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Tentative hierarchization of the influence of milk properties and technological practices on rheological properties of Abondance cheese

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An attempt at classifying the influence of different characteristics of milk and cheesemaking on the rheological properties of Abondance cheese is presented. Abondance is a traditional farmhouse French hard cheese with protected denomination of origin (PDO). Thirty-nine cheeses made from unpasteurized cows' milk were sampled. Spline partial least squares regression was used to relate milk properties and cheesemaking practices to rheological properties of the six-month-old cheeses. These properties were the deformability modulus and the strain and stress at fracture measured by compression. Milk properties and technological practices had overall the same degree of relationship with the rheological properties investigated: plasminogen-derived activity in milk and mineral-protein equilibrium, on the one hand, and brining and resting, on the other hand. However, acidification kinetics and 1-d pH, which result from both milk properties and technological practices, showed the strongest relationships with rheological characteristics. Factors that were most appropriate for modelling Abondance rheological properties are discussed.

Keywords: Milk properties, technological practices, rheological properties, prediction, PLS regression, Abondance cheese.

Abondance (also known as Tomme d'Abondance) is a traditional farmhouse hard French cheese from the Savoie region (northern French Alps). It is a protected Denomination of Origin (PDO) cheese made from cows' milk and, like the majority of PDO cheeses, it is manufactured from unpasteurized milk. Milk used in the making of PDO cheeses varies widely in composition because breeding practices are diverse. This variability is preserved because milk is processed very little, or not at all, before being made into cheese. Diversity in the technological processes results from the know-how of each cheesemaker, who tailors the procedure to meet the variable milk properties. This leads to the wide diversity in the characteristics of the final cheeses. Managing this diversity requires knowledge of the effects of milk properties and technological practices on cheese characteristics.

The objective of the present study was to hierarchize the influences of milk properties and technological practices on rheological characteristics of Abondance cheese. Although there are numerous publications on the influence of milk or technological factors on cheese quality, they take into account only a limited number of factors. For Reblochon cheese, Martin (1993) found links between milk properties and technological practices, on the one hand, and cheese characteristics, on the other hand, without hierarchizing them. The only other papers where an overall view of the influence of these factors on cheese texture is presented are reviews (Adda et al. 1982; Lawrence et al. 1987; Walstra et al. 1987). To fulfil our objective, we gathered a database of milk properties, technological practices and cheese rheological characteristics for a series of Abondance cheeses chosen to be as diverse as possible. We then used a multidimensional prediction-oriented statistical method that handles non linear relationships. The statistical analysis gave relationships that, with the help of the literature, could or could not be interpreted as physicochemical effects.

Materials and Methods

Experimental setting

Experimental conditions were described in Bugaud et al. (2000, 2001a, b). Thirty-nine cheeses were collected during April–September 1998 in the Abondance cheese PDO area of the French Alps. The cheeses were made on the

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Table 1. List of the milk composition variables used in the study

Values are means ± SD for $n = 39$

		Mean ± SD
Gross composition (g/kg)		
	Milk pH	6·70 ± 0·04
	Protein content	32·5 ± 1·0
	Fat content	37·7 ± 2·0
	Urea	0·317 ± 0·080
	Calcium	1·23 ± 0·03
	Phosphorus	0·88 ± 0·05
Fatty acid composition (% of total fatty acids)		
	C4	5·47 ± 0·23
	C6–14	19·7 ± 3·5
	C16	27·6 ± 2·9
	C18	9·9 ± 1·1
	C18 : 1	24·4 ± 3·3
	C18 : 2+C18 : 3	5·7 ± 1·7
	Unsaturated C18	30·1 ± 4·8
Enzyme composition (dA_{405} . $dt^{-1} \times 10^3$)		
	Plasmin activity†	0·247 ± 0·060
	Plasminogen-derived activity†	1·86 ± 0·25
	Plasminogen-derived activity over plasmin activity ratio	8·02 ± 2·42
Casein composition (% of peak total area)		
	γ+κ casein	6·9 ± 1·1
	β-casein	38·6 ± 1·2
	C-variant of the β-casein	2·1 ± 1·9
	αs1-casein	50·7 ± 1·1
Microflora (log(cfu))	Total microflora	3·54 ± 0·54

† Analysis in triplicate; all other variables were analysed in duplicate

farm by three farmer-cheesemakers using unpasteurized milk. Nine of them (three replicates per farmer) were made from milk produced by cows given hay and the others were made from milk produced by cows given different types of pasture (five from valleys and five from mountains). For each pasture, three cheeses were collected corresponding to three consecutive cheesemaking days. Farmer X fed his herd on two valley pastures and three mountain pastures; farmer Y fed his herd on two mountain pastures and farmer Z fed his herd on three valley pastures.

Raw milk composition

Table 1 lists the milk composition variables that were evaluated for their ability to predict the rheological properties of Abondance cheese. Protein and fat contents were assessed by infrared spectroscopy (Milkoscan; Foss Electric, DK-3400 Hillerød, Denmark). Urea content was determined by the dimethylamino-4-benzaldehyde colorimetric method (Tondu, 1986). Total calcium was measured with a complexometric method (Pearce, 1977) and phosphorus content by a colorimetric method (AFNOR, 1992). Plasmin and plasminogen activities were determined by a modification of the method of Rollema et al. (1983) described by Bugaud et al. (2001a). Casein composition was analysed by polyacrylamide gel electrophoresis using urea (Andrews, 1983). The surface of each peak was expressed as a percentage of the total area. The fatty acid (FA) composition was analysed by gas chromatography (Buchin et al. 1998).

All analyses were performed in duplicate except plasmin and plasminogen-derived activities, which were in triplicate. Among these variables, a calculated variable was included in the study: the ratio of plasminogen-derived activity to plasmin activity, which may indicate an interaction between plasmin activity and plasminogen-derived activity. Because of the high correlations between the fatty acid proportions (the absolute values of the correlation coefficients were $>0·8$ ($P<0·001$), we used a synthetic variable to take them into account. This synthetic variable was the first axis of the Principal Component Analysis (PCA) built with the C6–14, C16, C18, C18 : 1 and polyunsaturated C18 variables. This axis, which represented 65 % of the total variance, opposed shorter fatty acids (C16 and C6–14) to longer ones (all forms of C18). We verified that the other axes of the PCA were not among the best ranked variables in the Spline PLS regression models.

Cheesemaking

Abondance cheese is made from unpasteurized whole milk, cooked at 45–50 °C and weighing 7–12 kg. Cheesemaking was monitored on the farm and cheesemaking parameters were recorded. Clotting time is the duration between renneting and the moment particles of casein begin to appear. It was determined by the traditional method: when particles of casein began to stick to the cheesemaker's finger when plunged into the milk. Firming time is the duration between clotting and the moment the gel has the correct texture. It is evaluated by the breaking ability of the gel. The same person made all determinations to ensure good repeatability. In the following, we used all the variables related to cheesemaking (Table 2) except the ones concerning the starters. The description of the starters was not detailed enough to be of interest in this paper. Instead, we considered the result of the starter activity, i.e., the acidification kinetics during pressing. As for milk composition, we added a calculated variable, the ratio of firming time over clotting time, which may indicate an interaction between these two processes. To take acidification kinetics into account, we regressed pH values between pH 0 h (i.e., milk pH) and the value of pH attained after 6 h of cheesemaking against time. The slope of the linear regression was the variable kept for further analysis.

We should discuss the meaning of the cheesemaking variables, action or state variables. Most of them are technological practices, i.e., actions decided by the cheesemaker, while some others – clotting time and acidification variables – are the results of interactions between technological practices and milk properties, and describe the

Table 2. List of the technological variables used in the study

Values are means ± SD for $n = 39$

		Mean ± SD
Milk maturation	Maturation time (min)	25·0 ± 9·3
	Maturation temperature (°C)	32·1 ± 2·6
Renneting	Rennet quantity (ml/100 l)	18·7 ± 2·6
	Renneting temperature (°C)	33·7 ± 1·0
	Renneting pH	6·67 ± 0·04
Gelation	Clotting time (min)†	22·0 ± 2·3
	Firming time (min)	10·4 ± 3·5
	Firming time over clotting time ratio	2·40 ± 1·05
Work in vat	Cutting time (min)	6·50 ± 1·47
	Cutting temperature (°C)	32·8 ± 1·1
	Stirring time (min)	7·8 ± 7·6
	Heating time (min)	44·6 ± 5·7
	Maximum temperature (°C)	47·6 ± 0·8
	Stirring time after heating (min)	24·4 ± 10·1
	Overall fabrication time (min)	132·8 ± 21·9
Resting	Resting time (min)	4·6 ± 1·4
Moulding	Moulding time (min)	12·4 ± 5·0
	Serum temperature (°C)	45·6 ± 1·4
Brining	Brining time (h)	12·6 ± 0·8
	Brining temperature (°C)	13·3 ± 2·0
	Brine density (kg/m^3)	1158 ± 31
	Brine acidity (°C)	32·0 ± 18·2
Acidification	pH at moulding†	6·52 ± 0·06
	pH at 2 h†	6·14 ± 0·24
	pH at 4 h†	5·66 ± 0·34
	pH at 6 h†	5·42 ± 0·28
	1-day pH†	5·12 ± 0·12

† Variables corresponding to interactions between technological practices and milk properties

state of the cheese to be. We consider three types of predictive variables: milk properties, technological practices and results of interactions between milk properties and technological practices.

Cheese rheology

Rheological measurements were made at the end of cheese ripening, i.e., after 6 months, using uniaxial compression at a constant displacement rate, as described by Noël et al. (1996), using a TA-XT2 texture analyser (Rhéo, Champlan, France). Four replicated measurements were performed at 15 °C on cylindrical samples (diameter ~15 mm, height ~20 mm). Three parameters were evaluated: the deformability modulus (M_D), the strain (ε_f) and stress (σ_f) at fracture (Table 3). M_D represents the elasticity of the material, ε_f, its deformability and σ_f, its mechanical resistance.

Statistical analysis

Relationships between rheological variables, on the one hand, and milk properties and technological practices, on the other hand, were investigated using Spline PLS regression (Durand & Sabatier, 1997). This method allies PLS regression with a B-spline representation of the relationships between the variables and gives non-linear relationships between the variables of interest.

Table 3. Rheological variables used in the study

Values are means ± SD for $n = 39$

	Mean ± SD
Deformability modulus (M_D) (kPa)	666·9 ± 166·2
Fracture strain (ε_f) (–)	0·48 ± 0·08
Fracture stress (σ_f) (kPa)	221·9 ± 52·9

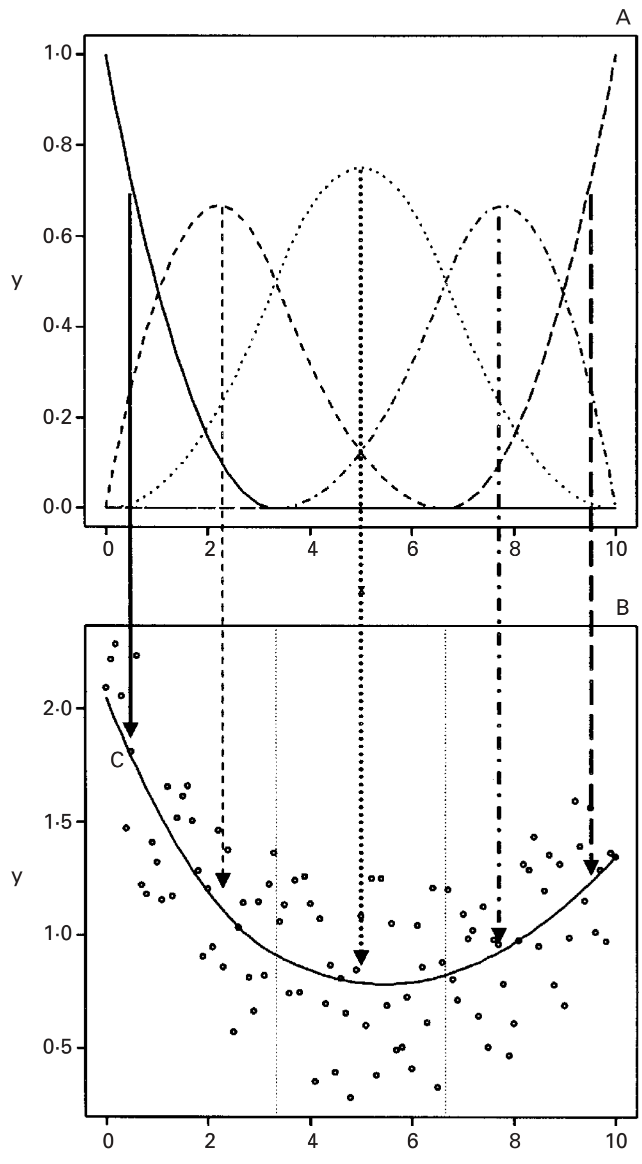

Fig. 1. Panel A. B-spline: basis for a B-spline with two knots and polynomials of degree two. Panel B. Example of a fit corresponding to a linear combination of the B-spline basis shown on panel A.

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PLS regression allows the construction of linear models between a set of predictive variables X and a set of variables to be predicted Y (this set can consist of only one variable). It is an iterative process. The general principle is to build a principal component for X and a principal component for Y under the constraint that their covariance is maximized. The next principal components are constructed with the residues of X and Y. The number of dimensions of the model is defined by a modified leave-one-out cross-validation, i.e., by randomly removing a certain proportion (here 5%) of the individuals at a time. The error of prediction of the removed individuals by this model is calculated for all components. The dimension that gives the smallest prediction error is selected.

B-splines are used to model non-linear relationships between two variables X and Y. The principle is to use a linear combination of a B-spline basis constituted by polynomials defined on successive intervals, partitioning the curve along the X axis. The intervals are defined by knots and the polynomials by their degree. Figure 1 shows the B-spline basis for 2 knots and polynomials of degree 2.

Spline PLS regression combines both methods. Instead of looking for linear relationships between the predictive variables and the variable(s) to be predicted, Spline PLS aims at calculating linear combinations of the B-spline bases defined for all of the predictive variables. This allows a representation of the linear combination of the B-spline basis for each predictive variable and therefore allows the non-linear relationship (curve C) between each predictive variable and the variable(s) to be predicted.

We used univariate Spline PLS. The dimension of each model was defined as described above. The variables were standardized. The degree of relationship that allowed the ranking of the predictive variables was defined as proposed by Durand & Sabatier (1997). On the Y axis, the differences between the maximum and the minimum of the curve C defined for each predictive variable are ranked in decreasing order (Fig. 2). Therefore, the degree of relationship cannot be quantified by statistical criteria, the only information given is that a variable shows a stronger relationship with the variable to be predicted than another. The choice of the number of variables to be presented was made *a priori*. Because the number of predictive variables was the same for the three rheological descriptors, we decided to select the same number of variables. Overall, the differences between the maximum and the minimum of the curve C decreased dramatically after the 10th best-ranked predictive variable, suggesting that the relationship with the following variables was weaker.

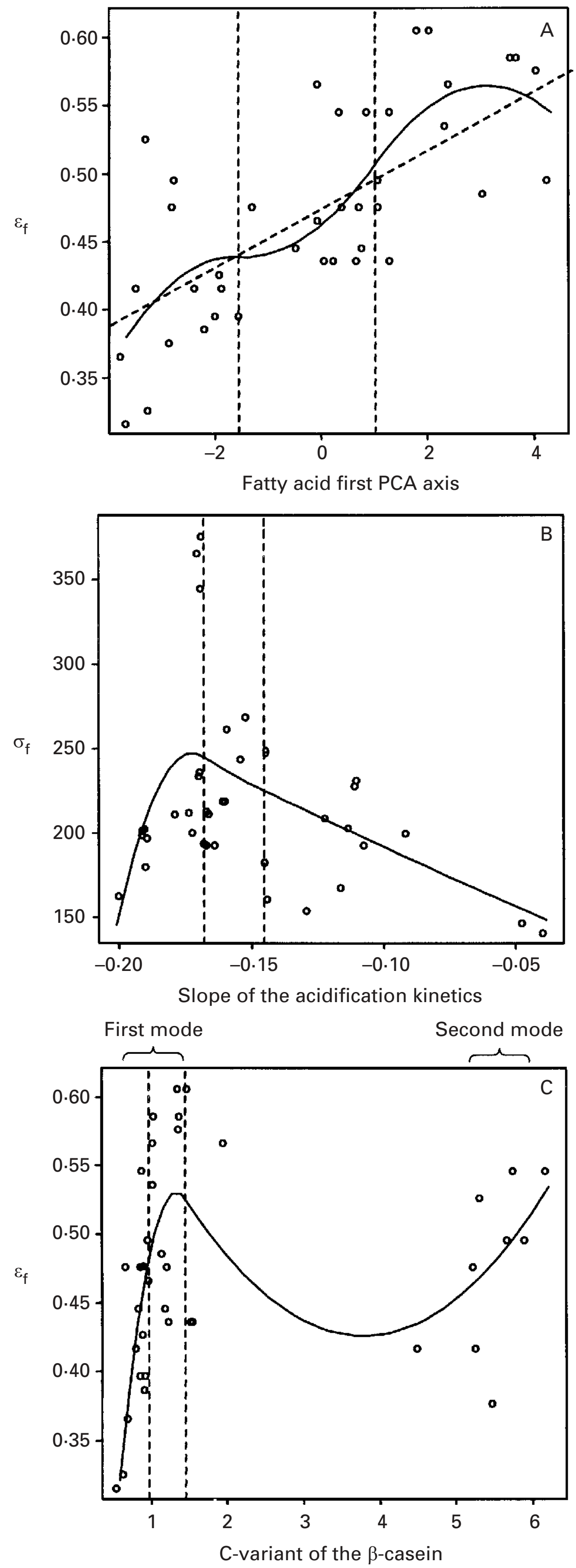

Fig. 2. Examples of relationships observed. Panel A: example of what we called a linear relationship, solid line shows the B-spline fit, dotted line the linear relationship. Panel B: example of a non-linear relationship we defined as NLU. Panel C: specific result for the relationship between the C-variant of the β-casein and ε_f.

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Table 4. Milk properties and cheesemaking variables as ranked by their degree of relationship with the three rheological variables (M_D, ε_f, σ_f)

	Deformation modulus (M_D)		Fracture strain (ε_f)		Fracture stress (σ_f)	
Goodness of fit	97·6%		98·6%		96·5%	
Model dimension	5		5		4	
Rank						
1	1-d pH	NLU	1-d pH	NLD	Acidification kinetics	NLU
2	Clotting time	NLU	Plasminogen-derived activity in milk	NLD	Resting time	L+
3	Brining temperature	NLU	Concentration of C-variant of the β-casein	NL	Brining time	L+
4	Cutting temperature	L+	Phosphorus concentration of milk	L+	Phosphorus concentration of milk	L+
5	Acidification kinetic	L+	Fatty acid composition of milk	L+	Clotting time	NLU
6	Phosphorus concentration of milk	L−	Plasmin activity of milk	L−	Plasminogen-derived activity in milk	L−
7	Milk pH	L−	Total microflora	NLD	Total microflora	NLD
8	Plasminogen-derived activity over plasmin activity ratio	NLU	Brining time	L+	γ+κ caseins in milk	L+
9	Plasminogen-derived activity in milk	NLU	Cutting temperature	L−	Concentration of C-variant of the β-casein	NL
10	Cutting time	L+	Resting time	NLD	Fatty acid composition of milk	L−

NL Non linear relationship
NLU Non linear relationship with a maximum (upward)
NLD Non linear relationship with a minimum (downward)
L+ Linear relationship with a positive correlation
L− Linear relationship with a negative correlation

We chose B-splines with two knots and with polynomials of degree two, because they allowed us to model non-linear relationships without their becoming too complex to interpret.

Results

Overall analysis

Table 4 presents the Spline PLS models obtained. For the three rheological variables, the variance explained by the models was always >95% (97·6%, 98·6% and 96·5% for M_D, ε_f and σ_f, respectively). The model dimensions were 5, 5 and 4 for M_D, ε_f and σ_f, respectively. For the three rheological variables, about half of the most related variables were milk properties and the other half were cheesemaking variables. Among these cheesemaking variables, eight were technological practices and six were interactions between milk properties and technological practices. However, the deformation modulus was more related to cheesemaking variables, as the five most related variables were cheesemaking variables. The fracture strain was more related to milk properties except for the 1-d pH which was ranked first in the Spline PLS model. For the fracture stress, the three most related variables were cheesemaking variables. Overall, we can see that both types of variables are well represented in the models.

Deformation modulus

The rank of the variables in the Spline PLS model is only part of the information that can be extracted from this type of analysis. The other part concerns the shape of the relationships evidenced with the predicted variables.

We present the results for each of the 10 most related variables in their ranking order in the model. The 1-d pH was not linearly related to the deformation modulus (M_D). A higher 1-d pH was associated with a lower M_D, i.e., with a higher elasticity. A maximum M_D was observed for a pH around 5·05. At pH<5·05, lower M_D values were observed. The relationship between M_D and the clotting time was not linear either. A higher M_D was observed for intermediate clotting times. For the brining temperature also, the relationship was not linear and again a higher M_D was observed for intermediate brining temperatures. Cutting temperature was linearly related to M_D. Higher cutting temperatures were associated with higher M_D. We should note the presence of an outlier with a very low cutting temperature which is certainly the result of a technological problem. The acidification kinetics translated by the slope of the milk pH *v.* the pH measured at 6 h of pressing was linearly related to M_D. Steeper slopes were observed for cheeses with a higher M_D. Phosphorus concentration in the milk was also linearly related to M_D and higher concentrations were associated with lower M_D. Milk pH was linearly related to M_D with higher milk pH observed for cheeses with lower M_D. The ratio of plasminogen-derived activity to plasmin activity in milk was not linearly related to M_D. Intermediate values were associated with higher M_D. A similar relationship was observed for the plasminogen-derived activity in milk. Cutting time showed a linear relationship with M_D with longer cutting times associated with higher M_D.

Fracture strain

As for M_D, the 1-d pH was the variable most related to the fracture strain. Again, the relationship was not linear, as lower fracture strain (ε_f) were observed for pH values around 5·05. As for M_D, the plasminogen-derived activity in milk was not linearly related to ε_f. Intermediate plasminogen-derived activities were associated with lower ε_f. The higher plasminogen-derived activities responsible for the non linearity of the relationship were due to three samples only. The C-variant of β-casein was not linearly related to ε_f and presented a bimodal distribution (Fig. 2c). For each mode, a different relationship was observed. For the first mode corresponding to lower values, higher C-variant concentrations were associated with higher ε_f. For the second mode, no relationship was observed. The phosphorus concentration in milk was linearly related to ε_f with higher concentrations for cheeses with higher ε_f. The fatty acid composition was ranked next. It was the first axis of a PCA performed on the proportions of the fatty acids measured in the milk, which was linearly related to ε_f. More unsaturated fatty acids were associated with higher ε_f. Plasmin activity in milk was also linearly related to ε_f. Higher plasmin activities were present in milks that gave lower ε_f. The relationship between the total microflora (expressed in log form) and ε_f was not linear. A minimum fracture strain was seen for intermediate microflora levels. Longer brining times were linearly related to higher ε_f. Cutting temperature was linearly related to ε_f; higher cutting temperatures were seen for cheeses with a lower ε_f. Resting time was not linearly related to ε_f. Intermediate resting times were associated with lower ε_f.

Fracture stress

The kinetics of acidification was the variable most related to fracture stress (σ_f). The relationship was not linear and higher σ_f were observed for intermediate slopes. Resting time was linearly related to σ_f except for one outlier. Longer resting times were associated with higher σ_f. Brining time was positively correlated to σ_f. Phosphorus concentration in milk was linearly related to σ_f such that higher σ_f were observed for higher concentrations. As with M_D, the clotting time showed a non-linear relationship with σ_f. Higher σ_f were associated with intermediate clotting times. Plasminogen-derived activity in milks was linearly related to σ_f. Higher plasminogen-derived activities were associated with lower σ_f. Total microflora was not linearly related to σ_f. Intermediate microflora levels were associated with lower σ_f. The $\gamma+\kappa$ casein concentration in milk was linearly related to σ_f. Higher concentrations of $\gamma+\kappa$ casein were associated with higher σ_f. As for ε_f, the bimodal distribution of the C-variant of β-casein concentration was responsible for two relationships. For the lower values (the first mode), a linear one was observed with higher C-variant of β-casein concentrations showing higher σ_f. For the second mode, as for ε_f, no relationship was observed. Finally the fatty acid composition was linearly related to σ_f. Higher unsaturated fatty acid proportions were related to lower σ_f.

Discussion

As yet, we have described relationships between variables, and not influences. Our goal here is to discuss whether some of these relationships could be real influences. We structure the discussion in three parts: first, we discuss the influence of the milk composition; secondly, the influence of the technological practices ordered chronologically; and thirdly, the influence of clotting time and acidification variables, i.e., interactions between milk properties and technological practices.

Influence of milk composition on cheese rheological properties

Milk fat composition. It is well known that a higher fat content leads to a less firm and elastic body (Adda et al. 1982) which in terms of rheological properties can be translated into a higher fat content giving a higher M_D and a lower σ_f (Walstra et al. 1987). In our case, however, the total fat content was poorly ranked in the three models, which suggests that a weak relationship or no relationship at all was observed between the total fat content and the rheological variables, although full fat milk was used. With regard to fat composition, in a similar technology, for Comté cheese, whose main difference is a cooking temperature of 53–56 °C, Masson et al. (1981) found little difference between milks and cheeses. In our study, a linear relationship was observed between the fat composition and ε_f. Cheeses with a higher C18 (all forms and especially unsaturated C18) proportion showed a higher deformability. Steffen (1975) reported a relationship between cheese firmness and iodine value for Emmental. A higher iodine value (i.e., a more unsaturated fat) results in a softer body. Even in cheeses processed with a very different technology, Camembert cheeses, the influence of milk fat composition on rheological properties is evident. Milks with higher proportions of unsaturated fatty acids give softer cheeses (Houssin et al. 2000). Moreover, for processed cheese analogues, made with four fats of very different physical properties, fat fluidity influenced the mechanical properties at fracture (Marshall, 1991).

Mineral-protein influence on cheese rheology. We observed relationships among the cheese rheological properties and phosphorus concentration in milk, some caseins

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(C-variant of the β-casein) and milk pH. It is impossible to identify a direct influence of any of these three variables. Milk pH influences the equilibrium between the colloidal and soluble forms of phosphate (Gaucheron et al. 1995) and thus micelle geometry. The geometry of the micelles (their average diameter) influences clotting time, firming time and gel firmness (Remeuf et al. 1991) – i.e., gel mechanical properties – for pressed cheeses. This could lead to the relationships we observed, and illustrates the importance of gel structure to cheese structure (Green & Grandison, 1993) although the gel was cut, heated and pressed differently for each of the cheeses in this study.

The relationship between the presence of the C-variant of β-casein on the sensory quality of the hard cheese, Beaufort, was investigated by Marie & Delacroix-Buchet (1994). They found that cheeses with C-variant of β-casein were firmer than cheeses without it. In our study, two modes of C-variant of β-casein were identified corresponding to two herds, on the one hand, and the third herd, on the other hand. The first mode of the distribution of the C-variant of β-casein showed a positive correlation with ε_f and σ_f in accordance with the observations of Marie & Delacroix-Buchet (1994). The second mode, however, for which the proportion of the C-variant was much more important, showed no relationship with the mechanical properties of the cheeses. As the second mode corresponded to a different cheesemaker as well as a different herd, different practices may have masked the C-variant effect.

Proteolysis: influence of microflora and enzymes on cheese rheology. The level of indigenous microflora and the activity of milk enzymes can affect proteolysis. Indigenous microflora levels controlled by microfiltration influence proteolysis in Comté cheese but not its texture (Bouton & Grappin, 1995). The non-linear relationship we observed between the indigenous microflora level and ε_f and σ_f may be an artefact. In fact, the proportion of C-variant of β-casein was correlated with the level of microflora ($P<0{\cdot}001$). This results from the fact that one farmer-cheesemaker owned a herd with a higher level of C-variant and had milking practices that led to a lower level of indigenous microflora. Moreover, the proteolysis variables measured during ripening (Bugaud et al. 2001b) were not related to the microflora level (data not shown).

Enzyme activities may be related to proteolysis (Lawrence et al. 1987) and therefore possibly to cheese texture (Walstra et al. 1987). The only enzymes we quantified were plasmin and plasminogen. Plasminogen activity in milk was much more related to cheese rheological properties than was plasmin activity. Visser (1993) showed that high cooking temperatures enhance plasmin activity in ripening cheese, which may be due to an increased conversion of plasminogen into plasmin. We can thus suppose than the plasminogen activity measured in milk represents potential plasmin activity in cheese. In our study, the non-linearity of the relationships between plasminogen activity and rheological properties is due to only three cheeses. Except for these three cheeses, plasminogen activity was positively correlated with M_D and negatively with ε_f and σ_f, which is in accord with proteolysis breaking down cheese structure, leading to a less elastic and resistant body. We can therefore assume that plasmin activity in cheese influences cheese texture.

Influence of technological practices

Influence of work in vat on cheese rheology. Cutting temperature was related to M_D and ε_f. We wondered whether it was actually the temperature when cutting that was important or whether this cutting temperature also reflected the temperature at renneting and in the interval until cutting. This would involve at least two different phenomena: cutting temperature could influence grain contraction, i.e., syneresis, the temperature at renneting and its evolution could influence rennet activity, i.e., gelation and gel structure. These two phenomena are well known to influence cheese texture (see Walstra, 1987). Nevertheless, the shape of the relationship does not allow us to distinguish between them.

Curd grain aggregation: resting time influence on cheese rheology. Akkerman et al. (1993) found that resting time after work in the vat, during which curd grains were left undisturbed for a few minutes, promoted fusion of adjacent curd grains. Greater fusion increased the fracture stress, which was what we observed for Abondance cheeses. This is associated in the final cheese with higher σ_f, as observed by Akkerman et al. (1993).

Influence of brining on cheese rheology. Brining time and brining temperature can affect NaCl uptake by the cheese. Brining time affects the diffusion of salt into the cheese (Geurts et al. 1974; Guinee & Fox, 1993; Simal et al. 2001). Chamba (1988) investigated the effect of brining conditions on salt absorption and its kinetics on Emmental cheeses, and observed a linear relationship between salt uptake by the cheese and brining temperature. Moreover, relationships between salt concentration and cheese mechanical properties are well documented (Walstra et al. 1987): salt concentration is negatively correlated with M_D and positively with ε_f and σ_f. In our study, the relationships between brining time and rheological properties agree with those found by Walstra et al. (1987). For brining temperature, however, the relationship we observed was not linear and therefore does not agree with the observations of Chamba (1988).

Influence of clotting time and acidification

Influence of clotting time on cheese rheology. We found a non-linear relationship between the clotting time and M_D

and σ_f. Intermediate clotting times were associated with higher M_D and σ_f. It is difficult to link the clotting time to gel structure. As the amount of rennet was not related to cheese rheological behaviour, we can only suppose that the milk properties were responsible for differences in clotting time and that these differences could lead to differences in the gel mechanical properties. These mechanical properties might influence the cheese texture (Green & Grandison, 1993).

Influence of acidification kinetics and 1-d pH on cheese texture. In Abondance cheese, acidification occurs during pressing. The pH after 1 d greatly influences cheese rheological properties. The relationships were not linear. Two components could be distinguished: for pH<5·05 and pH>5·05. Above pH 5·05, pH was positively correlated with ε_f and negatively with M_D, in accord with the findings of Lucey & Fox (1993) who reported variations of texture between pH 5·1 and 5·3 for Cheddar cheese. They suggested that variations of pH modify Ca solubility and therefore cheese texture. At pH<5·05, we may suppose that other phenomena might be involved. The relationships we observed are likely to correspond to a real influence of the acidification kinetics and 1-d pH on the rheological properties of Abondance cheese.

Conclusion

Our study fulfilled its objectives, in that we could hierarchize the respective influences of milk properties and technological parameters on cheese rheological properties after ripening. For this particular cheese variety, milk properties and cheesemaking variables have somehow the same overall influence. Milk properties of interest concern mainly the protein-mineral equilibrium and plasmin supposed activity, and, to a lesser degree, the milk fat composition. The technological practice having most influence is brining. However, it is noteworthy that the most influential variables of all are acidification kinetics and 1-d pH which result from the interaction between technological practices and milk properties.

Further studies are required to confirm these preliminary results and establish the overall mechanisms involved in the development of cheese texture. The same strategy could be applied to other cheese characteristics such as aroma. Such information on the influence of both milk property and technological practice would be of great interest for cheesemakers in optimizing their process. A further step in the investigation would be to study the influence of breeding practices on the milk properties shown to be important to cheese characteristics.

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References

Adda J, Gripon JC & Vassal L 1982 The chemistry of flavour and texture generation in cheese. *Food Chemistry* **9** 115–129

AFNOR Lait 1992 [Determination of total phosphorus concentration in milk. Molecular absorption spectrometric method.] Norme NF ISO 9874

Akkerman JC, Lewis RO & Walstra P 1993 Fusion of curd grains. *Netherlands Milk and Dairy Journal* **47** 137–144

Andrews A 1983 Proteinases in normal bovine milk and their action on caseins. *Journal of Dairy Research* **50** 45–55

Bouton Y & Grappin R 1995 Comparison of the quality of scalded-curd cheeses manufactured from raw or microfiltered milk. *Lait* **75** 31–44

Buchin S, Delague V, Duboz G, Berdagué JL, Beuvier E, Pochet S & Grappin R 1998 Influence of pasteurization and fat composition of milk on the volatile compounds and flavor characteristics of a semi-hard cheese. *Journal of Dairy Science* **81** 3097–3108

Bugaud C, Bornard A, Hauwuy A, Martin B, Salmon JC, Tessier L & Buchin S 2000 [Relationships between the botanical composition of mountain vegetation and its content of volatile compounds.] *Fourrages* **162** 141–155

Bugaud C, Buchin S, Coulon JB, Hauwuy A & Dupont D 2001a Influence of the nature of alpine pastures on plasmin activity, fatty acid and volatile compound composition of milk. *Lait* **81** 401–414

Bugaud C, Buchin S, Noël Y, Tessier L, Pochet S, Martin B & Chamba JF 2001b Relationships between Abondance cheese texture, its composition and that of milk produced by cows grazing different types of pastures. *Lait* **81** 593–607

Chamba JF 1988 Emmental cheese salting. I. Effect of brining conditions on salt absorption and its kinetics. *Lait* **68** 121–142

Durand JF & Sabatier R 1997 Additive Splines for Partial Least Squares regression. *Journal of the American Statistical Association* **92** (440) 1546–1554

Gaucheron F, Graet Y, le Sinbandhit S, Guenot P & Brule G 1995 Binding of calcium to beta-casein in the presence of inorganic phosphate. *Sciences des Aliments* **15** 481–489

Geurts TJ, Walstra P & Mulder H 1974 Transport of salt and water during salting of cheese. I. Analysis of the processes involved. *Netherlands Milk and Dairy Journal* **28** 102–129

Green ML & Grandison AS 1993 Secondary (non-enzymatic) phase of rennet coagulation and post-coagulation phenomena. In *Cheese: Chemistry, Physics and Microbiology*, pp. 101–140 (Ed. PF Fox). London: Elsevier Applied Science

Guinee TP & Fox PF 1993 Salt in cheese: physical, chemical and biological aspects. In *Cheese: Chemistry, Physics and Microbiology*, pp. 257–302 (Ed. PF Fox). London: Elsevier Applied Science

Houssin B, Foret A, Chenais F, Cotinot A & Besnier F 2000 Influence of the winter diet of dairy cows on the organoleptic quality of butters and Camembert cheeses. In *7emes Rencontres autour des Recherches sur les Ruminants. Paris, France, 6–7 decembre 2000*, pp. 296–299. INRA, Paris, France

Lawrence RC, Creamer LK & Gilles J 1987 Texture development during cheese ripening. *Journal of Dairy Science* **70** 1748–1760

Lucey JA & Fox PF 1993 Importance of calcium and phosphate in cheese manufacture: a review. *Journal of Dairy Science* **76** 1714–1724

Marie C & Delacroix-Buchet A 1994 Comparison of A and C variants of the beta- casein in milk from Tarentaise cows used in Beaufort type cheese production. II. Proteolysis and cheese quality. *Lait* **74** 443–459

Marshall RJ 1991 Combined instrumental and sensory measurement of the role of fat in food texture. *Food Quality and Preference Journal* **2** 117–124

Martin B 1993 Influence of breeding practices and cheese manufacturing on milk and cheese characteristics. Doctoral thesis, École Nationale Supérieure Agronomique de Montpellier

Masson C, Rousseaux P & Decaen C 1981 Geographical and seasonal variations in Comté cheese quality. *Lait* **61** 31–48

Noel Y, Zannoni M & Hunter EA 1996 Texture of Parmigiano Reggiano cheese: statistical relationships between rheological and sensory variates. *Lait* **76** 243–254

Pearce KN 1977 The complexometric determination of calcium in dairy products. *New Zealand Journal of Dairy Science and Technology* **12** 113–115

Remeuf F, Vossin V, Dervin C, Lenoir J & Tomassone R 1991 Relationships between the physicochemical characteristics of milk and their suitability for cheesemaking. *Lait* **71** 397–421

Rollema HS, Visser S & Poll JK 1983 Spectrophotometric assay of plasmin and plasminogen in bovine milk. *Milchwissenschaft* **38** 214–217

Simal S, Sanchez ES, Bon J, Femenia A & Rossello C 2001 Water and salt diffusion during cheese ripening: effect of the external and internal resistances to mass transfer. *Journal of Food Engineering* **48** 269–275

Steffen C 1975 Properties and defects of Emmental cheese. *Schweizerische Milchzeitung* **101** 569–570

Tondu F 1986 Urea analysis in cows milk: development of a colorimetric method and study of the milk variability. Report, Maîtrise de Sciences et Techniques, Université de Créteil

Visser S 1993 Proteolytic enzymes and their relation to cheese ripening and flavor: an overview. *Journal of Dairy Science* **76** 329–350

Walstra P, Luyten H & Vliet T van 1987 Consistency of cheese. *Milk the vital force. Proceedings of the XXII International Dairy Congress, The Hague, September 29–October 3, 1986*, pp. 159–168. *D Reidel Publishing Company, Dordrecht, Netherlands*