages. I refrain from positing specific tones or glottal stop of preceding constituents that would have conditioned the modified sets. Doing so would be very speculative, given that we do not understand floating tones and tone sandhi phenomena in modern Mixtec languages on a comparative level, let alone the history of these phenomena (see Beam de Azcona, 2007, for a similar finding in a Zapotec subgroup). However, it is often still possible to posit which basic melody a modified set is based on (as seen in Swanton and Mendoza Ruiz, 2021). To still be able to distinguish between sets and environments (even if only on an abstract level), I labeled them with a capital letter and number combination, summarized in Table 6. It is possible that some of these groups could be collapsed in the future if more data becomes available and we are better able to identify irregular tone reflexes and inconsistencies in source materials. More research might also show that some of the modified sets are actually based on a different basic set than I propose here, but note that this would not impact the correspondences as such.

Based on the correspondences found in the cognate sets and the 18 tone melodies, I identified sound change variables in a bottom-up fashion. The process is much the same as with segmental sound changes. For each unique reflex of a given Proto-Mixtec tone in a tone group, which represents a change, I created a variable and coded the presence or absence of said change in each language of the sample. I illustrate this with a small example. Table 7 shows the reflexes of Proto-Mixtec *low tone in sets B1, B2, and B5 across four languages. Since I follow the reconstruction of tone values proposed in Dürr (1987), low tone reflexes are not coded as a change but viewed as a retention in these sets. In set B1, Yoloxóchitl and Ixpantepec Nieves thus show no change, while

Table 6: Schematic overview of reconstructed tone melodies with the labels used in this study. The preposed "?" represents a conditioning environment that cannot be currently further specified. H^A represents an adjectival high tone. Suggestions about possible reconstructions for those environments are given in the third column (where "TBD" indicates that this is yet to be determined; that is, based on the material available at this point and my current understanding of tone change, I cannot provide a suggestion for the lost conditioning environment). The final column shows the reconstruction of the melody by Swanton and Mendoza Ruiz (2021). Melodies in parentheses are not considered because of lack of data.

Label	Reconstruction	Possible environment	Swanton and Mendoza Ruiz (2021)
A1	*HH		*HH
A2	*HHʔ		*HHʔ
(A3)	*?-HH	TBD	—
A4	*H^A-HH(ʔ)	adjectival high tone	*ʔ²-HH
A5	*H^A-HH(ʔ)	adjectival high tone	*ʔ¹-HH
A6	*L-HH(ʔ)	low tone from classifier	—
A7	*?-HH(ʔ)	TBD	*ʔ-HHʔ
A8	*?-HHʔ	TBD	*HHʔ
B1	*LL		*LL
B2	*LLʔ		*LLʔ
(B3)	*?-LL	TBD	*ʔ-LL
(B4)	*?-LL	TBD	—
B5	*H^A-LLʔ	adjectival high tone	—
B6	*?-LLʔ	TBD	*ʔ-LLʔ
C1	*HL		*HL
C2	*?-HL	TBD	*HL
C3	*?-HL	TBD	*HL
C4	*H^A-HL	adjectival high tone	*ʔ-HL
C5	*L-HL	low tone	L-HL, Lʔ-HL
C6	*?-HL		—
D1	*LH		*LH

San Andrés Yutatío shows a change to mid tone in the first mora (Tone14) and Santa María Peñoles to high in both morae (Tone18 and Tone19). In set B2, most varieties show the same reflexes as in set B1, but in Yoloxóchitl there is a high tone in the second mora, conditioned by the final glottal stop (Tone20). In set B5, where more research is needed to clarify the conditioning environment before the low tone bimoraic morpheme, all varieties but Santa María Peñoles have a high tone in the first mora (Tone47), Santa María Peñoles and Ixpantepec Nieves also in the second mora (Tone48). Yoloxóchitl has a contour tone on the second mora in this set (Tone50), and Santa María Peñoles has a contour tone on the first mora (Tone49). Thus I identify seven tone change variables based on this example set, which are summarized with the coding for each variety in Table 8. I apply the same methodology to all 42 varieties across the 17 correspondence sets. This results in a total of 66 tone change variables, of which 27 pertain to "basic" tone sets and 39 to "modified" ones. The full database is available in the supplementary materials (at "DefinitionFiles" and “VariableFiles”).[7]

Table 7: Example tone correspondence sets.

Mixtec variety	B1 *L.L	B2 *L.Lʔ	B5 *ʔ.L.Lʔ
Santa María Peñoles	5.5	5.5	51.5
San Andrés Yutatío	3.1	3.1	5.1
Yoloxóchitl	1.1	1.5	5.15
Ixpantepec Nieves	1.1	1.1	5.5

Table 8: Example tone variables derived from the correspondences in Table 7.

VariableID	Proto-Mixtec	Reflex	Environment	Santa María Peñoles	San Andrés Yutatío	Yoloxóchitl
Tone14	*L	3	#_L#	no	yes	no
Tone19	*L	5	#_L#	yes	no	no
Tone18	*L	5	L_#	yes	no	yes
Tone20	*L	5	_ʔ#	yes	no	yes
Tone47	*L	5	(B5)#_	no	yes	yes
Tone48	*L	5	(B5)_#	yes	no	no
Tone49	*L	51	(B5)#_	yes	no	no
Tone50	*L	15	(B5)_#	no	no	yes

2.3 Overview of basic tone correspondences

Before describing the methods and results in more detail, I present a qualitative overview of tone correspondences found in the data set. With respect to the basic melodies, the correspondences in this data set align quite well with Dürr’s (1987) findings. Figure 4 summarizes the default reflexes of Proto-Mixtec *high and Fig. 5 of Proto-Mixtec *low. While the reflexes do not neatly fall into two groups for either of the Proto-Mixtec tones, the tendencies observed in Dürr (1987) are recovered in our sample. All varieties except Santa María Peñoles, San Juan Coatzóspam, Tepango, and Santa María Jicaltepec have a mid tone reflex for Proto-Mixtec *high, while the four mentioned varieties have a low tone reflex. These two sets of varieties largely mirror Dürr’s areas A vs. B. The varieties with a mid tone reflex are further divided into five smaller groups depending on the effect of the glottal stop or absence thereof. In a cluster of varieties in the southeastern part of the Mixteca region, commonly referred to as the Mixteca Alta, the final glottal stop has no effect. In the northern area, we predominantly find varieties in which the glottal stop has a lowering effect, resulting in a low tone reflex. In the southwestern area, the glottal stop has a raising effect, such that these varieties show a high tone reflex in that context. These two groups of varieties are somewhat intermeshed and neither geographically nor genealogically neatly separated. There are two smaller divisions in which we find reflexes with a rising contour

[7]The variables excluded due to low coverage are: Tone30, Tone31, Tone32, Tone33, Tone34, Tone35, Tone36, Tone37, Tone38, Tone42, Tone43.

tone before glottal stop, which could perhaps be seen as a subtype of the high tone reflexes. In Yucunani and La Batea Mixtec (Group 7.1), there is additionally a split between monosyllabic and bisyllabic reflexes before glottal stop: with the former, there is a high tone reflex, but with the latter there is a low-high contour reflex. Tepango Mixtec and Zacatepec Mixtec, the two varieties which retain the final glottal stop, do not fall into either of those groups.

A similar but not identical pattern is found with reflexes of Proto-Mixtec *low, see Fig. 5. Most varieties have a low tone reflex, but Santa María Jicaltepec, Santa María Peñoles, and San Juan Coatzóspam have a high tone reflex. There is also a set of varieties, mostly concentrated in the east, which seem to show a dissimilation, such that the reflex is mid in the first mora instead of the expected low. The glottal stop has largely the same effects on Proto-Mixtec *low as it did on Proto-Mixtec *high, except that we cannot see the lowering effect, since all of the varieties that would exhibit it have a low tone reflex anyway. The varieties which exhibit an effect of the final glottal stop are all in Group 7 (the "Baja" region of Josserand, 1983), while those that do not fall into Groups 1–6 (the "Alta" region of Josserand, 1983). The raising vs. lowering effect does not exactly separate varieties along lower-level subgroups, but there are definitely tendencies worth exploring further. In Group 7.1 (the Mixtepec area of Josserand, 1983) for example, all varieties show a raising effect, while all varieties in Linkage 7.2 and Groups 7.4–7.6 (the Central and Western Baja and Tezoatlán areas of Josserand, 1983) show a lowering effect. Group 7.3 (the Guerrero and Southern Baja area of Josserand, 1983) is split, with the majority of reflexes showing a raising effect, but a minority a lowering effect.

3 Methods

Phylogenetic signal and rates of change can only be calculated based on a tree or set of trees. I use the posterior distribution of trees from a previous Bayesian phylogenetic analysis of Mixtecan with BEAST2 (Bouckaert et al., 2019), which was based on annotated cognate sets from 110 varieties (for details, see Auderset et al., 2023a). I pruned the posterior distribution of trees to only contain the 42 languages for which I have adequate tonal data. From this, I took a sample of 1,000 trees (sampled with LogCombiner from BEAST2) for further analysis. The maximum clade credibility tree of the sample languages is presented in Fig. 2. This is the most up-to-date family tree available, as previous classifications of Mixtec relied on dialect areas based on isoglosses (Josserand, 1983). Given that the Mixtec languages are described as a dialect continuum, one could argue that geographic distance should largely reflect phylogenetic distance as well. However, the Mixtec peoples are also known for a long history of migration, for example to the coast and the far northeast of Oaxaca state (Josserand, 1983). Indeed, geographic distance does not correlate with phylogenetic distance as straightforwardly as one might expect. Figure 6 shows pairwise geographic distances plotted against phylogenetic distances. One can observe a general tendency for languages that are closely related to be geographically close and vice versa—most of the language pairs that are closely related to each other are less than 25 km apart. However, languages that are geographically further apart from each other (50 km or more) can also be closely or relatively closely related to each other.

I measure phylogenetic signal with the metric D for binary traits (Fritz and Purvis, 2010) calculated with the function *phylo.d* from the R package *caper* (Orme et al., 2018). This metric is based on the sum of sister-clade differences across a given tree. It provides a measure for the

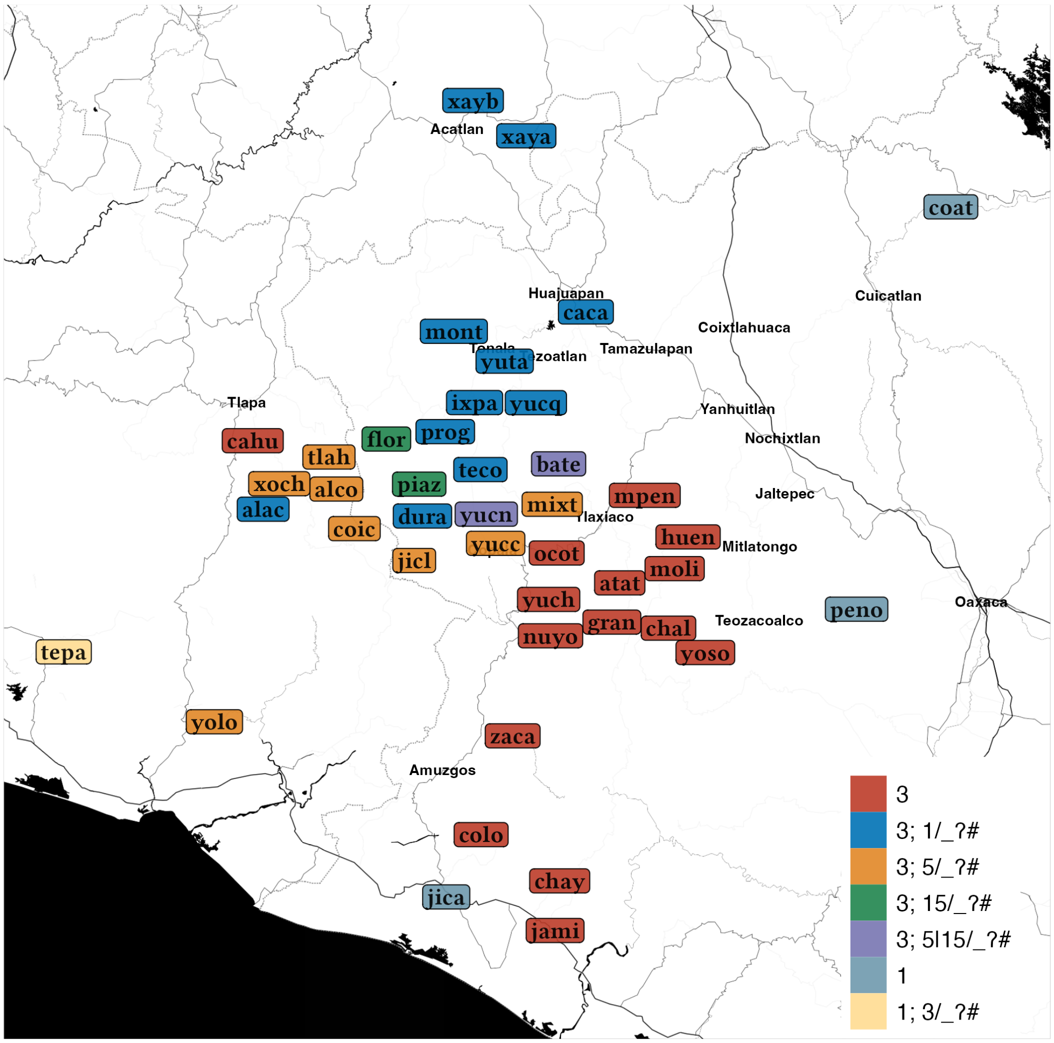

Figure 4: Reflexes of Proto-Mixtec *high in basic sets with conditioning environments (where applicable) in the standardized tone notation. The | separates reflexes in mono- vs. bisyllabic forms, for the varieties that exhibit such a split.

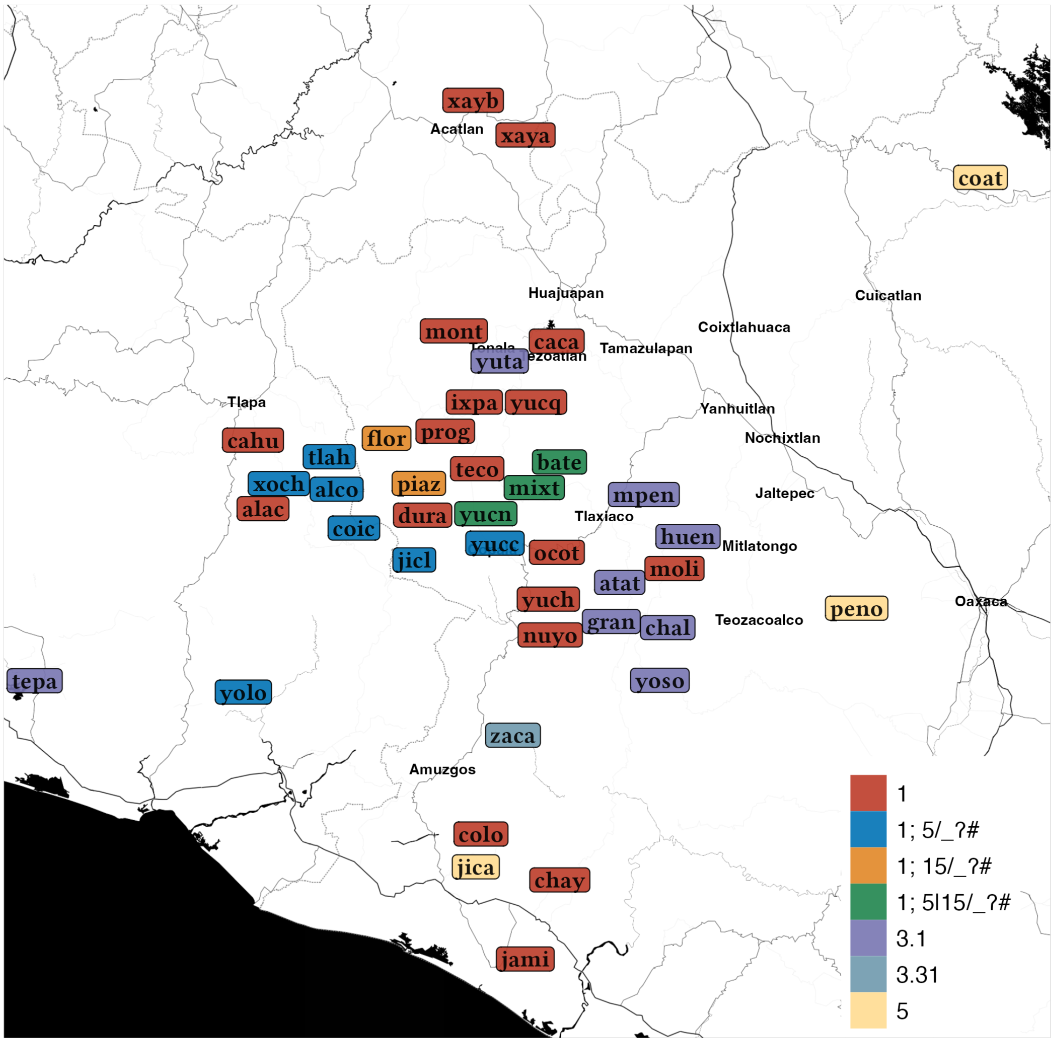

Figure 5: Reflexes of Proto-Mixtec *low in basic sets with conditioning environments (where applicable) in the standardized tone notation. The | separates reflexes in mono- vs. bisyllabic forms, for the varieties that exhibit such a split. The period is used to separate morae, where the reflex is given as the full tone melody.

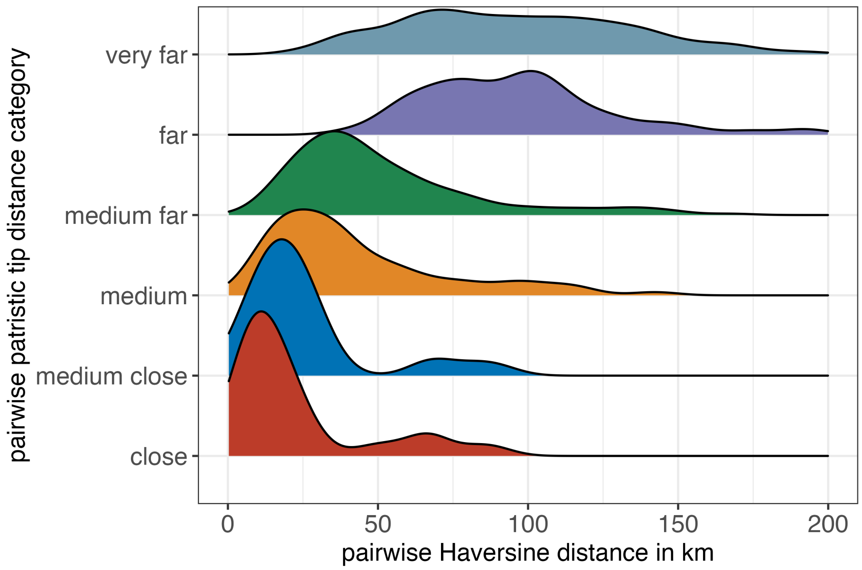

Figure 6: Density plot of geographic and phylogenetic distance between each language pair of the sample plotted against each other; distances over 200 km not shown because of very low density. Phylogenetic distance is measured as patristic tip distance based on the maximum clade credibility tree in Fig. 2 and then grouped into six categories (for exact distances, see supplementary materials at "Data and explanations/all_distances").

tendency of related species (sisters in the tree) to be more similar to each other than to other species sampled randomly from the tree (Fritz and Purvis, 2010; Münkemüller et al., 2012). This reflects the tendency of closely related languages to be more similar to each other with respect to a given variable than to more distantly related languages in a given language family tree. This metric has been widely used in ecology and biology, but has more recently also been successfully applied in historical linguistics (Macklin-Cordes et al., 2021; Hübler, 2022; Skirgård, 2024). A brief conceptual introduction to the D metric in linguistics can be found in the supplementary materials (at "Data and explanations/dmetric_rates"). I calculate the D metric for each sound change for each tree from the posterior sample and aggregate the results per variable. The metric is interpreted with respect to two anchor points: if a trait, here a sound change, is the same across sister languages, D will be around 0, indicating phylogenetic signal; if a trait has completely different values in sister languages, D will be around 1, indicating low phylogenetic signal (Fritz and Purvis, 2010: 1043–1044). Values between 0 and 1 or outside of this range are interpreted with respect to these anchor points.

I measure evolutionary rate with a hidden Markov model as implemented in the function *corHMM* from the R package *corHMM* (Beaulieu et al., 2021). This model estimates transition rates between the presence and absence of a sound correspondence across a tree from the posterior sample. There are two states (presence and absence) and two rate categories (fast and slow) and the model assigns equal probability to a feature for belonging to one of these categories. This means that there are eight possible transition rates, from each state-rate combination to all others. Those transition rates cannot be observed directly but only derived from the states, therefore the term "hidden" (Beaulieu et al., 2013: 726). I follow Maddison et al. (2007) and FitzJohn et al. (2009)

in the settings of the root prior. Transitions are observed at given points across the tree and each time there is a transition from presence to absence, this is referred to as "loss" and when there is a transition of absence to presence, this is referred to as "gain". Note that this usage differs from how these terms might be used in a traditional historical framework. In the latter, a sound change is always tied to a specific node in a tree (the reconstructed or attested sound in language A) and a tip (the reflex of the sound in language B), so that we could say it is "gained" from language A to B or it could be absent in language B, but not "lost" (see the supplementary materials at "Data and explanations/dmetric_rates" for a visual example). Since we do not expect the rates of gain and loss of sound changes to be the same, I used the ARD (all rates differ) setting, which allows them to vary. To assess the correlation—or absence thereof—of phylogenetic signal and evolutionary rate, I calculated the Kendall rank correlation coefficient (Kendall's tau) with the function *cor.test* in R (R Core Team, 2022).

4 Results

4.1 Phylogenetic signal in tonal and segmental changes

To analyze and interpret the phylogenetic signal of tone changes on the one hand and segmental changes on the other, I summarized *D* metric and standard deviation for each sound change variable across the 1,000 trees by taking the median. For ease of interpretation, I classified the median *D* metric values into four broader categories following Fritz and Purvis (2010), based on the anchor points mentioned above: a median *D* value higher than 1 is classified as overdispersed, values between 0.5 and 1 as random, values between 0 and 0.5 as showing Brownian motion (phylogenetic signal), and values under 0 as showing strong phylogenetic signal, also referred to as clumped. For more explanation on this categorization and a summary of Fritz and Purvis (2010), see the supplementary materials (at "Data and explanations/dmetric_rates"). Each sound change variable thus falls into one of these four categories based on their median *D* metric. Some of the variables exhibit a very large standard deviation. I set the threshold for a "high' standard deviation at half the range of phylogenetic signal at 12 (values range from -8 to 4, which means that a standard deviation of 6 or more would cover all attested values in most cases, which is not informative). A closer look at the variables with such high standard deviation reveals that most of them are absent in all but one language. While such a sound change is highly informative for the one language it appears in, it is not informative for the internal structure of the language family as a whole. I thus exclude all variables that have a very high standard deviation from further analysis. This affects 48 variables in total (20 pertain to consonants, 17 to vowels, and 11 to tones).[8]

Over three-quarters (77%) of the remaining 215 sound changes analyzed show phylogenetic signal and over half (58%) exhibit strong phylogenetic signal. This indicates that the sound changes identified (and the coding schema implemented) correlate well with the cognacy data underlying the phylogenetic trees. This might seem obvious, but given the characterization of the Mixtec language family as a dialect continuum which violates the standard assumptions of

[8]The excluded variables are: A08, A13, D05, D07, E13, E18, I16, J02, J07, J09, K02, O03, O14, O16, O24, O30, Q05, S04, S08, S12, T03, T06, T08, T16, T18, T21, U04, U06, U17, U23, U26, U37, U38, W03, W18, X02, X20; and Tone10, Tone13, Tone15, Tone22, Tone26, Tone58, Tone60, Tone62, Tone66, Tone69, Tone76.

the comparative method and should thus not be represented as a tree (Bradley and Josserand, 1982: 303) it is an important finding. It adds further support to the view that even if parts of the family are not tree-like, the comparative method applies just as in other families. In interpreting these results it is important to keep in mind the difficulties and lack of research with respect to tone change, as well as the lower number of changes in this category. This means that we expect more noise and less clear patterns in the tone change variables as a result of data interpretation issues—and not necessarily as evidence for their "irregularity" and "volatility". Conversely, with segments there is a lot of earlier research to draw on, such that both the interpretation of the source material and the changes as such is much more straightforward. Table 9 provides an overview of *D* metric categories by type of sound change variable. Consonants have the most variables with strong phylogenetic signal, closely followed by vowels. Tones do exhibit a lower percentage than segments (as expected), but the majority of tone change variables (61%) still show phylogenetic signal ("Brownian" + "clumped").

Table 9: Percentage of variables in each *D* metric category by sound change type, with absolute numbers given in parentheses. Variables with very high standard deviation have been excluded.

D category	Consonants		Vowels		Tones	
clumped ($D < 0$)	71%	(52)	61%	(53)	36%	(20)
Brownian ($D \sim 0$)	12%	(9)	20%	(17)	25%	(14)
random ($D \sim 1$)	5%	(4)	9%	(8)	24%	(13)
overdispersed ($D > 1$)	11%	(8)	10%	(9)	15%	(8)

The distribution of median *D* values across the three categories of sound change is illustrated in Fig. 7. The mean and standard deviations of the three categories are summarized in Table 10 and for each variable separately in the supplementary materials (at "Dmetric"). Tones have a higher mean and median than both consonants and vowels, but the lowest standard deviation; see Table 10. Taking into account the standard deviations, the three sets of sound changes are not significantly different from each other, or, in other words, they all overlap. This is reflected in the density distributions as well, which also show that all three categories have a small number of variables with very high phylogenetic signal (< -2). Both vowels and consonants also have a small number of highly overdispersed variables, which we do not find in tones. All of these overviews and summary statistics reflect relatively small differences between tones and segments with respect to phylogenetic signal. It is certainly not the case that tone change variables overall are distributed randomly across varieties and carry no phylogenetic signal. If anything, consonants seem to behave differently from vowels and tones, showing a stronger phylogenetic signal overall.

Of course, the variables within each of these aggregated categories do not behave uniformly. I thus explore consonantal, vowel, and tonal variables in more detail below. Figure 8 shows the distribution of *D* in consonant variables split according to the manner of articulation.[9] This is of interest because the glides *j and *w undergo many changes and are often lost (Bradley and Josserand, 1982) and could thus be expected to show less phylogenetic signal than plosives

[9]Nasal and glottal stop variables are excluded because they are so few in number that they cannot be displayed on this plot.

Table 10: Mean, median, and standard deviation of D per sound change category. Variables with very high standard deviation have been excluded.

Type	Mean	Median	SD
Consonants	-0.35	-0.36	0.91
Vowels	-0.16	-0.17	1.17
Tones	0.24	0.39	0.74

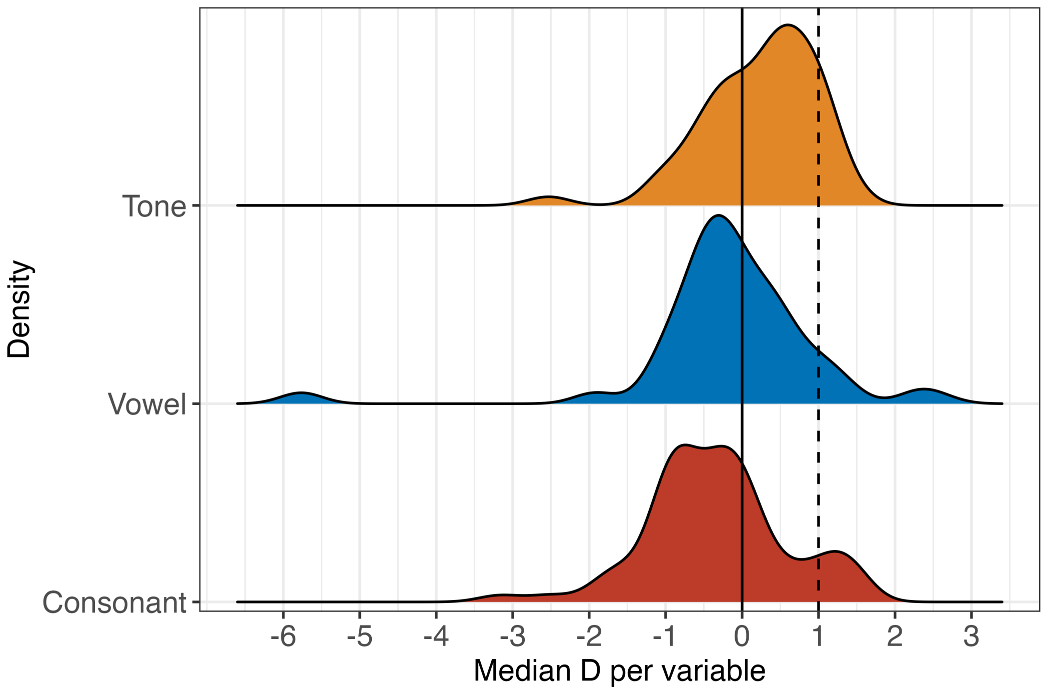

Figure 7: Density distribution of median D per sound change variable, split by type with anchor points at 0 (line) and 1 (dashed line).

or fricatives. They also constitute the conditioning environment for many other sound changes (Auderset and Campbell, 2024). Glides are not substantially different from fricatives and plosives, although their peak density is slightly higher than that of the other two categories. Glides have the highest density just under 0 (median $D = -0.24$, SD $= 0.26$), followed by plosives (median $D = -0.64$, SD $= 0.36$) and then fricatives (median $D = -0.68$, SD $= 0.27$), but the differences are small. Overall, the distribution of plosive variables is different from both fricatives and glides in that it is more spread out, indicating that plosive changes behave somewhat less uniformly than glide and fricative changes.

Mixtec vowels are often divided into two groups: the weak or "inner triangle" vowels *e, ɨ, o* and the strong or "outer triangle" vowels *a, i, u*. The triangle terminology is based on the common representation of the vowel space as a triangle or trapezoid. The strong vs. weak labels are based on the impression that weak vowels undergo more changes than strong vowels and on the observation that they are less frequent in contemporary varieties (Josserand, 1983: 245–250). Figure 9 shows the distribution of median D in vowels split into these two categories. The outer

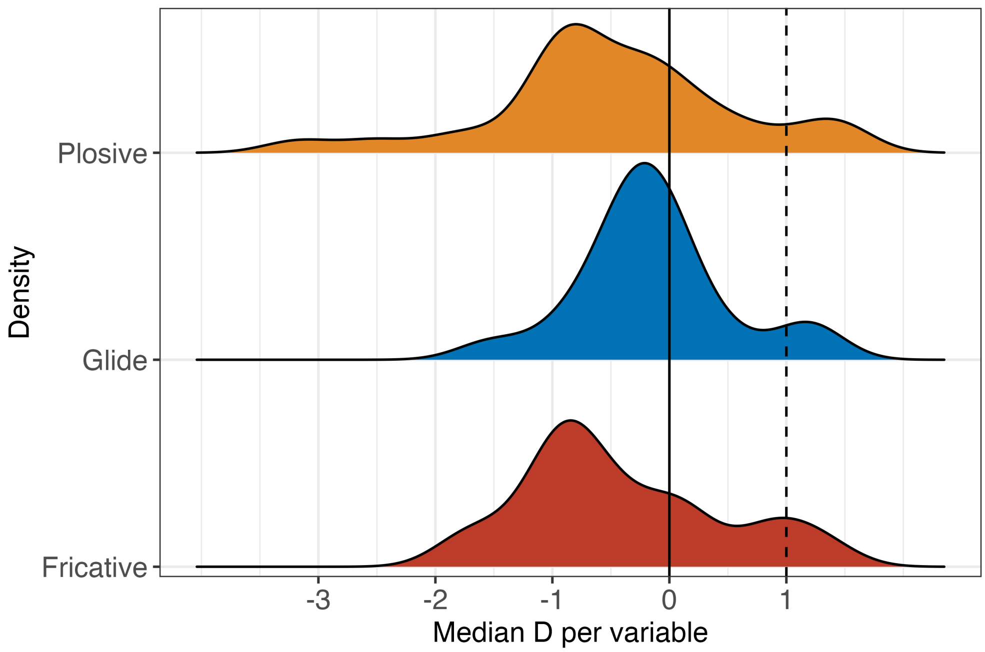

Figure 8: Density distribution of median D per consonant variable, split by type with anchor points at 0 (line) and 1 (dashed line).

Table 11: Vowel, consonant, and tone changes with very high phylogenetic signal (D < -2), with median and standard deviation, and a description of the change and where it applies.

Variable	Median D	SD of D	Description	Applies in
D04	-2.52	0.50	*^{n}d > n /_{a,ɨ,o,u}	Group 6.2.1
T13	-3.17	0.73	*t > s /_ɨ	Group 7.4
E03	-5.78	5.12	*e > i /_(ʔ)ji	all but Group 1 (Coatzóspam)
E01	-5.75	5.52	*e > a /j_{ni, tĩ}	Group 1 (Coatzóspam)
Tone73	-2.53	0.73	*H > M /(C5)_L	Santa María Zacatepec and Santa María Jicaltepec (Grou

vowels have a peak slightly closer to zero (median $D = -0.02$, SD = 0.66) and more overdispersed variables than the inner vowels (median $D = -0.32$, SD = 0.75). All variables with very high phylogenetic signal are found in the inner triangle vowels. To sum up, there are more outer vowel variables that show no phylogenetic signal than inner vowel variables. This suggests that the changes of the inner triangle vowels mostly fall along the lines of subgroups. There are two vowel variables that show very strong phylogenetic signal with a D value under -2, both of which concern Proto-Mixtec *e, an inner triangle vowel. These two vowel changes with the lowest D single out the Group 1 variety San Juan Coatzóspam, either by only being present in that group or present in all other groups (see Table 11). This group, also referred to as Northeastern Alta (Josserand, 1983), is widely believed to have migrated to this region early on, and thus it makes sense that it underwent changes that the other varieties did not and conversely, that the other varieties underwent changes after Group 1 varieties had already left.

As explained in Section 2.2, tone melodies in Mixtec are usually classified into two groups,

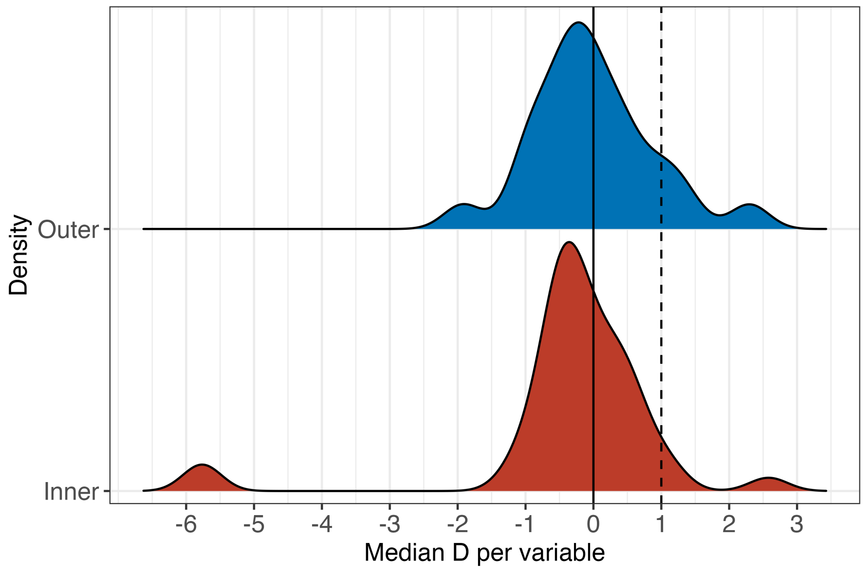

Figure 9: Density distribution of median D per vowel variable, split by type with anchor points at 0 (line) and 1 (dashed line).

"basic" and "modified" (Longacre, 1957). To recap, modified means that the tone melody contains a tone restricted to tone sandhi environments and is said to have an unpredictable reflex, while basic tone melodies contain only reflexes of the Proto-Mixtec *high and *low tone with or without final glottal stop. Figure 10 shows the distribution of D values in basic and modified tone sets. Both basic tones (median $D = 0.12$, SD = 0.38) and modified tones (median $D = 0.31$, SD = 0.33) have the peak just above zero. Only modified tones have a few variables with very strong phylogenetic signal, but basic tones have overall more changes with phylogenetic signal, as can be seen in Fig. 10. While there are small differences between these two sets of tones, in terms of diachronic change, "modified" tones operate much the same as basic tones.

I also investigated potential differences between reconstructed Proto-Mixtec tones *high and *low. The phylogenetic signal is a bit weaker with Proto-Mixtec *low (median $D = 0.30$, SD = 0.36) than *high (median $D = 0.17$, SD = 0.34), but again the difference is minor. There is one tone variable that shows very strong phylogenetic signal ($D < -2$); see Fig. 11 and Table 11. This change, from reconstructed high tone to a mid tone in set C5, is found only in Santa María Zacatepec and Santa María Jicaltepec. These two varieties are found on the coast and are part of Group 2.2, together with San Juan Colorado. They are however more closely related to each other than either is to San Juan Colorado Mixtec (see Fig. 2), so most likely the high phylogenetic signal is reflecting that separation.

Figure 11 reveals interesting differences with respect to the tone melodies. In A melodies, where the basic set is reconstructed as *HH(ʔ), most tone change variables show phylogenetic signal—some even quite strong phylogenetic signal—and this is true for changes in modified as well as basic sets. Conversely, melodies B (basic set reconstructed as *LL(ʔ)) and C (basic set reconstructed as *HL) both have more variables with weak phylogenetic signal or none at all. With the data available as of now and the lack of detailed phonetic studies, I cannot explain the discrepancy between the tonal changes in these sets. However, these questions open avenues for

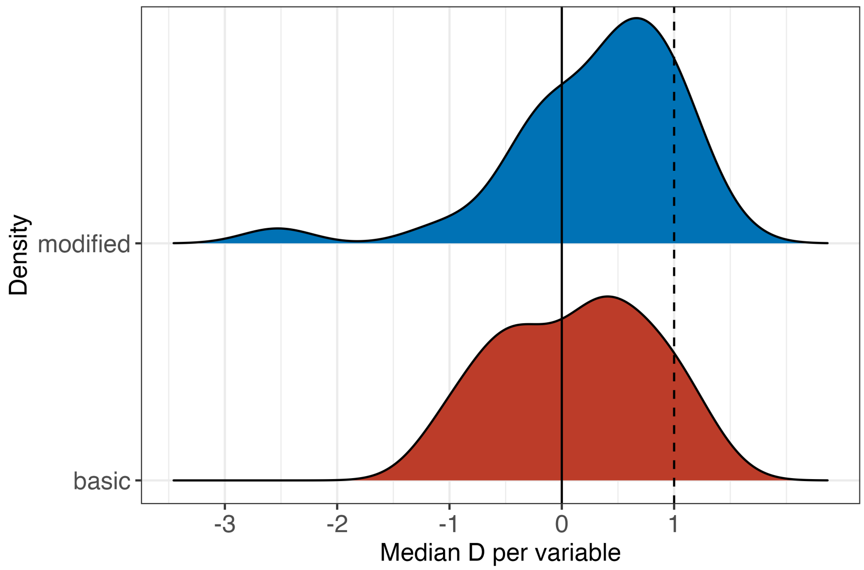

Figure 10: Density distribution of median D per tone variable, split by type with anchor points at 0 (line) and 1 (dashed line).

further research, which should investigate the diachrony of each of those changes in more detail.

4.2 Rates of gain and loss in tonal and segmental changes

I calculated the rate of gain and loss for each sound change variable across the 1,000 trees with a hidden Markov model (see Section 3). The resulting rates cannot be interpreted in absolute terms, but only relative to each other, because the phylogenetic trees cannot be anchored in real time due to the absence of good calibration points. I log-transformed the rates for better visualization and easier interpretation. I excluded variables that show a high standard deviation in both the rate of loss and gain. I set the threshold for this at 0 (for the log-transformed SD), since no variables show a non-negative log-transformed rate. This excludes eight variables in total: one vowel variable, and seven tone variables.[10] Figure 12 summarizes the results split into consonant, vowel, and tone variables on rates of gain and loss. (Histograms of the raw, unaggregated values can be found in the supplementary materials at "Scripts/analysis".) Values that are close to zero indicate a fast rate of change (raw value just below 1) and values close to -10 a very slow rate of change (raw value approaching 0). In all three categories—consonants, vowels, and tones—the rate of gain is overall slower than the rate of loss, but the difference is not large. Furthermore, the median rates of gain and loss across the three categories are similar and tones do not stand out against consonants and vowels in this respect either. In all three groups, there are some variables with rates around -10, which means that they do not change at all, or that they change extremely slowly. The majority of variables in all three groups appear around the median rate value. This means that variables are overall gained and lost at relatively similar rates. Vowels have a few variables which are lost quite fast (rate > -1), but in tones and consonants we do not find such a fast rate of loss to the same extent. Consonants also have a small number of variables that are

[10]Excluded variables: I13, Tone06, Tone16, Tone45, Tone47, Tone59, Tone61, Tone64.

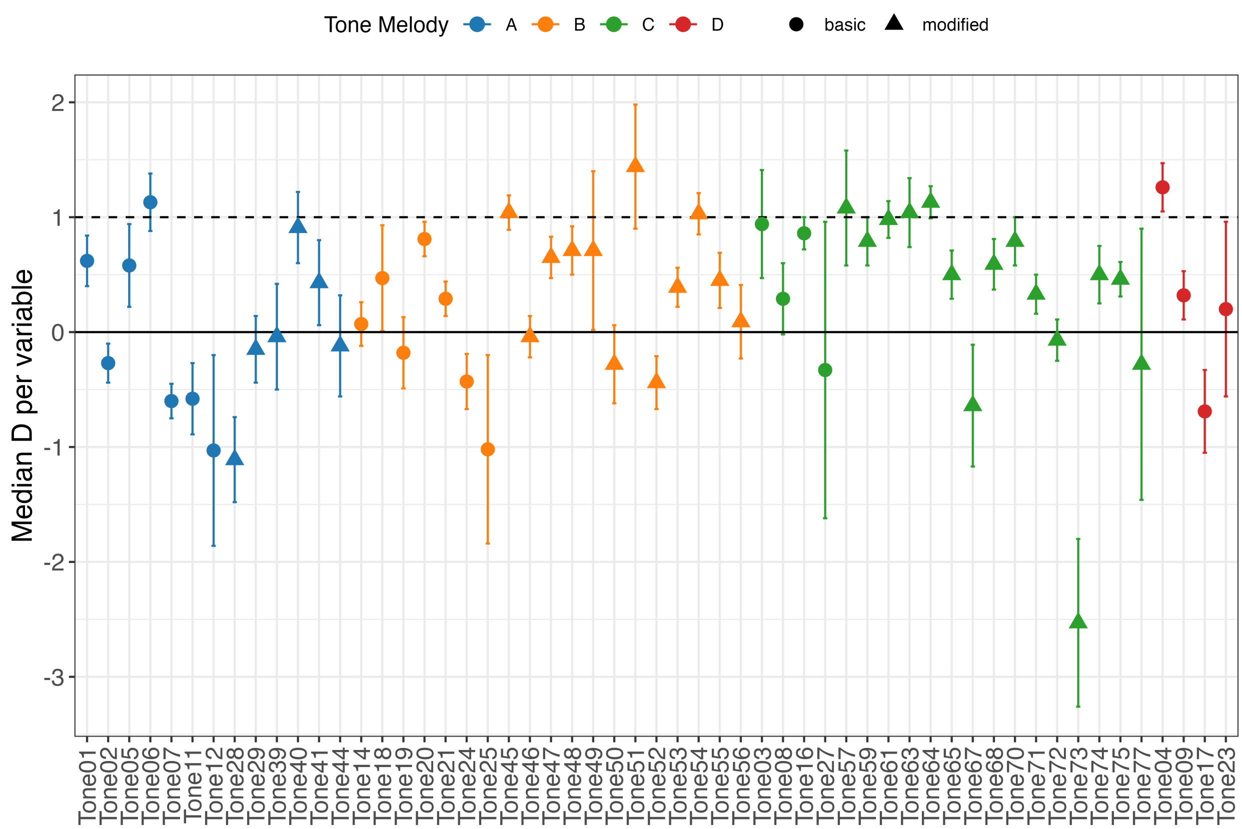

Figure 11: Median *D* per tone variables with anchor points at 0 (line) and 1 (dashed line). Colors represent tone melody and shapes basic vs. modified tones.

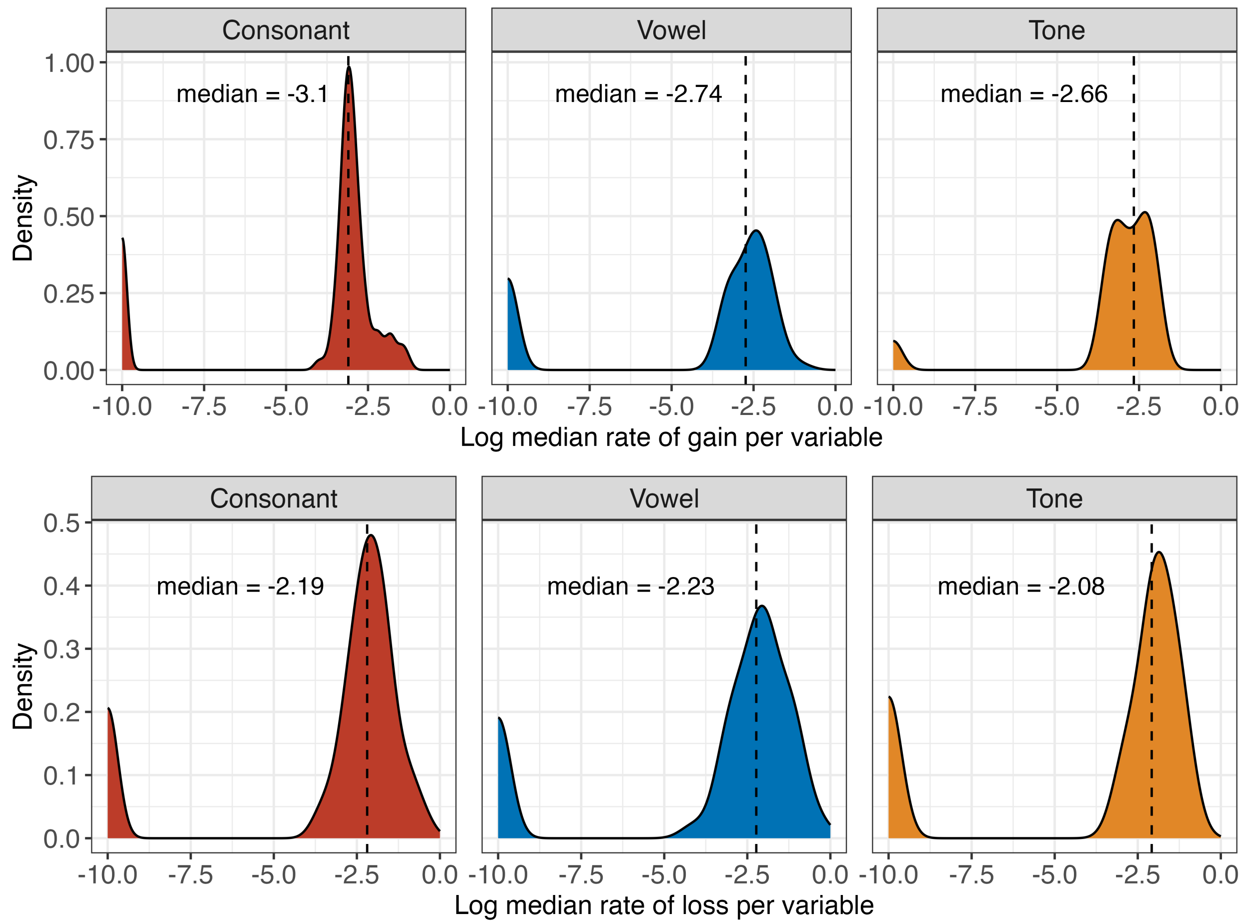

Figure 12: Median rates of gain and loss per variable aggregated by variable with the all rates differ (ARD) model. Dashed lines indicates group medians.

gained fast, a pattern absent in vowels and tones.

There is a tendency to equate low phylogenetic signal with a high rate of change and conversely high phylogenetic signal with a low rate of change (Revell et al., 2008). Framed in linguistic terms, structural variables that are very stable are often assumed to be good candidates for establishing relationships between languages or language families (Nichols, 2003; Dediu and Levinson, 2012). However, the relationship between these two processes is more complex than that and they are not usually correlated in biology (Revell et al., 2008).

To assess whether there is a correlation between phylogenetic signal (*D*) and rates of gain and loss in sound changes, I computed the Kendall rank correlation coefficient for these two measures. The results are summarized in Table 12. There is a moderately strong positive correlation between phylogenetic signal and the rate of both gain and loss of sound changes. However, consonants, vowels, and tones behave quite differently with respect to this correlation. Consonants exhibit a stronger correlation of the rate of gain than loss. The opposite is true of vowels, which show a quite strong correlation of the rate of loss with phylogenetic signal, but a weaker one with the rate of gain. Tones not only exhibit the overall strongest correlation, it is also almost the same for rate of loss and gain.

The overall correlation is not as strong as the one found in Hübler (2022) with structural variables in five Eurasian language families ($\tau = 0.51$ for loss and $\tau = 0.50$ for gain), but it is interesting that it occurs in a completely different language family based on sound change variables. As mentioned above, in biology this correlation between phylogenetic signal and rates of change is not generally found. It is possible, and this should be investigated further, that the correlation between phylogenetic signal and rates of change is perhaps a characteristic of linguistic evolution that sets it apart from biological evolution. In fact, if it could be shown that a slow rate of change and strong phylogenetic signal correlate cross-linguistically and across different components of language, this would make a strong case for further investigating deep relationships beyond the comparative method.

Table 12: Correlations between phylogenetic signal and rates of gain and loss (Kendall's tau).

Category	Loss		Gain	
	τ	p	τ	p
Overall	0.42	<0.01	0.44	<0.01
Consonants	0.30	<0.01	0.52	<0.01
Vowels	0.45	<0.01	0.28	<0.01
Tones	0.55	<0.01	0.54	<0.01

Intuitively, we also expect that variables which are present in almost all languages would have a high rate of gain and a low rate of loss, and conversely, variables that are absent in almost all languages would have a low rate of gain and a high rate of loss. Figure 13 plots the rate of loss and gain against phylogenetic signal indicating the number of languages in which each variable is present across the data set with color. We do see that the variables with the highest rates of gain are present in the majority of languages, while those lost at the highest rates are absent in most languages. The variables present in almost all languages do indeed generally exhibit a relatively low rate of loss and a high rate of gain. Since many variables are absent in the majority of languages of the sample, this distribution is less clear. However, the plot also reveals that the relationship between presence or absence of a variable and its rate of change is not a simple linear correlation. To explore this relationship further, I calculated Kendall's tau for the presence of each variable with phylogenetic signal, rate of loss, and rate of gain. There is a moderately strong correlation with the rate of gain ($\tau = -0.34$, $p < 0.01$), a moderate correlation with the rate of loss ($\tau = -0.18$, $p < 0.01$), but no correlation with phylogenetic signal ($\tau = 0.02$, $p < 0.01$). We can explain the latter in terms of mechanisms of sound change more broadly. Both sound changes that are very frequent and those that are very rare within a family could be innovations of closely related varieties or subgroups and thus help resolve the family tree. This is what is reflected in the absence of correlation of presence of a variable with phylogenetic signal.

Since this study is primarily concerned with comparing rates of change in tones vs. segments, Fig. 14 shows the same rates against phylogenetic signal plot, but this time colored by type of sound change. Based on the recurring statements in the literature that tones change faster than segments (see Section 1 for references), I expected to find faster rates of gain and loss for tones than for vowels and consonants. This is not borne out by the data, as variables of all three types are spread out over slow and fast rates of gain and loss.

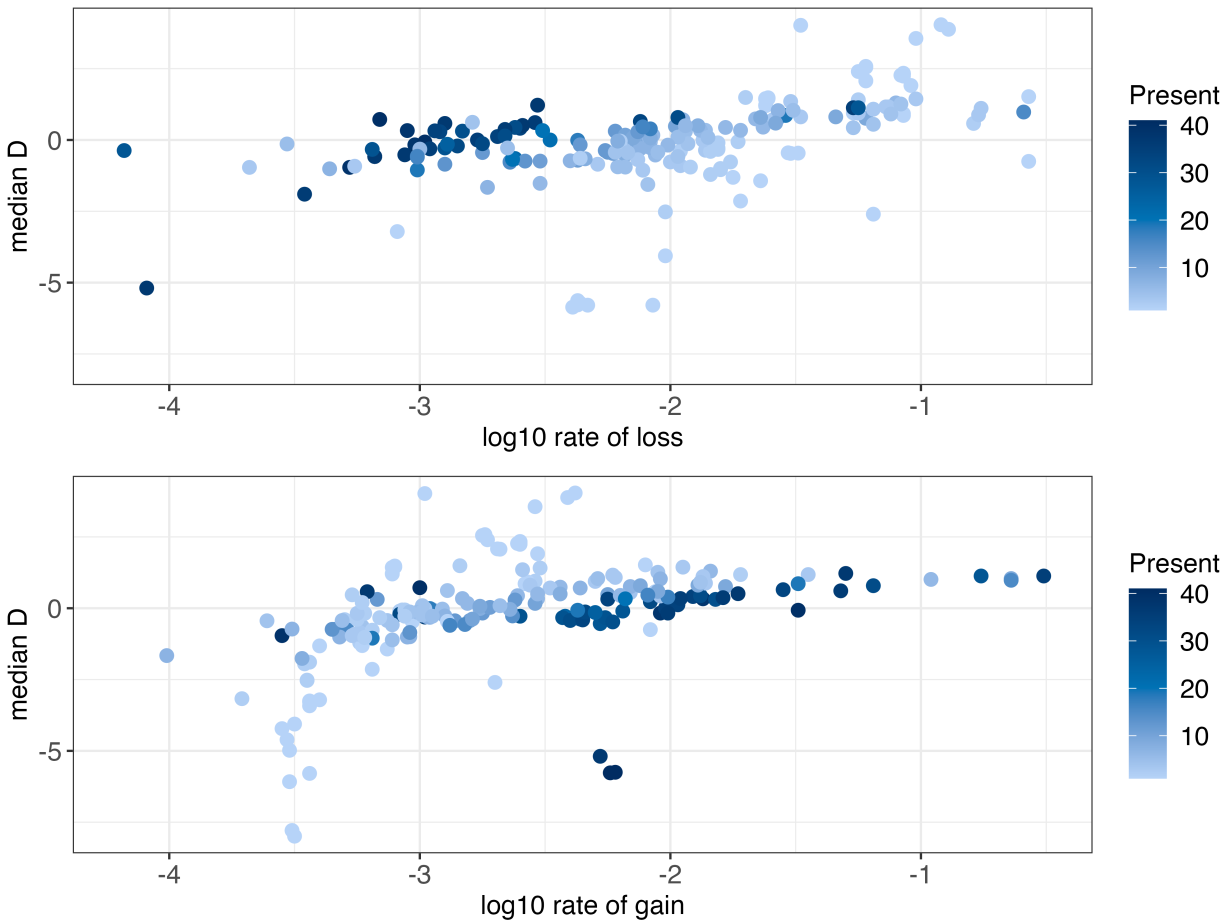

Figure 13: Rate of loss and gain (log10) against D, colored by the number of languages in which a variable is present.

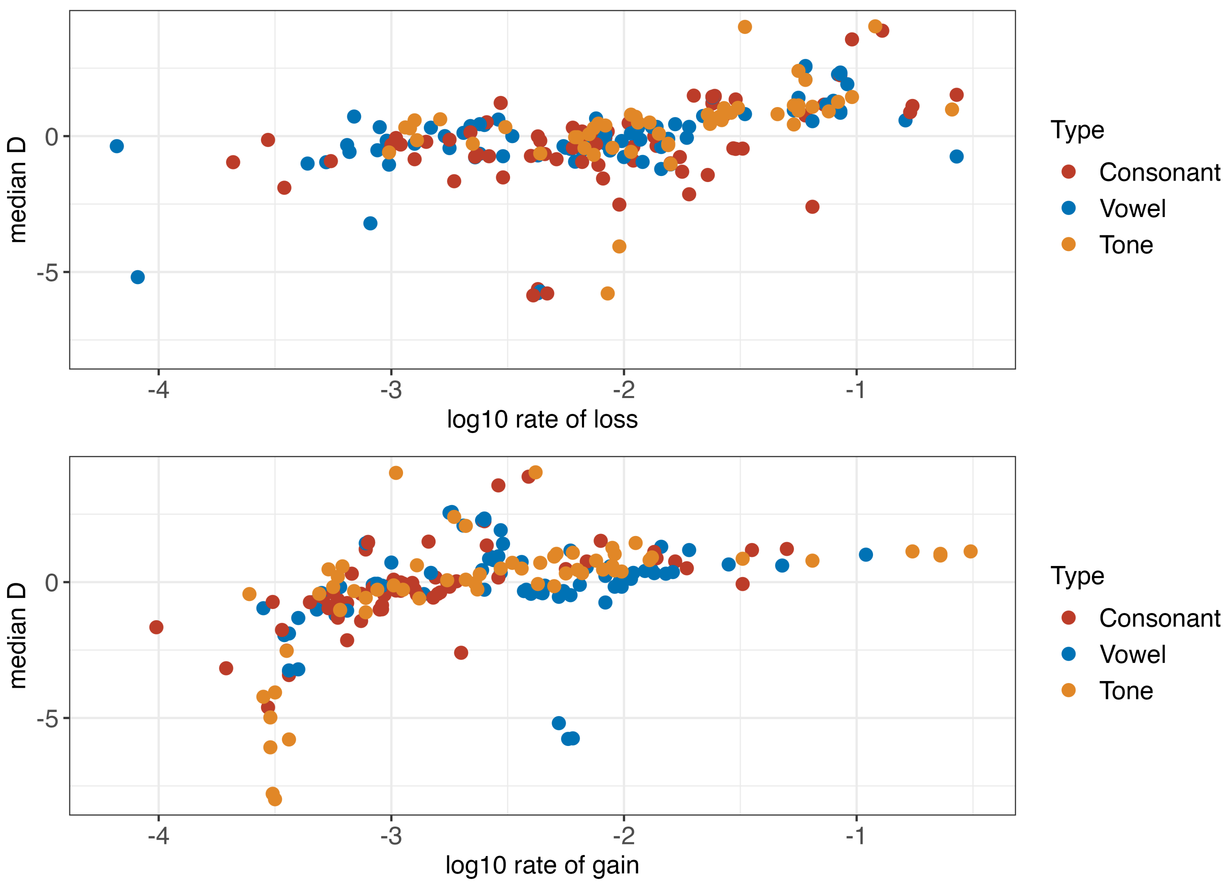

Figure 14: Rate of loss and gain (log10) against *D*, colored by type of variable. Languages that show no change are excluded from the plot.

5 Discussion

In the previous Sections, I explored phylogenetic signal and rates of change in tone across 42 Mixtec languages. Based on the metrics calculated, tones do not generally change faster than segments, nor do they show less phylogenetic signal in this language family. I found a moderately strong positive correlation between phylogenetic signal and rates of loss and gain. This means that as the rate increases, D also increases. As a higher D means less phylogenetic signal, this indicates that sound changes which proceed more slowly in general have stronger phylogenetic signal than those that proceed at a faster rate. This is true of both tones and segments, although the correlation is stronger in the former. The relationship between the presence of a sound change across the sample languages with phylogenetic signal is, as expected, more complex, such that both changes which are frequent and those which are rare can contribute to subgrouping.

There are certain limitations to the study that invite follow-up research of similar scope in the future. First, due to lack of good descriptions of tone systems, the sample of Mixtec varieties is somewhat limited and does not cover all previously identified subgroups to the same extent and excludes one subgroup (Linkage 5) completely. With two groups (Groups 1 and 4), I was only able to sample one variety each and thus we cannot know how representative these varieties are of their respective subgroups. The same applies within the large Group 7, where the sample does not cover all subgroups to the same extent. Second, the reconstruction of tone and the identification of tone changes similarly suffers from this lack of coverage. While I believe that the reconstruction proposed by Dürr (1987) and confirmed by Swanton and Mendoza Ruiz (2021) and the data used in this study is in broad strokes correct, the "modified" sets are still in need of revision, especially with respect to the potential environments that conditioned them. Third, the sound changes were identified and coded based on the same word list that served as the basis for the cognate sets used to construct the phylogenetic trees. The reason for this is predominantly a practical one, since no other comparative Mixtec data on such a large scale is available and assembling such a data set is an undertaking of considerable time and effort, outside the scope of the present study. However, this does not invalidate the results of the study nor is this reuse of data fundamentally different from traditional applications of the comparative method. Sound changes are regular and should operate the same across the lexicon, since we assume that the relationship between form and meaning is (largely) arbitrary (Rankin, 2003: 184). There are parts of the lexicon in which this assumption is violated, for example where we find sound symbolism or other forms of iconicity. However, such forms are excluded when creating cognate sets, precisely because they often display various irregularities. This means that the sound changes identified based on the cognates sets used for the phylogeny should be identical to those we would find based on a different, non-overlapping set of cognates. In practice, they constitute a subset of all sound changes that took place in Mixtec and future studies might identify additional changes or lead to modifications of existing ones. But this is not a consequence of the non-independence from the earlier data set, but rather of the practical necessity of working with a subset of the lexicon. Furthermore, traditional approaches also use overlapping or even identical data sets for establishing subgroups and for identifying sound changes (see, e.g., Usher and Schapper, 2022; Robertson, 1977, among others). If this circularity is an issue, then this applies equally with respect to the comparative method as traditionally applied and the current study.

6 Conclusion

Historical comparative linguistics is an important tool for furthering our understanding of the past, not least because it provides a resolution and granularity that is often not possible to achieve in archaeology and genetics (Kaufman, 1990: 14–15). Tone is an integral feature of Mixtec languages, as well as of many other languages of Mesoamerica and beyond. Despite its prevalence, tone has received limited attention in historical linguistics, with respect to both traditional and quantitative methods. As a consequence, our knowledge of tone change processes, as opposed to those of segmental change, is still limited. This study presents a first step towards filling this lacuna by making some of the assumptions with respect to tone change explicit and testing them with quantitative methods based on a carefully curated data set. As I have shown, tone change in Mixtec does not behave differently from segmental change in any significant way. Many tone changes carry phylogenetic signal and can thus contribute to our understanding of the internal structure of this language family just like segmental changes. Tones also do not change faster or slower than segments overall, exhibiting similar transition rates as segments. These two measures suggest that tone change operates in much the same way as segmental change and should be investigated on a par with segmental change. Even though this study is limited to one language family, the methodology presented here can easily be expanded to other language families, and it is indeed my hope that it will inspire follow-up studies to close the tone gap in historical linguistics in the near future.

Supplementary materials

The data sets underlying this study as well as all scripts used to analyze and visualize the data and results are available on OSF at: `https://osf.io/9sfmq/`. This repository contains the language sample with metadata, annotated cognate sets, and sound change variables and coding files. There is also a detailed document explaining the tone standardization in each language of the sample and one giving more conceptual background on the *D* metric and the rates model. The scripts used to compute phylogenetic signal and evolutionary rate are provided, as is the script used to generate the visualizations and analyses presented in the paper.

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