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Research Article

Minerality in Wine: Textual Analysis of Chablis Premier Cru Tasting Notes

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The term minerality is often used to describe high-quality still white wines produced in cooler regions, such as Chablis. What minerality means in sensory terms and what is responsible for its presence is the subject of debate, however. This study explored the concept of minerality by analysing 16,542 Chablis Premier Cru tasting notes entered into CellarTracker between 2003 and 2022 on wines three to seven years old, together with weather, topography, and soil data for the Chablis area. The top three words used to describe Chablis Premier Cru wine were citrus, minerality, and acidity. Mentions of minerality declined between 1999 and 2019 vintages, whereas those of acidity, salinity, floral, orchard fruit, and stone fruit increased. The trends for minerality and salinity were slightly stronger with the year of tasting (2005 to 2022) than vintage. Bigram analysis indicated that consumers were more than 1.5 times as likely to refer to a stony kind of minerality as a saline one and only rarely smoky minerality. Use of the term minerality was correlated with growing season temperature and sunshine hours (negatively with each), as well as vineyard aspect (negatively with percentage vineyard area facing South or South-West), but not with Kimmeridgian soil type. The results imply that soils and geology are not a principal source of minerality in Chablis wine, but growing season warmth and sunshine are relevant to minerality. There is no simple explanation of minerality in Chablis wine; however, the recent decline in the use of this term for Chablis wine may be a consequence of three factors in combination: (i) it has become less fashionable; (ii) consumers are choosing "saline" instead of "mineral" when appropriate, but retaining it for "stony" sensations; and/or (iii) warming from climate change has reduced minerality.

1. Introduction

"Minerality" is a wine descriptor that was reportedly first mentioned in the French wine lexicon (as "minéralité") in 1988 [1] and which gained popularity among wine professionals and consumers from around 2000 [2]. It has been the centre of considerable debate by sensory researchers [3] and wine market participants who question what it is, what causes it, and whether it is a discrete wine characteristic. It is typically used as a sensory descriptor for still dry white wine from cool climate viticulture regions [4] and has been variously profiled as gunflint, wet stones, and/or seashells (amongst many descriptors), possibly with three or more subdimensions [5–7], although it remains unclear whether it is perceived as an aroma, taste, mouthfeel, or combination of these [3, 5, 7]. Wines with perceived minerality may also be said to be "mineral" or "minerally."

Producers, merchants, and critics regularly refer to minerality as a defining high-quality characteristic of wine [3, 5] and make connections between its presence and the "terroir" of the region or vineyard in which the wine is produced [8–10]. The suggestion is that the inorganic components of an area's geology and soil can be sensed in its wine by virtue of a wine's "minerality," although this literal understanding of the term has since been disputed in the academic literature [2, 3, 11]. Even so, the term still continues to be used in this way by many winemakers, merchants, and consumers [12, 13]. Some go further by describing, for example, a "gravelly" or "chalky" minerality in accordance with the geology of the wine region [6].

The counterargument to this is that minerality is used metaphorically; no one is tasting rock minerals in wine (as opposed to elemental minerals such as sodium), but there are characteristics of a wine that remind consumers of certain sensations [13]. Unlike most other descriptors, however, no compound, or combination of compounds, has been unequivocally associated with minerality, in a way that rotundone and isoamyl acetate, for example, have been associated with "peppery" [14] and "banana" [15, 16] characteristics, respectively.

Minerality in wine is often associated with acidity [5, 6, 17], although whether this is because cool climate wines tend to be both distinctly acidic and mineral, or whether minerality and acidity are different ways of describing a similar sensation, or whether the acidity is a subdimension of minerality [17], is unclear. Of the several types of acidity present in wine, succinic acid is said to be intense, salty, and bitter [6] and could potentially be responsible for minerality [3, 8]. Minor acids, such as octanoic acid, have also been associated with minerality [18]. The other major acids, however, are perhaps less likely to be confused with minerality—tartaric ("hard"), malic ("green"), citric ("fresh"), lactic ("lightly acid, tart, and sour"), and acetic ("vinegary") [6]. Wine notes, however, rarely distinguish between different types of acidity.

Some have suggested that minerality is perceived in wine when there is a lack of fruit and floral aromas and flavours [5, 6, 19], though this possibly excludes citrus fruit characteristics which are often associated with minerality [3]. Anecdotally this makes some sense, as Chardonnay wines from warmer climates tend towards the stone and tropical fruit aromas and flavours, and less mineral [3].

Rodrigues et al. [17] found that some producers think minerality can be masked by winemaking practices. These include oak barrel fermentation and ageing (particularly with new oak), contact with sediment (lees; primarily dead yeast cells) through ageing on lees or batonnage (stirring lees into wine), and/or malolactic fermentation (a process that converts the harsh malic acid to the softer lactic acid). In other words, the strong aromas, flavours, and/or textures associated with these vinification practices could mask the expression of minerality in wine (though some respondents in Rodrigues et al.'s study thought that lees contact kept the wine in a moderately reduced state and thus was good for minerality).

One hypothesis gaining more traction is that minerality comes from reductive wine-making and storage processes that produce or maintain sulphurous compounds, but not enough to spoil the wine with off flavours [4, 20, 21]. For example, insufficient yeast assimilable nitrogen (YAN) in wine must can lead to the production of more permanent sulphur compounds (such as methionol) as opposed to the highly volatile forms (such as hydrogen sulphide, ethanethiol, and methanethiol) that have low boiling points and volatilise when a bottle of wine is aerated [20]. Insufficient YAN can also result in the production of hydrogen sulphide at a later stage of fermentation when it is less likely to be purged [22]. The increased use of stainless steel vats for fermentation and increased use of synthetic cork and screw cap bottle closure systems in cool climate wine regions, which reduce oxygen permeability into the wine compared to the use of oak barrels and traditional cork closure systems respectively, are also consistent with the simultaneous rise of minerality since around 2000 [3].

Certain sulphurous compounds may produce reductive off-aromas or more desirable minerality-related traits depending on their concentration levels and what other compounds they are present with. It may be that hydrogen disulfane, for example, a polysulfane which generally produces eggy and sewage-like aromas, produces instead a flint-like aroma when smelt in isolation [4]. Similarly, other sulphur compounds can contribute to aromas that have been associated with minerality, such as methaniol for shellfish-related aromas [19] and benzyl mercaptan [23] and benzenemethanethiol [24] for "empyreumatic" (smoky) characteristics.

A major difficulty is that agreement has not been reached on what minerality is in terms of its sensory profile [25] or, equally problematic, that the sensations referenced are too numerous. Minerality remains an ill-defined concept [5, 21]. Nonetheless, most wine professionals and consumers maintain it is a real and distinct sensation, for example, Szymanski [13].

Chablis is a wine known for its mineral flavours [5, 13, 26] and is thus an excellent test case for the concept of minerality [17, 19, 27]. Chablis typicity is said to come from its unique terroir. The natural terroir features that are most often used to explain the typicity of Chablis wines are (i) its weather, primarily a function of its relatively northerly latitude (for Chardonnay) and semicontinental position [26]; (ii) its Kimmeridgian geology and associated soils [28]; and (iii) its topography and associated microclimate [29].

This paper uses text analyses to explore Chablis Premier Cru tasting notes in CellarTracker, a crowd-sourced database of wine-tasting notes. It looks at how "minerality" has been used as a wine descriptor since CellarTracker was created in 2003 and whether there are any trends in its usage since that time. The paper goes on to explore associations between minerality and other wine characteristics, such as acidity. Finally, an attempt is made to relate minerality to vintage weather, topography, and soil type. The overall aim is to understand whether any existing theories for the source of minerality are borne out by wine notes in the CellarTracker database. This includes testing the following hypotheses:

(1) Minerality is associated with the following flavours, aromas, and/or textures: acidity (positive) [5]; shellfish (positive) [19]; reduction (positive) [4–6, 21]; fruit and floral (negative) [19]; oak (negative) [17]

(2) Minerality is not associated with geology and soils [2]

(3) Minerality is positively associated with cooler vintage weather [4]

(4) Minerality is more positively associated with South-East and Eastern facing slopes than South and South-West slopes [19]

(5) Chablis wines from the left side of the river Serein exhibit higher levels of minerality than those from the right side [19]

We also consider whether textual analysis of CellarTracker notes can be used to increase understanding of minerality. Substantial research combining sensory panels with chemical analyses of wines has investigated the concept of minerality, which led to some of the hypotheses for minerality discussed above (including Ballester et al. [5]; Baroň and Fiala [8]; Heymann et al. [6]; Zaldívar Santamaría et al. [25]). Malfeito-Ferreira [3], however, states that consumers' perception of minerality has been relatively little studied. The examination here of a large body of wine-tasting notes from consumers aims to redress that balance and confirm, or not, if some of the explanations provided previously are consistent with Chablis Premier Cru wine, probably the most famous mineral wine.

2. Materials and Methods

2.1. Study Area. The Chablis wine region is located in the department of Yonne, in the northern part of Burgundy, France (Figure 1). The vineyards are within a relatively compact area (approximately 16 km (North-South) by 18 km (East-West) centred around the town of Chablis (latitude 47°48′49″N, longitude 3°47′54″E, 140 metres above sea level). The topography is hilly, rising to around 320 metres, and the vineyards lie on both sides of the river Serein which runs broadly North-South through the area. Chablis wines are produced from Chardonnay grapes only and are divided into four appellation d'origine contrôlée (AOC). In decreasing order of quality recognition, these are Chablis Grand Cru, Chablis Premier Cru, Chablis, and Petit Chablis. The Grand Cru and Premier Cru appellations are divided into 7 and 40 vineyard areas, respectively, called "Climats" (Figure 1). The 40 Premier Cru Climats are grouped into 17 larger principal Climats (Supplementary Table S1).

For the purposes of this study, only Chablis Premier Cru wine was analysed. Chablis Premier Cru is widely regarded as the AOC that produces the most typical Chablis wine [32]. Moreover, Chablis Premier Cru vineyards are planted on both sides of the river Serein and provide the opportunity to test the effect of topography on minerality [19, 30]. By contrast, Grand Cru Chablis vineyards are located in a much smaller area concentrated on the eastern side of the river ("right bank"), close to the town, with a predominantly South-West aspect (Figure 1). They produce less than one-eighth the amount of wine as the Chablis Premier Cru AOC [32], resulting in considerably fewer tasting notes. Chablis and Petit Chablis AOC wines rarely state which vineyards their grapes come from and were therefore unsuitable for this study.

2.2. Tasting Notes. Wine tasting notes for Chablis Premier Cru wines were extracted from CellarTracker (https://www.cellartracker.com), an online crowd-sourced database of tasting reviews that was created in 2003 and publicly launched in 2004 [33]. Of the 29,999 Chablis Premier Cru tasting notes entered into CellarTracker on 31 August 2022, 27,672 notes were written in English and selected for analysis.

The mean age of Chablis Premier Cru wine tasted by its contributors increased from 4.3 yrs in 2003 to 7.3 yrs in 2022 (Supplementary Figure S1, red line). This trend was controlled for by limiting the wine notes analysed to wines between 3 and 7 years in age (Supplementary Figure S1, black line). This is also the peak drinking window for Chablis Premier Cru wine [32]. A larger drinking window of between 3 and 10 years, which some commentators may argue is more appropriate [34], would still have left an upward trend in the data (Supplementary Figure S1, blue line). There were a total of 16,542 English-language tasting notes within the 3- to 7-year age range.

The 16,542 tasting notes were then grouped and analysed by (i) vintage year (1999–2019), (ii) tasting year (2005–2022, i.e. excluding earlier years with insufficient tasting notes), and (iii) principal Climat (14 Climats, i.e., 17 minus three with insufficient tasting notes—Berdiot, Chaume de Talvat and Côte de Vaubarousse) (Supplementary Figure S2).

Though the tasting notes related to vintages as far back as 1995, over 99.7% of them were for vintages from 1999 to 2019. Supplementary Table S2 and Figure S3 provide further details on the database, including the numbers of distinct tasters, distinct wines, tasting notes per vintage, tasting notes per age of wine when tasted, and tasting notes per principal Climat.

Most contributors to CellarTracker are amateurs, from different backgrounds, with different levels of tasting experience. They are also mostly from North America and northern Europe [30]. These factors may have a cultural influence on how the wines are reviewed [35, 36] and how minerality is perceived [7, 9]. Nonetheless, CellarTracker is the largest consumer-submitted database of wine ratings in the world [37] and the closest thing available to a market judgement for wines, especially for wines that do not have a traded secondary market. It offers a large sample size of tasting notes from enthusiastic wine consumers who wrote their notes unprompted by academic study. The data are, therefore, free from response biases [38] and can be usefully employed for identifying associations and testing hypotheses about the sensory profile of minerality in wine and its causes.

2.3. Text Analyses, Indices, and Statistics

2.3.1. Organising Tasting Note Words into Wine Descriptor Groups. Tasting notes were tokenized into separate words according to the method described by Silge and Robinson [39]. The words were then organised into groups that were appropriate for describing white wine (Supplementary Figure S4), based on a survey of online and academic sources (e.g., Ballester et al. [5]; BIVB [40, 41]; Iobbi et al. [42]; Miquel [43]; Espinase Nandorfy et al. [21]; Seal [44]; Wine Folly [45]). Derivatives and common misspellings of each

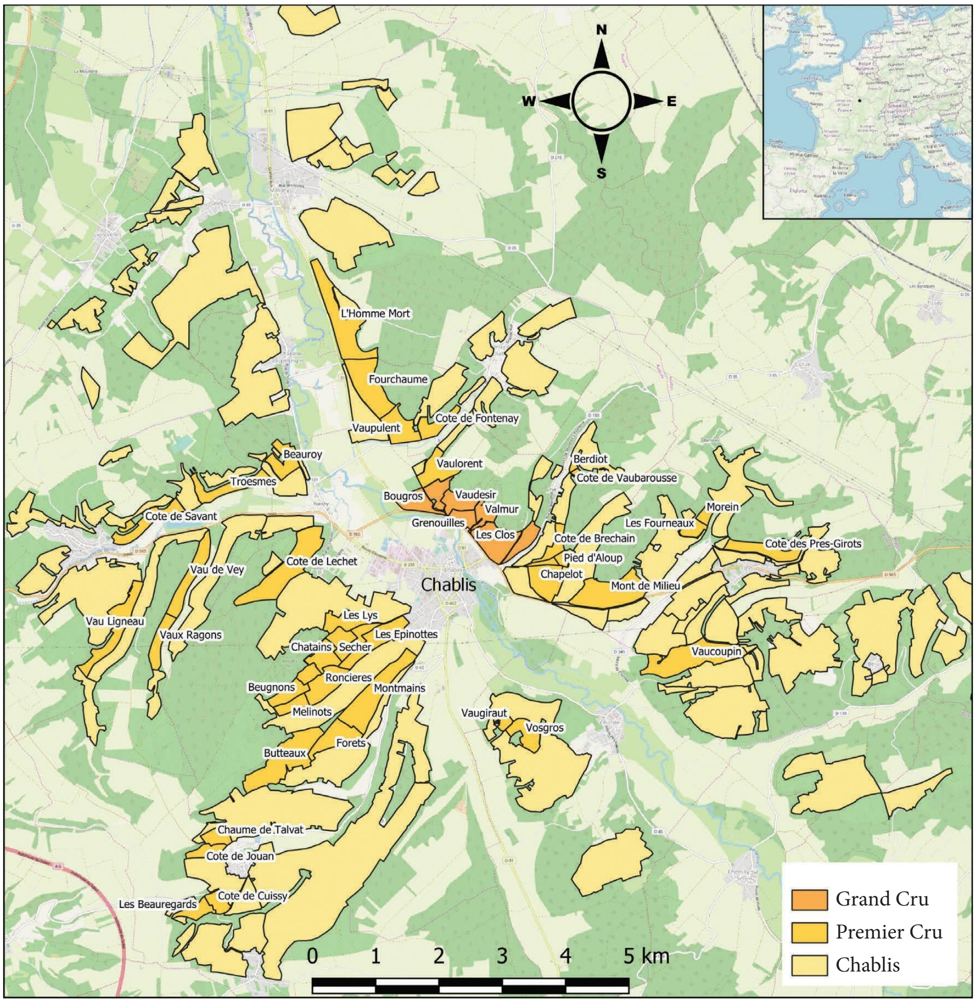


Figure 1: Map of study area showing the location of vineyards for the three main appellation d'origine contrôlée (AOC) of Chablis: Chablis Grand Cru (dark orange), Chablis Premier Cru (orange), and Chablis (yellow) (also referred to as "Village Chablis") from Biss [30] and Bureau Interprofessionnel des Vins de Bourgogne (BIVB) [31].

component word were included; for example, "lemon", "lemony", and "lemoney" were all allocated to the citrus word group (see Supplementary Table S3 for a detailed breakdown of each group).

Some words required clarification using a bigram (two consecutive words) before they could be allocated to the correct group. For example, the word "stone" may refer to a large pebble or if followed directly by the word "fruit" would instead refer to aromas and flavours of apricot, nectarine, or peach.

In a similar vein to Ballester et al. [5] three subdimensions, the official website for marketing Chablis wine says there are three categories to describe minerality: "ocean," "land," and "smoke" [40]. Their ocean category includes salty aromas and flavours such as iodine, "ocean spray," "fresh oyster," and "inside of a shell"; their smoke category includes terms such as sulphur and "freshly struck match"; and their land category includes chalk, limestone, flint, wet stone, and "rain on warm ground" (perhaps alluding to the aromas of petrichor). These categories were used for bigram analysis of the word "minerality" in order to investigate if a word before a mineral word specified what kind of minerality the taster was referring to, such as chalky minerality. Interestingly, BIVB's land category includes gunpowder and gunflint, which we instead included in the smoke category based on an understanding of its sensory perception in the literature [4, 21, 24]. This reclassification, however, had a negligible impact on the results (Supplementary Figure S5).

No distinction was made between aroma (nose), flavour (palate), and texture (mouthfeel) given the inconsistency with which CellarTracker users noted these distinctions. Some issues were difficult to automate and require manual oversight. For example, the word "oysters" could be referring to the oyster shell flavours of a wine or a food pairing.

2.3.2. Negations. Each word belonging to a descriptive group was checked for a negation word up to four words before and four words after it. For example, "none of the Chablis minerality I expect" would be identified because of the words "none" and "minerality" in positions 1 and 5, respectively. These lists were produced in R but checked manually, and a score of 0, −0.5, or −1 was ascribed dependent on whether the negation was invalid (e.g., "no lemon but minerality is there"), partial (e.g., "not quite the minerality of 2002"), or total (e.g., "none of that classic minerality"), respectively.

2.3.3. Creating the Indices. An index value was calculated for each descriptive group (for each vintage, tasting year and Climat) by applying the following rules:

(i) An occurrence comprised at least one mention of the characteristic. Repeated mentions within the same wine note of any words within the descriptive group were only counted once. For example, "Excellent wine. Lemon and lime aromas, good salinity and minerality." would register +1 for each of the citrus, saline, and minerality word groups.

(ii) An occurrence was deducted or halved depending on whether the characteristic was said to be negated/missing/very low (deducted in full) or low/less than it should be/less than expected (halved) (see above).

(iii) For the dataset sorted by tasting year, there were no deductions, however. This dataset was used to discover whether some descriptive terms had become more or less fashionable, in which case it did not matter whether a contributor was using the term to indicate the presence or not of an aroma, flavour, or texture.

(iv) The number of occurrences for each descriptive group (less negation) was summed by (i) vintage, (ii) tasting year, and (iii) Climat and expressed as a proportion of the total number of tasting notes in that vintage, tasting year, or Climat. This gave an index number from 0 to 1, where 0.5 was equivalent to 50% of tasting notes.

2.4. Soils. Soil data were taken from Biss [30]. The Chablis vineyards are distributed over eight cartographic soil units [Unités Cartographique de Sol (UCS)]. Each comprises between three and ten different soil types (Unites Typologique de Sols). The unit of most importance to this study is UCS n_30 (UCS30). It is associated with the Kimmeridgian slopes which are considered a key characteristic of the Chablis terroir and so relevant to these wines' mineral character [32, 41]. The proportion of UCS30 soil in the principal Premier Cru Climats varied from 0 to 100 [30].

2.5. Topography. Topographic data for the principal Chablis Premier Cru Climats were taken from Biss [30]. This comprised the following variables: aspect, slope gradient, elevation, and relative elevation. Relative elevation, the magnitude of one cell's elevation in relation to the cells around it, was calculated according to Goings [46].

2.6. Chablis Vintage Weather. Weather data for the Chablis region were obtained from the French meteorological service, Météo-France, using the procedures outlined by Biss and Ellis [47]. Climate indices typically used for viticulture were then derived. These included mean growing season temperature (GST) [48]; the cool night index (CNI), which in the Northern Hemisphere is the mean minimum temperature for September [49]; and precipitation during veraison and/or ripening [50–52]. Most weather data were from the Chablis weather station (number 89068001, latitude 47°49′19″N, longitude 3°47′26″E, elevation 141 m just outside the town of Chablis). The exception was sunshine data, which was merged from two weather stations in Auxerre, about 19 km west of Chablis: Auxerre (latitude 47°48′05″N, longitude 3°32′43″E, elevation 207 m, and Auxerre–Perrigny (latitude 47°49′28″N, longitude 3°32′58″E, elevation 152 m).

2.7. Statistics and Tools. We used R/R Studio (version 1.3.1093) for textual analyses (using the tidytext package), statistical analyses and data visualisation, and ArcGIS 10.4.1 (ArcGIS) (Esri, Woodlands, CA, USA) for mapping and spatial analysis. The Bonferroni correction was applied for multiple correlations where stated. This correction method is conservative [53]; i.e., it is good for screening out false positives and controlling the family-wise error rate [54] but can result in a high rate of false negatives. Spearman's rank was preferred to Pearson correlation throughout the study as some variables under investigation failed normality tests.

3. Results

3.1. Trends in Minerality and Other Wine Characteristics

3.1.1. By Vintage. The top three word groups used to describe the flavours and aromas of Chablis Premier Cru wine were citrus, minerality, and acidity (Table 1). While these word groups dominated wine-tasting notes for vintages from 1999 to 2019 (Table 1), orchard fruit aromas and flavours more than doubled in mentions over this period of vintages are from 0.12 to 0.31 (Figure 2, Table 1). Acidity, stone fruit, and floral notes also trended upward significantly (Figure 2, Table 1).

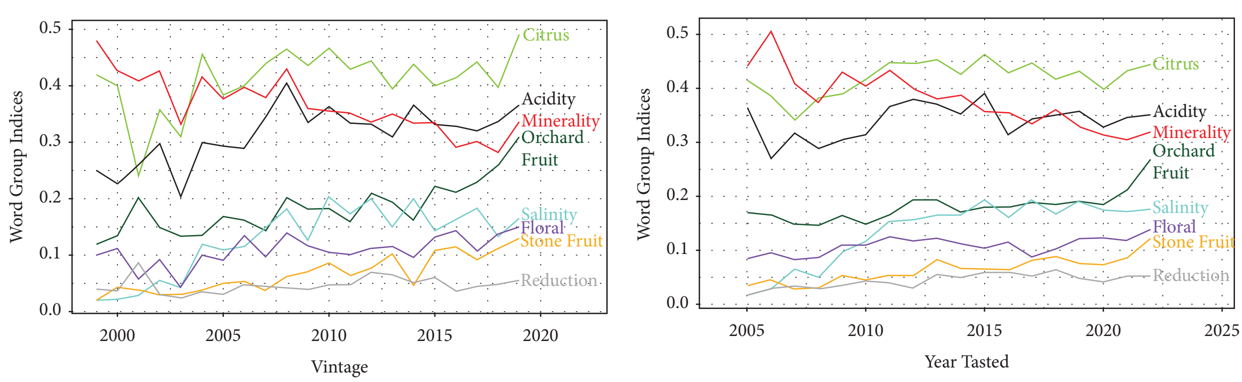
The minerality word group decreased by an average of 0.007 per year between the 1999 and 2019 vintages, equivalent to a total fall of 0.14 in the index (Figure 2, Table 1). None of the other word groups, including the potential minerality-related word groups (reduction, salinity, shellfish, and stony), experienced a similar statistically significant decline with vintage (Figure 2, Table 1); in fact, the saline word group increased over the same vintage period by 0.15 (Figure 2, Table 1).

3.1.2. By Year Tasted. Similar (though smoother) trends were found when these word groups were plotted against tasting year instead of vintage (Figure 2, Table 1). The trends

Table 1: Median, interquartile range (IQR), and linear trend in word groups used to describe Chablis Premier Cru wine in CellarTracker tasting notes against vintage (1999 to 2019) and tasting year (2005 to 2022). Word groups in bold exhibited linear trends that were significant at the p < 0.05 level with Bonferroni correction, i.e., (0.05/14). The word group indices range in value from 0 (zero presence) to 1 (found in 100% of all tasting notes); thus, a slope of 0.01 is effectively a 1% increase per year of the word group in absolute terms. All wines were between 3 and 7 years of age when tasted.

	Vintage (1999 to 2019)						Tasting year (2005 to 2022)					
	Median	IQR	Slope	SE	R^2	p	Median	IQR	Slope	SE	R^2	p
Acidity	**0.33**	**0.04**	**0.0053**	**0.0013**	**0.45**	**<0.001**	0.35	0.05	0.0023	0.0014	0.14	0.129
Citrus	0.42	0.05	0.0043	0.0018	0.22	0.030	0.43	0.04	0.0030	0.0013	0.26	0.031
Floral	**0.11**	**0.04**	**0.0026**	**0.0008**	**0.37**	**0.003**	0.11	0.02	0.0019	0.0006	0.40	0.005
Lees	0.04	0.01	−0.0005	0.0005	0.04	0.364	0.04	0.01	−0.0005	0.0005	0.05	0.394
Minerality	**0.36**	**0.07**	**−0.0070**	**0.0010**	**0.70**	**<0.001**	**0.38**	**0.07**	**−0.0087**	**0.0011**	**0.79**	**<0.001**
MLF	0.14	0.04	−0.0011	0.0013	0.04	0.404	0.13	0.02	−0.0002	0.0009	0.00	0.800
Oak	0.11	0.03	−0.0026	0.0011	0.23	0.028	0.12	0.02	−0.0014	0.0006	0.29	0.021
Orchard fruit	**0.18**	**0.06**	**0.0060**	**0.0010**	**0.63**	**<0.001**	**0.18**	**0.02**	**0.0039**	**0.0009**	**0.55**	**<0.001**
Reduction[a]	0.04	0.01	0.0006	0.0005	0.07	0.260	**0.05**	**0.02**	**0.0018**	**0.0004**	**0.57**	**< 0.001**
Salinity	**0.14**	**0.06**	**0.0077**	**0.0014**	**0.62**	**<0.001**	**0.16**	**0.07**	**0.0095**	**0.0014**	**0.75**	**< 0.001**
Shellfish	0.08	0.03	−0.0006	0.0007	0.04	0.360	0.09	0.02	0.0000	0.0007	0.00	0.957
Stone fruit	**0.06**	**0.05**	**0.0047**	**0.0006**	**0.79**	**<0.001**	**0.06**	**0.03**	**0.0040**	**0.0005**	**0.78**	**< 0.001**
Stony[a]	0.21	0.03	−0.0001	0.0016	0.00	0.940	0.20	0.02	0.0001	0.0007	0.00	0.851
Tropical fruit	0.09	0.03	−0.0003	0.0010	0.00	0.795	0.08	0.02	0.0005	0.0007	0.04	0.453

[a]In this study, "gunflint" words were included in the reduction word group and "flint" words in the stony word group. Flint, however, may be used in tasting notes as shorthand for gunflint and could thus be considered a reductive or smoky characteristic rather than stony. Simulation of this alternative categorisation for flint showed that it had little material effect on the results (Supplementary Figure S6, Tables S4 and S5).



(a) (b)

Figure 2: Trends in word groups used to describe Chablis Premier Cru wine in CellarTracker tasting notes against vintage (a) and year tasted (b). Secondary and tertiary word groups (lees, MLF, and oak) or word groups that did not exhibit a linear trend (lees, MLF, shellfish, stony, and tropical fruit $p > 0.05$) have been omitted from the Figure. All wines were between 3 and 7 years of age when tasted.

for minerality, salinity, and reduction were slightly stronger for tasting year than vintage (compare slopes for each in left and right of Table 1).

3.2. Associations between Minerality and Other Wine Characteristics

3.2.1. Bigram. Bigram analysis on the CellarTracker database showed that users occasionally qualified what they meant by "minerality" by adding a word before it in their tasting notes, broadly falling into "stony minerality" (593 occurrences, mostly "chalk" and "stone"), "saline minerality" (255), "seashell minerality" (105), and "smoky minerality" (44) groups (Table 2). These bigrams occurred in approximately 6% of tasting notes.

3.2.2. By Vintage. A significant negative correlation was found between the minerality index and each of the orchard fruit, salinity, and stone fruit indices (r_s (19) = −0.57, −0.48, −0.66 and p = 0.0071, 0.0294, 0.0012, respectively) but not with any of the other ten word groups. Only the correlation with stone fruit was significant after Bonferroni correction, however ($p < 0.00385$, i.e., $p < 0.05$ with Bonferroni correction for 13 pairwise correlations).

Table 2: Bigram analysis of Chablis Premier Cru tasting notes in CellarTracker, where a "mineral," "minerals," "minerally," or "minerality" word is the second word in the bigram.

Bigram group	First word[ab] (number of occurrences)[c]	Total occurrences
Stony minerality (Land)	chalk (220), **ferrous (1)**, earth (8), **flint (75)**, graphite (0), gravel (5), granite (1), gypsum (0), **iron (1)**, kimmeridgian (3), lead (0), limestone (40), marl (0), pebble (1), rock (23), soil (1), slate (18), stone (196)	593
Saline minerality (Ocean)	brine (9), **iodine (4)**, marine (5), ocean (11), oceanspray (0), saline (128), salt (76), saltwater (0), sea (13), seabreeze (0), seasalt (0), seashore (3), seaside (3), seaweed (3), seawater (0)	255
Seashell minerality (Ocean)	oyster (4), oystershell (2), seashell (27), shell (72), shellfish (0)	105
Smoky minerality (Smoke)	cabbage (0), cardboard (0), corn (0), egg (0), funk (0), fusil (0), gunflint (1), gunmetal (0), gunpowder (1), gunsmoke (1), lapsang (0), matchstick (0), reduction (5), rotten (0), rubber (0), smoke (34), skunk (0), struckmatch (0), sulphide (0), sulfide (0), sulfur (1), sulphur (1)	44

[a]Includes derivatives and common misspellings of the word type, for example, "chalky" and "chalkey". [b]Categorisation of first-word types has been made in accordance with BIVB descriptions for minerality [40] with adjustment for "gun-" words (gunflint and gunpowder) which were moved to the smoke group. Seashell was separated from saline in order to test the work of Rodrigues et al. [19], though BIVB groups the two together into an "ocean" category. BIVB refers to the stony category described here as "land." [c]Word types marked in bold highlight potential miscategorisations. Flint may be shorthand for gunflint and possibly considered smoky instead of stony; iron and ferrous could be confused with iodine and therefore considered saline rather than "land." Given the number of occurrences involved, only the categorisation of "flint" is materially an issue (see Discussion). The overall order and magnitude of importance between the bigram groups would remain, however, even with these alternative categorisations. All wines were between 3 and 7 years of age when tasted.

For associations among all word groups (not just minerality), only the correlation between acidity and salinity ($r_s(19) = 0.75$, $p = 0.0001$) was significant (Figure 3). The other pairs did not pass the significance test of $p < 0.00055$ (i.e., $p < 0.05$ with Bonferroni correction for 91 pairwise correlations) and/or were overly dependent on an outlier (assessed using a Grubbs' test followed by a new correlation without the outlier).

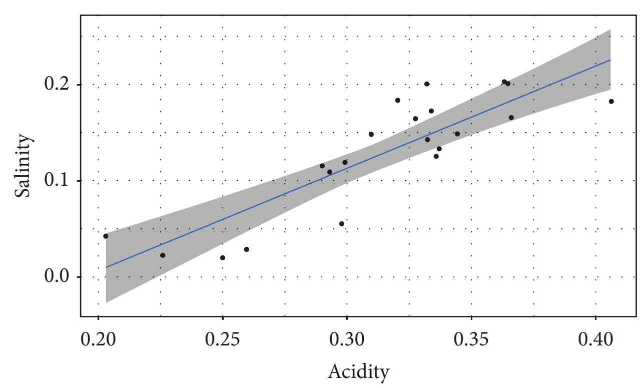


Figure 3: Mean salinity versus mean acidity for Chablis Premier Cru wine (1999 to 2019 vintages) from CellarTracker tasting notes. All wines were between 3 and 7 years of age when tasted.

3.2.3. Minerality Differences between Left- and Right-Bank Premier Cru Wines. A paired-samples t-test revealed a small but statistically significant difference in mean minerality between left- and right-bank wines when averaged by vintage ($t\ (19) = 2.30$, $p = 0.033$). Left-bank wines were 0.022 higher in mean minerality than right-bank wines (Figure 4).

3.3. Associations with Weather. Moderate Spearman's rank correlations were found between certain wine characteristics and weather, though some at a lower significance ($p < 0.10$) and without Bonferroni correction (Table 3).

In general, minerality was negatively and tropical fruit was positively associated with temperature and sunshine hours, while fruit and floral characteristics, excluding citrus, were negatively associated with precipitation during the growing season (Table 3 and Supplementary Figure S7). Minerality was not correlated with precipitation variables. Stone fruit was positively associated with the sunshine indices only ($p < 0.10$).

Acidity was significantly ($p < 0.05$) correlated (negatively) with mean minimum temperature in both the August and September ($Tmin_{Aug\text{-}Sep}$) and September (CNI) periods (Table 3 and Supplementary Figure S7).

3.4. Associations with Soil Type. No significant Spearman's rank correlations were found between the percentage of vineyard area with Kimmeridgian UCS30 soil type and wine characteristics ($p > 0.05$ with Bonferroni correction for 11 pairwise comparisons (excluding lees, MLF and oak)), except for the association with the reduction word group ($r_s\ (12) = 0.87$, $p < 0.001$). The effect was small, however (range in reduction index <0.04).

3.5. Associations with Topography

3.5.1. Aspect. Minerality was the only word group found to have a significant association ($p < 0.05$) with aspect. It was negatively associated with the percentage of Climat vineyard area facing South or South-West ($r_s\ (12) = -0.65$, $p = 0.012$) and positively facing East or South-East ($r_s\ (12) = +0.56$, $p = 0.037$) (Figure 5).

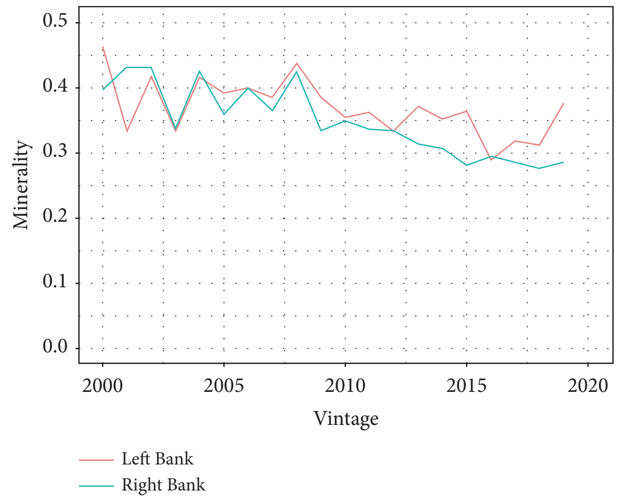


Figure 4: Mean minerality versus vintage for left- (red) and right-bank (blue) Chablis Premier Cru wine from CellarTracker tasting notes. The 1999 vintage was omitted from the analysis due to insufficient sample numbers (<30 tasting notes) after splitting into left- and right-bank wines. All wines were between 3 and 7 years of age when tasted.

Table 3: Significant Spearman's rank correlation coefficients ($p < 0.10$) between vintage weather indices and word groups used to describe Chablis Premier Cru wine (1999 to 2019) in CellarTracker tasting notes. Nonprimary aroma and flavour word groups (lees, MLF, and oak) were excluded from the analysis. All wines were between 3 and 7 years of age when tasted.

		Coefficient (r_s)	Significance (p)
Temperature			
$T\text{mean}_{\text{Apr-Sep}}$	vs. minerality	−0.43	0.052
	vs. tropical fruit	0.59	0.005
$T\text{mean}_{\text{Apr-Oct}}$ (GST)	vs. minerality	−0.48	0.029
	vs. tropical fruit	0.54	0.011
$T\text{mean}_{\text{May-Jul}}$	vs. tropical fruit	0.50	0.022
$T\text{min}_{\text{Sep}}$ (cool night index)	vs. acidity	−0.45	0.043
$T\text{min}_{\text{Aug-Sep}}$	vs. acidity	−0.57	0.007
	vs. orchard fruit	−0.37	0.099
	vs. salinity	−0.41	0.064
	vs. tropical fruit	0.40	0.069
Sunshine			
$\text{Sunhours}_{\text{Apr-Sep}}$	vs. minerality	−0.57	0.007
	vs. stone fruit	0.40	0.072
	vs. tropical fruit	0.38	0.086
$\text{Sunhours}_{\text{Aug-Sep}}$	vs. minerality	−0.51	0.019
	vs. stone fruit	0.41	0.063
	vs. tropical fruit	0.38	0.093
Precipitation			
$P_{\text{Jun-Sep}}$	vs. floral	−0.55	0.010
	vs. stone fruit	−0.38	0.086
$P_{\text{Jun-Oct}}$	vs. floral	−0.54	0.013
	vs. orchard fruit	−0.42	0.059
	vs. stone fruit	−0.42	0.062
	vs. tropical fruit	−0.46	0.035

3.5.2. Gradient. The mean slope of vineyards in each Climat was not associated with the minerality index (r_s (12) = 0.25, p = 0.383) but was negatively associated with shellfish (r_s (12) = −0.82, $p < 0.001$), saline (r_s (12) = −0.69, p = 0.008), and stony (r_s (12) = −0.56, p = 0.038) characteristics (Figure 6). Only that with shellfish was significant with Bonferroni correction ($p < 0.0045$) however.

3.5.3. Elevation. The mean elevation of the Climat vineyard area was not associated with the minerality index (r_s (12) = 0.09, p = 0.773), nor any other wine characteristic.

3.5.4. Relative Elevation. The mean relative elevation of Climat vineyard was not associated with reports of minerality (r_s (12) = −0.38, p = 0.186), but it was positively

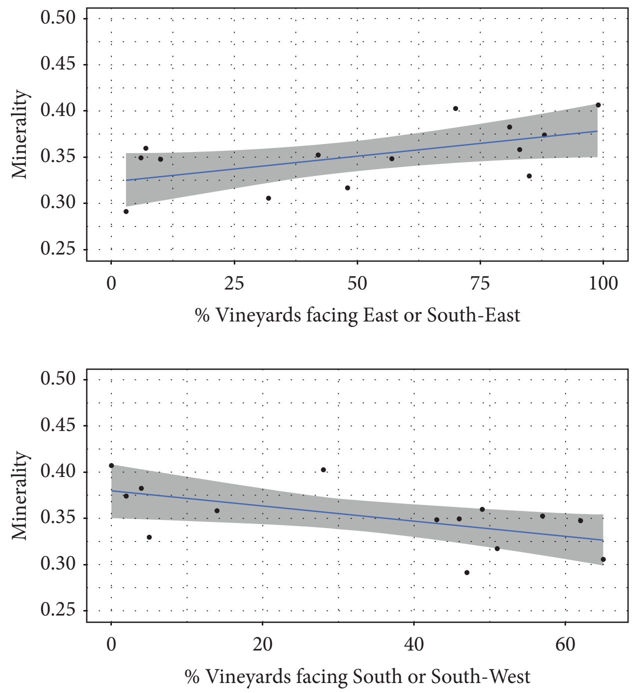


Figure 5: Mean minerality of principal Chablis Premier Cru Climats (from CellarTracker tasting notes) in relation to aspect, i.e., the percentage of Chablis Premier Cru Climat area facing East or South-East (upper pane; regression slope = +0.0006, SE = 0.0002, $R^2 = 0.32$) or South or South-West (lower pane; regression slope = −0.0008, SE = 0.0003, $R^2 = 0.34$). The Premier Cru wines ranked from highest to lowest for minerality (with side of river) were Vau de Vey (Left, 0.41), Côtes de Jouan (Left, 0.40), Vaillons (Left, 0.38), Côte de Léchet (Left, 0.37), Montée de Tonnerre (Right, 0.36), Montmains (Left, 0.36), Les Fourneaux (Right, 0.35), Fourchaume (Right, 0.35), Beauregard (Left, 0.35), Vaucoupin (Right, 0.35), Vauligneau (Left, 0.33), Beauroy (Left, 0.32), Mont de Milieu (Right, 0.31), and Vosgros (Left, 0.29). All wines were between 3 and 7 years of age when tasted.

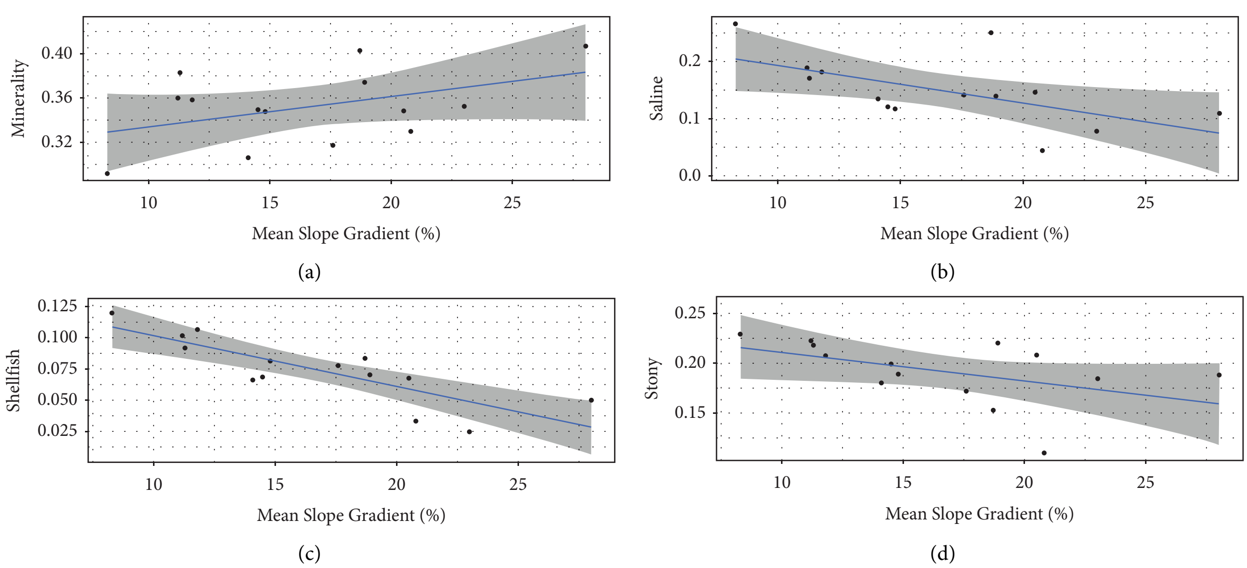


Figure 6: Mean indices for the word groups (a) minerality, (b) saline, (c) shellfish, and (d) stony (from CellarTracker tasting notes) in relation to the mean slope gradient of 14 principal Chablis Premier Cru Climats. Spearman's rank correlation between slope gradient and minerality was not significant ($p > 0.05$), but that for slope gradient versus saline, shellfish, and stony characteristics was. All wines were between 3 and 7 years of age when tasted.

associated with the shellfish (r_s (12) = +0.64, $p = 0.017$) and stony (r_s (12) = +0.59, $p = 0.029$) word groups. The total range in these word group indices was small (around 0.05), however, and neither was significant with the Bonferroni correction. No other word groupings were correlated ($p < 0.05$) with relative elevation, except for the floral word group (r_s (12) = +0.59, $p = 0.030$), but this was overly dependent on an outlier (assessed using a Grubbs' test followed by a new correlation without the outlier; (r_s (11) = +0.50, $p = 0.072$)).

4. Discussion

Textual analysis of Chablis Premier Cru tasting notes in CellarTracker has provided an understanding of what consumers mean in sensory terms when they refer to minerality, what may be driving the presence of minerality in wine, and how the use of the term minerality has changed over the study period.

Bigram analysis on the CellarTracker database showed that users occasionally specified what they meant by "minerality" by using a qualifying word before it in their tasting notes (Table 2). If this is representative of the whole, it suggests nonspecific minerality references in Chablis Premier Cru tasting notes are over 1.5 times as likely to be referring to stony sensations such as chalk, stones, and pebbles than they are saline, salty, and seashell sensations [40].

The decline in the use of the term "minerality" over the last 20 years or so can be interpreted in several ways (i) that it has become less fashionable as a descriptive term, especially since the idea that it is directly connected to the soils and geology has been widely discredited [2, 10]; (ii) that users have been more careful in its usage—perhaps choosing the term "saline" (and to a lesser extent "reduction") instead of "mineral" when appropriate, but perhaps retaining the term for "stony" sensations; and/or (iii) that there has been a real decrease in "minerality" in Chablis wine over the study period.

Our analyses suggest that all three explanations may have played a part. The rate of decline in the use of the term minerality and the rate of increase in the use of the term salinity are greater when looked at by year of tasting than by vintage (Table 1), which is not the case for most other wine descriptor groups (the one exception is reduction). This suggests that a change in fashion may have played a part and that users may have instead chosen to substitute minerality with a more precise saline descriptive term or less frequently a reductive or acidic term. Malfeito-Ferreira [3] points out that experts generally prefer using words other than minerality. This preference may be spreading to the wider consumer market.

Nonetheless, the negative correlations between minerality and each of sunshine and warmth (Table 3) suggest that it is a real phenomenon affected by the vintage year's weather. This ties in with the widely accepted idea that minerality is associated with cool-climate wines [3, 17]. An alternative explanation, however, could be that CellarTracker users were aware of which vintages were "hot," "classic," or "cold" and adjusted their expectations and perceptions accordingly.

Our observation that Climats on the left side of the river Serein provided slightly more mineral wines than those on the right side (Figure 4) confirms the findings of Rodrigues et al. [19]. Once again, however, this might be explained by preconceptions about the "minerality" of Climats on the part of CellarTracker users. The findings are more convincing, however, when minerality is plotted against the vineyard aspect, with East and South-East facing Climats (typically left bank) more mineral than the South and South-West facing Climats (typically right bank) (Figure 5). This is consistent with research suggesting minerality may be inversely related to berry maturity [17], with the South and South-West facing slopes receiving greater warmth from the accumulation of heat into the afternoon, promoting greater berry maturity and consequently less mineral wines [19].

The increase, by vintage, in floral, orchard fruit, and stone fruit wine notes (Table 1 and Figure 2), typical of warmer climate Chardonnay styles, suggests the simultaneous decline in minerality may be real and correspond to the long-term warming trend in Chablis [47]. Arguably, the perception of floral, orchard fruit, or stone fruit descriptors would be less affected by preconceptions about wine from warmer vintages because it is a more subtle observation than detecting tropical aromas and flavours in a wine from a hot year. It also ties in with research that suggests minerality may be perceived when there is an absence of fruit and floral notes [7, 19, 25].

However, fruit and floral aromas and flavours were related (negatively) to precipitation, whereas minerality, acidity, reduction, and salinity (the minerality and minerality-related terms) were not (Table 3). In other words, a wet period from fruit set to harvest may result in a lack of fruit and floral aromas and flavours, but this does not necessarily translate into an increase in minerality.

Interestingly, there was little evidence for the widely accepted observation that minerality and acidity are closely and positively associated [5]. While it is true that minerality, acidity, and citrus descriptive word groups characterised Chablis Premier Cru wines over the study period (Figure 2), evidence from this study suggests that acidity and minerality (albeit there may be a changing definition of minerality throughout the study period) may be determined by different environmental conditions. While minerality was related to warmth and sunshine, acidity was associated (negatively) with mean minimum temperatures during the ripening period ($Tmin_{Aug\text{-}Sep}$ and CNI) (Table 3) when high night temperatures increase respiration and the degradation of malic acid in grape berries [55].

Instead, acidity was most strongly associated with salinity (Figure 3), suggesting these word groups are either being used to describe similar sensations or that many tasters had difficulty differentiating between them. Salinity was also associated with mean minimum temperature in August and September ($Tmin_{Aug\text{-}Sep}$), albeit at a lower significance ($p < 0.10$) than acidity (Table 3), providing further evidence for the association between acidity and salinity. One of the acids naturally present in wine, succinic acid, is in fact salty in taste [3, 6, 8].

The negative association found between vineyard gradient and shellfish notes (Figure 6) is also interesting. Rodrigues et al. [19] found that methanethiol, a sulphur-containing volatile compound responsible for shellfish aromas, was higher in left-side Chablis wines compared to right-side wines, and they postulated it could play a role in the sensation of minerality by masking fruit and floral aromas. Indeed, left bank Climats are steeper (17.3%) on average than right bank Climats (14.7%) (excluding the smallest Climats of Berdiot, Chaume de Talvat, and Côte de

Vaubarousse which had too few wine-tasting notes for separate analysis). Thus, the gradient may be positively correlated to the presence of methanethiol, and this may lead to the masking of fruit and floral aromas, though the process by which this might happen is unclear. No direct association, however, was found in this study between vineyard gradient and minerality.

Reductive terms were (with lees) the least mentioned of all descriptive word groups for vintages from 1999 to 2019 (Table 1). Only 4% of tasting notes (i.e., a median index score of 0.04) referred to any kind of reduction in the wine. This compares to minerality with a median index score of 0.36.

This result implies that "overt" signs of reductive processes, i.e., ones that produce sulphur compounds responsible for empyreumatic and/or off-odours, are not a key feature of Chablis Premier Cru wine. This does not necessarily mean, however, that reduction is not involved in other minerality-related characteristics, such as flinty [4] and shellfish [19] aromas.

Our choice of how to allocate descriptive words to particular word groups obviously had an impact on the results, though we believe not in a material way. We chose to put flint words into the stony word group given a literal understanding of the term and the possibility that CellarTracker users are referring to some kind of edgy stony character [56], rather than using the term as shorthand for gunflint. When we tested moving over these words to the reduction word group instead, the change to the results was small and immaterial to our overall findings (Supplementary Figure S6 and Tables S4 and S5).

Our study found no evidence for any association (positive or negative) between minerality and (i) percentage of Kimmeridgian soil type [11, 17, 30] or (ii) flavours and aromas associated with lees contact, oak ageing/fermentation, and/or malolactic fermentation. Thus, no support can be given to the idea that minerality is related to soils and geology or that minerality can be masked by winemaking processes [17, 25]. That said, there may be other soil characteristics—such as stoniness, soil depth, and clay content—that affect soil temperature and water availability and thus affect ripening [17], which were not investigated here.

Minerality is an ill-defined and enigmatic concept [5, 10] that needs clarity for producers, merchants, and consumers alike and needs standardising into a group of aroma and/or taste compounds [6]. In this regard, the findings of this study help in understanding what minerality means for consumers of Chablis wine and—given Chablis is widely accepted as an archetypal mineral wine [13]—this would likely translate to other cool climate white wines.

How minerality is perceived, however, may vary with grapevine variety [3]. This may be due to differences in biochemistry. Tominaga et al. [24], for example, found that Chardonnay wines from Burgundy, France, contained two to three times as much benzenemethanethiol as the other grape varieties in their study (Sauvignon blanc, Semillon, Cabernet Sauvignon, and Merlot). As such, despite the need for a universal understanding of minerality [4, 36], some caution is required in applying the findings of this study to cultivars other than Chardonnay.

These findings may also be of value to cool-climate wine producers who want to make mineral wines, including those from emerging wine regions such as the UK. This is because the best explanation for the presence of minerality in our data was one where minerality is driven by vintage weather rather than any direct connection to soils and geology, winemaking practices, or wine storage. As such, although the CellarTracker data were unable to throw light on the mechanism and compounds that cause minerality, we hypothesise high minerality wines could be produced anywhere with a suitable climate and with generally good conditions for growing cool climate grapevines.

5. Conclusions

The use of the descriptive term "minerality" has declined over the last 20 or so years in Chablis Premier Cru tasting notes in CellarTracker. This was probably due to three factors: (i) the warming of growing season temperature (GST) due to climate change, (ii) a decline in the popularity of the term, and (iii) the increasing use of alternative descriptive terms, such as "saline" (where appropriate) with retention of the minerality word for "stony" perceptions.

For CellarTracker users, the term "minerality" was primarily associated with "stony" perceptions (including "chalky," "flinty," and "stony") and secondarily with "saline" and "seashell" perceptions (including "saline," "salty," and "shelly"). Empyreumatic and off-odour words associated with reductive processes and sulphurous compounds, however, such as "egg," "smoky," and "sulphur," were not a major feature of Chablis Premier Cru wine.

The hypothesis that minerality in Chardonnay wine is driven by vintage weather (i.e., negatively correlated with GST and sunshine hours) was supported by the study. No evidence was found to support the suggested association of minerality with soils and geology (specifically the presence of Kimmeredigan soils), nor that malolactic fermentation and/or contact with oak barrels and lees have any masking effect on minerality. Some evidence was detected, however, to support the idea that minerality is inversely correlated with stone and tropical fruit, though only by virtue of them being oppositely associated with GST and/or sunshine hours, rather than any direct relationship between them.

Though minerality and acidity are both a typical feature of Chablis Premier Cru wine, the presence of each is likely driven by different vintage weather factors: acidity is driven by night-time temperatures during ripening, whereas minerality is driven by temperatures and sunshine throughout the growing season.

Textual analysis of the large database of tasting notes in CellarTracker has provided interesting insights about the perception of wine characteristics and the sources of these characteristics. The specific findings of this study in relation to the minerality of Chablis wine (arguably the most famous wine for minerality) may be useful to wine industry professionals and consumers who want clarity on the meaning and causes of minerality in wine and perhaps also to winemakers in both traditional and emerging wine regions who seek to produce mineral wines.

Data Availability

The data used to support the findings of this study are available from the following sources: tasting notes https://www.cellartracker.com/; weather https://meteofrance.com/; topography and soils https://onlinelibrary.wiley.com/doi/full/10.1111/ajgw.12433.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Supplementary Materials

Supplementary Table S1 lists the 17 principal Chablis Premier Cru Climats and their land area. Supplementary Figure S1 shows the mean age of Chablis Premier Cru wine tasted in CellarTracker notes against Year Tasted. Supplementary Figure S2 provides a schematic representation of how the CellarTracker Chablis Premier Cru tasting notes were organised into separate subdatabases for analyses. Supplementary Table S2 and Supplementary Figure S3 provide descriptive statistics for the CellarTracker Chablis Premier Cru tasting notes. Supplementary Figure S4 shows the descriptive word groups selected by the authors for text analysis, and Supplementary Table S3 lists the component words and bigrams for these word groups. Supplementary Figure S5 shows how the assignment of gunflint, gunpowder, and gunmetal words to the "reduction" word group instead of the "stony" word group made a negligible difference in the results. Supplementary Figure S6 shows how the assignment of flint words to the "reduction" word group instead of the "stony" word group would have made some small difference to the results. Supplementary Table S4 and Table S5 show the relationship differences that would have resulted from the reassignment of flint words from the "stony" to the "reduction" word group. Supplementary Figure S7 provides selected significant Spearman's rank correlation scatterplots between word groups used to describe Chablis Premier Cru wine and certain vintage weather variables. (*Supplementary Materials*)

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