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Changes in physicochemical characteristics and volatile compounds of apricot (*Prunus armeniaca* L. cv. Bergeron) during storage and post-harvest maturation

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ABSTRACT

The effects of storage and post-harvest maturation on the physicochemical characteristics and volatile constituents of Bergeron apricot were investigated during the 2007 season over two experiments. Fruits, harvested at two distinct stages of maturity, in two different experimental orchards, were stored in cold chambers at +1 °C for up to 3 weeks and then subjected to a post-harvest maturation in ripening chambers at 20 °C and 60–70% RH up to 7 days. Firmness, soluble solids (SS), titratable acidity (TA), and the levels of the main volatiles were determined. Physicochemical changes included a significant decrease of firmness during both storage and post-harvest maturation whereas the levels of SS and TA were found to be very similar. The results also indicated that, whatever their initial stage of maturity at harvest, the rates of softening of apricots during storage and/or post-harvest maturation were very comparable. During post-harvest maturation, the levels of C_6-compounds decreased drastically whereas, at the same time, those of esters, lactones and terpenic compounds greatly increased. During storage at 1 °C, a decrease of C_6-compounds was also observed. As regards other compounds, there were some statistically different results between samples but the changes observed for lactones, esters and terpenic compounds were relatively small in comparison to those observed during post-harvest maturation at 20 °C. The results also showed that, at the end, qualitative and quantitative differences can be observed in the "ready-to-eat" apricots according to their initial stage of maturity at harvest. On average, apricots harvested at the most advanced stage of maturity have, on average, the highest levels of soluble solids and the highest levels of volatile compounds of interest.

1. Introduction

Like peach, apricot (*Prunus armeniaca* L.) originates from China and was introduced into Europe at the beginning of the Roman era (Crouzet, Etievant, & Bayonove, 1990). A member of the Rosaceae family, along with pear, strawberry, apple, cherry, and peach, apricot belongs to the subfamily Prunoideae and the subgenus *Prunus* of the genus *Prunus*. Botanically, apricots are drupes or "stone fruits" – like peaches, plums, cherries, and mangoes – in which an outer fleshy part (exocarp and mesocarp) surrounds a hard stone (endocarp) with a seed inside.

In 2007, the world production was ~3.1 Mt with ~55% in Asia and ~26% in Europe (http://faostat.fao.org). With ~17% of the world production, Turkey is the main producer and provides ~85% of the world's dried apricot and apricot kernels. In Europe, production remains concentrated in Mediterranean-type areas, and the four main producers are Italy (6.9%), France (5.9%), Greece (3.1%), and Spain (2.8%). In France, the production is mainly located in Languedoc-Roussillon and in Vallée du Rhône, and five cultivars represent ~65% of the production. Among them, Bergeron is the main variety and accounts for ~50% of the French production (Lichou, Vaysse, Jay, & Lespinasse, 2003).

It is generally agreed that apricot quality is highly dependent on the maturity stage at harvest. Nevertheless, for commercial reasons (handling, long-distance transport), Bergeron apricot is generally harvested at an early stage of maturity and stored at low temperature (1–2 °C) for up to 3 weeks. Because the formation of the volatile compounds in this fruit is a dynamic process, the typical flavour of apricot is generally not present at harvest but develops after a ripening process. Nevertheless, this post-harvest maturation stage is rarely carried out under optimal conditions and, generally, consumers often complain about the poor quality of Bergeron, incriminating its lack of both sugar and aroma (Bruhn et al., 1991; Guillot et al., 2003; Mencarelli, Botondi, De Santis, & Vizovitis, 2006). Although the first comprehensive studies on apricot volatiles were performed about 40 years ago by Tang and Jennings (1967 and 1968), little work has been done on the flavour of this fruit in comparison to other fruits, such as apple, strawberry or peach (Aubert & Chanforan, 2007; Bitteur

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et al., 1990; Bolzoni, Careri, & Mangia, 1990; Botondi, DeSantis, Bellincontro, Vizovitis, & Mencarelli 2003; Chairote, Rodriguez, & Crouzet, 1981; Crouzet, Chairote, Rodriguez, & Seck, 1983; Crouzet et al., 1990; Genovese et al., 2004; Greger & Schieberle, 2007; Guichard, Schlich, & Issanchou, 1990; Guichard & Souty, 1988; Guillot et al., 2003; Guillot et al., 2006; Gómez & Ledbetter, 1997; Gómez, Ledbetter, & Hartsell, 1993; Issanchou, Schlich, & Guichard, 1989; Mencarelli et al., 2006; Riu-Aumatell, Castellari, Lopez-Tamames, Galassi, & Buxaderas, 2004; Takeoka, Flath, Mon, Teranishi, & Guentert, 1990; Tang & Jennings, 1967, 1968; Tóth-Marcus, Boross, Blazsó, & Kerek, 1989a, 1989b) but variability in aroma compounds has been previously reported to depend on cultivars (Aubert & Chanforan, 2007; Bitteur et al., 1990; Crouzet et al., 1983; Issanchou et al., 1989; Takeoka et al., 1990; Tóth-Marcus et al., 1989a, 1989b), maturity (Aubert & Chanforan, 2007; Gómez et al., 1993; Issanchou et al., 1989), or processing and storage conditions (Aubert & Chanforan, 2007; Bitteur et al., 1990; Chairote et al., 1981; Gómez & Ledbetter, 1997; Tóth-Marcus et al., 1989b). Concerning the variety Bergeron, most work has been done on its aroma composition (Aubert & Chanforan, 2007; Bolzoni et al., 1990; Crouzet et al., 1983; Greger & Schieberle, 2007; Issanchou et al., 1989; Tóth-Marcus et al., 1989a). The evolution of volatiles during storage and/or post-harvest maturation has, to our best knowledge, been scarcely studied (Aubert & Chanforan, 2007). The aim of this work was to investigate the changes in physicochemical properties and volatile constituents of Bergeron apricot harvested at two stages of maturity in two experimental orchards, stored at +1 °C for up to 3 weeks and then ripened under controlled conditions at 20 °C for up to 7 days.

2. Materials and methods

2.1. Solvent and chemicals

Analytical grade chloroform (Chromasolv Plus, 99.9%) was obtained from Sigma (Saint Quentin Fallavier, France). Ethanol (HPLC gradient grade, 99.8%) and *n*-propyl gallate ($\geqslant$98%) were from Fluka (Saint Quentin Fallavier, France). Ammonium sulfate $(NH_4)_2SO_4$ ($\geqslant$99%), and *n*-alkane standards (C_8–C_{40}) were from Riedel-de Haën (Saint Quentin Fallavier, France). Reference compounds were obtained from Sigma–Aldrich (Saint Quentin Fallavier, France) (butyl acetate, pentyl acetate, hexyl acetate, (*Z*)-3-hexenyl acetate, hexanal, (*E*)-2-hexenal, butanol, 6-methyl-5-hepten-2-ol, 6-methyl-5-hepten-2-one, benzaldehyde, linalool, α-terpineol, γ-octalactone, γ-nonalactone, and γ-decalactone), Interchim (Montluçon, France) (γ-hexalactone, δ-octalactone, δ-decalactone, and γ-dodecalactone), and Fluka (acetic acid, hexanol, (*Z*)-3-hexen-1-ol, and γ-jasmolactone). 2-Octanol (98%) was from Sigma (Saint Quentin Fallavier, France). Deionized water (0.050 $\mu S\ cm^{-1}$), used in all experiments, was obtained from Milli-Q system (Millipore, Molsheim, France).

2.2. Samples

Apricots (*P. armeniaca* L. cv. Bergeron), provided by the Groupement d'Intérêt Economique (GIE) of Tain l'Hermitage (France), were collected in July 2007, in two experimental orchards, namely Torras (experiment 1) and Gaec du Bergeron (experiment 2), located in Larnage (Drôme, France). In both experiments, the fruits were harvested at two stages of maturity, respectively, 3 and 5, determined by the measurement of the external colour of the skin, using the Ctifl apricot colour chart, that provides 10 shades from 1 (green) to 10 (red-orange). Fruits (~150 kg for each experiment) were hand-picked and immediately transported to the laboratory. Healthy fruits were then immediately selected on the basis of skin colour, uniformity and size, and divided into two batches according to their maturity stage. For each maturity stage, 60 kg-batches of apricot (~900 fruits) were divided into sub-samples of 10 fruits and placed in trays. Physicochemical measurements and analyses of volatiles were performed on apricots after a period of storage at +1 °C for up to 3 weeks (0, 7, 14 and 21 days), followed by a period of maturation at 20 °C and ~70% RH for up to one week (0, 48, 72, and 168 h). All measurements were performed in triplicate (3 replications of 10 fruits).

2.3. Firmness determination

Firmness was determined on two opposite sides of apricots ($N = 10$) using an electronic Durofel (licensed by Copa-Ctifl) with a 0.10 cm^2 tip. Durofel is a non-destructive dynamometer that provides a measure of the force used to press a spring-loaded pawl against the fruit surface (Aubert & Chanforan, 2007). The measurements are expressed in ID_{10} on a scale ranging from 0 (very soft) to 100 (very hard).

2.4. Soluble solids content and titratable acidity

For each sample, and after firmness determination, apricots ($N = 10$) were sliced and pitted and flesh cubes (~1 cm^3) were prepared. Cubes were then immediately frozen with liquid nitrogen, and stored at −25 °C prior to analysis. About one hundred grammes of frozen tissues were then thawed for ~30 min at ambient temperature, and homogenized in a blender (Waring, US). Soluble solids (SS) were then determined on the purée with an Atago PR-101 digital refractometer. Titratable acidity (TA) was determined by diluting 5 g of the purée with 50 ml of deionized water and titrating to pH 8.1 with 0.1 N NaOH, using a Crison Compact II automatic titrator with autosampler (Barcelone, Spain).

2.5. Isolation of volatiles

Isolation of volatiles was performed according to the liquid–liquid microextraction (LLME) method previously described by Aubert, Baumann, and Arguel (2005) with some modifications. One hundred grammes of frozen tissues (see above), 90 ml of deionized water and 100 μl of 2-octanol (401 μg/ml) (internal standard) were allowed to stand at room temperature for 3 min longer and homogenized in a blender for 90 s (Waring, US). Ten millilitres of *n*-propyl gallate (100 mM in EtOH) were then added, and the mixture was blended again for 15 s. The mixture was centrifuged (14,000*g*, 5 min, 4 °C) and the supernatant was filtered through a Whatman (Maidstone, UK) paper filter (grade 113v). Forty millilitres of supernatant, treated with 12.8 g of $(NH_4)_2SO_4$ (32%; w/v), were agitated until complete salt dissolution occurred and ultracentrifuged (21,000*g*, 5 min, 4 °C). The supernatant was then introduced into a 50 ml screw-capped conical centrifuge tube (34 × 98 mm glass borosilicate) containing a magnetic stir bar (15 × 6 mm); 200 μl of chloroform were added, and the mixture was extracted for 30 min under magnetic stirring at room temperature. After removing the magnetic stir bar, the tube was sonicated for 1 min in a Branson Ultrasonic Cleaner 5510 (Danbury, US), and centrifuged (2000*g*, 3 min, 4 °C). Chloroform extract was then recovered with a 50 μl syringe, transferred to a 100 μl vial and immediately injected into the GC–MS and GC–FID apparatus. Concentrations of volatiles (Tables 3–5) are given as averages and min–max ranges for the two experiments (3 replications of homogenized apricot pulp of 10 fruits). The average standard deviation was 23.3% for concentrations lower than

Table 1
Physicochemical characteristics of the different samples of apricot.

Stage of maturity	Post-harvest maturation at 20 °C (h)	Storage at 1 °C (days)								
		0		7		14		21		*F* (*p*)[a]
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	
Firmness (ID10)										
3	0	76 dC	75–77	73 bD	72–74	69 cA	66–73	67 cA	65–68	38.9(***)
	48	66 cD	64–68	59 aC	55–64	55 bB	53–56	48 bA	46–50	76.6(***)
	72	61 bC	59–62	54 aB	47–61	50 aB	47–55	40 aA	37–44	29.7(***)
	168	50 a	47–51							
F (*p*)		454.3(***)		29.5(***)		109.2(***)		380.8(***)		
5	0	72 dD	71–73	68 cC	67–70	66 cB	65–67	62 cA	59–64	62.1(***)
	48	61 cD	59–64	55 bC	48–59	48 bB	47–49	41 bA	38–46	46.7(***)
	72	53 bC	50–57	50 aC	45–54	42 aB	39–46	35 aA	33–37	50.5(***)
	168	43 a	39–44							
F (*p*)		264.7(***)		41.2(***)		340.3(***)		220.6(***)		
Soluble solids (%Brix)										
3	0	9.7 aA	9.2–10.0	10.3 aA	9.5–11.5	10.2 aA	9.3–11.4	10.5 aA	9.9–11.8	2.0 (ns)
	48	10.1 abA	9.6–10.6	10.6 aA	10.1–11.1	10.3 aA	9.9–10.7	10.5 aA	10.1–11.0	2.1 (ns)
	72	10.2 abA	9.7–10.8	10.3 aA	10.0–10.4	10.7 aA	10.2–11.4	10.7 aA	10.1–11.5	1.8 (ns)
	168	10.6 b	10.1–11.3							
F (*p*)		4.4(*)		0.8 (ns)		1.5 (ns)		0.1 (ns)		
5	0	10.5 aA	10.4–10.7	10.6 aA	10.3–10.9	10.6 aA	10.3–10.8	11.4 aB	10.6–12.1	7.9(**)
	48	10.8 abA	10.5–11.3	11.0 bA	10.6–11.4	11.3 bA	10.9–11.6	11.2 aA	10.8–11.7	2.5 (ns)
	72	11.0 abA	10.4–12.0	11.3 cA	11.2–11.8	11.1 bA	10.5–11.7	11.1 aA	10.7–11.6	0.8 (ns)
	168	11.3 b	10.9–11.8							
F (*p*)		5.2(**)		11.9(***)		8.2(**)		0.5 (ns)		
Titratable acidity (mequiv/100 g)										
3	0	29.5 aA	27.5–32.8	29.1 aA	26.3–32.3	28.9 aA	26.6–31	28.5 aA	25.8–31.6	0.2 (ns)
	48	29.0 aA	26.1–32.5	29.2 aA	26.5–30.9	26.9 aA	25.7–28.3	28.0 aA	24.8–31.3	1.2 (ns)
	72	28.8 aA	27.1–30.8	28.2 aA	25.0–30.3	27.5 aA	25.0–30.7	26.4 aA	23.6–29.6	1.4 (ns)
	168	28.8 a	26.8–31.2							
F (*p*)		0.1 (ns)		0.3 (ns)		1.7 (ns)		1 (ns)		
5	0	28.7 aA	26.6–31.2	28.7 aA	26.4–30.7	28.3 aA	26.2–31.3	28.0 aA	26.5–29.8	0.2 (ns)
	48	28.8 aA	27.3–30.5	28.2 aA	26.3–29.5	27.9 aA	26.1–29.8	26.3 aA	22.7–28.9	2.7 (ns)
	72	28.4 aB	26.8–30.5	28.6 aB	26.5–30.1	26.9 aAB	25.4–28.6	26.3 aA	25.0–27.3	4.3(*)
	168	28.6 a	26.4–30.6							
F (*p*)		0.1 (ns)		0.2 (ns)		1.2 (ns)		2.2 (ns)		

For a given stage of maturity, means within the same storage time followed by the same small letters are not significantly different ($F_{(0.05;\ 2,15)} = 3.7$; $F_{(0.05;\ 2,15)} = 6.4$; $F_{(0.05;\ 2,15)} = 11.3$ or $F_{(0.05;\ 3,20)} = 3.1$; $F_{(0.01;\ 3,20)} = 4.9$; $F_{(0.001;\ 3,20)} = 8.1$, respectively, for 3 and 4 levels). For a given stage of maturity, means within the same post-harvest maturation time followed by the same capital letters are not significantly different ($F_{(0.05;\ 3,20)} = 3.1$; $F_{(0.01;\ 3,20)} = 4.9$; $F_{(0.001;\ 3,20)} = 8.1$).

[a] ns, not significant.

[*] $p < 0.05$.

[**] $p < 0.01$.

[***] $p < 0.001$.

10 ppb, 21.3% from 10 to 50 ppb, and 23.7% for higher concentrations.

2.6. GC–FID conditions

A Varian 3800 gas chromatograph equipped with a DB-Wax Etr (J&W Scientific) capillary column (30 m × 0.25 mm i.d., 0.25 μm film thickness) was used. The flow of hydrogen 5.7 (Linde) carrier gas was 1.3 ml/min. The oven temperature was kept at 40 °C for 3 min, then programmed to 250 °C at 5 °C/min, and kept at 250 °C for 15 min. Injections (1 μl) were performed using a 1079 Programmable Temperature Vaporizing (PTV) injector from Varian, using the following injection programme: initially 20 °C for 0.1 min, then programmed to 250 °C at 200 °C/min, and kept at 250 °C. Injections were performed using a CombiPAL autosampler equipped with a Peltier cooling rack at 4 °C (CTC Analytics, Switzerland). The FID detector was kept at 250 °C. The levels of the volatile compounds were expressed as 2-octanol equivalents (assuming all of the response factors were 1). The concentrations are to be considered as relative data because recovery factors (after extraction and calibration) related to the standard were not determined.

2.7. GC–MS conditions

A Varian 3800 gas chromatograph was used with the same DB-Wax Etr capillary column as above. The oven and injector temperature programmes were as above. Injections (1 μl) were performed using a CombiPAL autosampler (CTC Analytics). The flow of helium 6.0 (Linde) carrier gas was 1 ml/min. A Saturn Ion-Trap mass spectrometer was used. Mass spectra were recorded in electronic impact (EI) ionization mode. The ion trap, the manifold, and the transfer line temperatures were set, respectively, at 150, 45, and 250 °C. Mass spectra were scanned in the range *m/z* 30–350 amu at 1 s intervals. Compounds were first identified using NIST/EPA/NIH MS Search 2.0 and our own mass spectra libraries. Identities of most of them were then confirmed by comparison of their linear retention indices and EI mass spectra with those of reference compounds.

2.8. Statistical analysis

Analysis of variance and principal component analysis (PCA) were performed using Statbox 6.7 (Grimmersoft, Paris).

Table 2
Volatiles identified in the different samples of apricot.

Compounds	Code	RI[a]	ID[b]
Butyl acetate	E1	1073	A
Hexanal	C1	1082	A
Butanol	O1	1123	A
Pentyl acetate	E2	1154	A
(*E*)-2-hexenal	C2	1221	A
Hexyl acetate	E3	1274	A
(*Z*)-3-Hexenyl acetate	E4	1317	A
6-Methyl-5-hepten-2one	O2	1347	A
Hexanol	C3	1356	A
(*Z*)-3-Hexen-1ol	C4	1386	A
Acetic acid	O3	1432	A
Benzaldehyde	O4	1521	A
Linalool	T1	1533	A
6-Methyl-5-hepten-2-ol	O5	1574	A
α-Terpineol	T2	1698	A
γ-Hexalactone	L1	1703	A
γ-Octalactone	L2	1920	A
δ-Octalactone	L3	1966	A
γ-Nonalactone	L4	2031	A
γ-Decalactone	L5	2146	A
γ-Jasmolactone	L6	2182	A
δ-Decalactone	L7	2193	A
(*Z*)-7-Decen-5-olide	L8	2261	B
Dihydroactinidiolide	T3	2296	B
γ-Dodecalactone	L9	2364	A

[a] Linear retention index on DB-Wax Etr (J&W Scientific) based on a series of *n*-hydrocarbons.

[b] A, identified by mass spectrum and linear retention index of reference compounds; B, tentatively identified by mass spectrum and linear retention index similar to mass libraries or published data.

3. Results and discussion

The effects of maturity stage, storage, and/or post-harvest maturation on the physicochemical characteristics and volatile constituents of Bergeron apricot were investigated during the 2007 season over two experiments. The fruits, harvested at two different stages of maturity in two different experimental orchards, were stored for up to 3 weeks in cold chambers at 1 °C and then subjected to post-harvest maturation in a ripening chamber at 20 °C and 60–70% RH until the apricots were considered "ready-to-eat". The maximum length of post-harvest maturation at 20 °C was set at 7 days for apricots not subjected to cold conservation at 1 °C. For the other samples, this period was limited to 3 days, in accordance with prior experiments. Firmness, soluble solids (SS), titratable acidity (TA), and the levels of the main volatiles were determined. Twenty-five volatile compounds, including 4 esters, 4 C_6-compounds, 3 terpenic compounds, 9 lactones and 5 other constituents (2 alcohols and 3 carbonyl compounds), were extracted by LLME and analyzed by GC–FID and GC–MS. The physicochemical characteristics and the levels of volatiles in the different samples are given in Tables 1 and 3–5, in which the sets of results from the two orchards have been merged. The data are given as averages and minimum–maximum ranges in the two experiments.

A principal component analysis (PCA) was performed to graphically summarize the distribution of the 28 variables (3 physicochemical characteristics and 25 volatiles) within the different Bergeron apricots (52 samples) (Fig. 1). As shown in Fig. 1A, 63% of the total variance was explained by the first two axes. The first axis (50% of the variance explained) mainly discriminates the samples with 72 or 168 h of post-harvest maturation at 20 °C from those without the ripening process, whereas the second axis (13% of the variance explained) mainly discriminates samples of experiment 1 from those of experiment 2. The distribution of the variables is shown in Fig. 1B. Except for 8 variables out of the 28 (O1–O4, C1, C4, IR, and L9), most of them are well correlated on the first two axes, and more particularly with PC1 (~50% of the variables showed a squared factor loading on the first axis >0.50). Samples with 3 or 7 days of post-harvest maturation, positively located on the first axis, are characterized by high levels of esters and lactones, and particularly those of butyl acetate (E1), pentyl acetate (E2), hexyl acetate (E3), (*Z*)-3-hexenyl acetate (E4), γ-hexalactone (L1), γ- and δ-octalactone (L2, L3), γ- and δ-decalactone (L5, L7), γ-jasmolactone (L6), and (*Z*)-5-decen-5-olide (L8). Samples without the ripening process, negatively located in the first axis, are mainly defined by high levels of firmness. Samples from the first experiment, positively located on the second axis, are mainly characterized by higher levels of titratable acidity (TA) and (*E*)-2-hexenal (C2) whereas those of the second experiment, negatively located on this axis, are mainly characterized by higher levels of dihydroactinidiolide (T3).

As shown in Table 1, the most significant changes observed in the physicochemical characteristics were a significant decrease of firmness during both storage and post-harvest maturation, with a more pronounced effect at 20 °C. As indicated, the rates of softening of apricots during storage and/or post-harvest maturation were found to be very similar, whatever their initial stage of maturity at harvest. For both stages, the decrease of firmness was ~0.4 ID_{10} per day at 1 °C over the 3 weeks, whereas it was 10 times higher (~4 ID_{10} per day) during ripening at 20 °C for samples not previously stored at 1 °C. The results also indicated that, the longer the samples were stored at 1 °C, the greater was the decrease of firmness during the phase of maturation at 20 °C (up to ~10 ID_{10} per day for 3 weeks of storage). Although soluble solids contents and titratable acidity results were statistically different between samples, the changes observed during storage and/or post-harvest maturation were relatively weak and the levels in samples were found overall, to be similar to those observed at harvest. Finally, it is important to note that, for a given storage and/or post-harvest maturation time, the levels of firmness and soluble solids were always, respectively, higher and lower in samples harvested at stage 3 in comparison to those observed in samples harvested at stage 5.

As indicated in Fig. 2 and Tables 3–5, the effects of storage and/or post-harvest maturation on Bergeron volatiles are mainly characterized by opposite changes in two major groups of volatiles. The first group consisted of C_6 compounds, alcohols and carbonyl compounds, and the second of lactones, esters and terpenic compounds. As shown, whatever the stage of maturity at harvest, C_6 compounds, aldehydes and alcohols, products of enzymatic breakdown of unsaturated fatty acids (Sanz, Olias, & Perez, 1997), are the main compounds isolated in unripened apricots, from 60% in samples harvested at stage 5 with 2 weeks of storage to 83% in apricots harvested at stage 3 (Fig. 2). During storage and/or post-harvest maturation, the relative proportion of these so-called green components, in particular those of (*E*)-2-hexenal (Tables 3 and 4), decreased drastically, up to ~20% in samples harvested at stage 5 with 7 days of ripening or 3 weeks of storage, followed by 3 days at 20 °C. The results also indicated that, after ripening at 20 °C, the relative proportion of C_6-compounds in "ready-to-eat" apricots was, on average, always higher in samples harvested at stage 3 than in samples harvested at stage 5, respectively, 53% and 27%. A diminution of the levels of alcohols and carbonyl compounds was also observed, mainly during maturation at 20 °C. With decreasing concentrations of C_6 compounds during the ripening process, lactones and esters increase during the same time and become the major volatiles in apricots. Among them γ-hexalactone , γ- and δ-octalactone, γ- and δ-hexalactone, γ-jasmolactone, and (*Z*)-7-decen-5-olide, previously reported to be important impact compounds in stone fruits (Berger, 1991; Derail, Hofmann, & Schieberle 1999; Engel et al., 1988; Greger & Schieberle, 2007; Takeoka et al., 1992) and to be responsible for the fruity background aroma of apricot (Chairote et al., 1981; Crouzet et al., 1983; Greger & Schi-

Table 3
Levels of volatiles[a] in the different samples of apricot harvested at maturity stage 3.

Code[b]	Storage at +1°C (days)												
	0				7			14			21		
	Postharvest maturation at +20°C (h)												
	0	48	72	168	0	48	72	0	48	72	0	48	72
Alcohols and carbonyl compounds													
O1	7	26	40	47	3	15	16	5	9	24	7	9	22
	0-18	4-47	15-64	18-100	0-9	12-18	7-31	2-9	6-12	16-33	4-11	7-11	10-36
O2	2	1	1	1	3	2	2	2	2	2	2	1	2
	0-5	0-2	0-2	0-3	0-7	1-2	1-2	1-3	2-2	2-2	1-3	1-2	1-2
O3	302	161	138	37	388	123	52	215	82	49	184	82	59
	165-405	39-322	41-318	27-58	118-536	88-165	18-119	168-308	25-195	10-116	30-325	14-156	33-86
O4	4	5	5	4	4	4	4	4	4	4	4	4	5
	0-8	3-9	3-6	2-6	3-8	1-8	3-5	3-7	3-6	3-6	2-6	3-5	4-8
O5	-[c]	2	2	4	3	2	2	3	3	3	2	2	3
		1-3	2-3	3-5	2-4	1-3	1-3	2-3	2-4	2-4	1-3	2-4	2-4
C_6 compounds													
C1	130	168	229	158	102	173	125	53	66	71	44	54	62
	70-182	67-271	164-279	89-249	74-138	127-210	89-180	36-78	25-92	59-97	33-66	46-67	52-77
C2	2057	1809	1344	926	1844	1487	1118	1107	755	635	704	617	540
	1832-2459	1611-1988	1091-1669	837-1055	1643-2200	1415-1653	884-1349	1001-1422	711-800	533-797	477-944	485-780	409-670
C3	1	7	11	8	1	6	7	3	5	6	3	4	6
	0-4	4-10	8-15	7-11	0-2	5-7	5-11	2-4	3-8	5-7	3-4	4-5	5-8
C4	-	3	3	3	-	3	2	0	1	2	0	1	1
		2-3	2-4	2-4		2-5	1-3	0-1	1-2	1-3	0-1	1-1	0-2
Esters													
E1	15	79	178	234	4	78	123	9	37	137	11	53	263
	7-40	27-143	97-300	140-283	2-6	53-119	43-211	3-21	26-50	83-181	5-18	38-62	181-331
E2	1	4	8	12	2	5	6	1	3	7	1	4	10
	0-3	1-7	5-12	8-16	0-10	3-7	3-8	0-1	2-3	5-8	0-2	3-4	9-12
E3	-	17	37	63	-	18	23	1	9	22	0	12	36
-		9-23	29-51	27-98		7-29	12-42	0-2	5-13	16-31	0-1	8-14	27-55
E4	-	2	2	8	-	-	2	-	1	3	-	1	4
		1-2	0-4	4-13			0-5		0-2	2-4		1-2	3-5
Lactones													
L1	12	51	94	177	17	58	102	29	56	128	26	66	119
	9-16	41-62	76-109	152-198	6-30	15-103	41-191	13-62	41-65	77-179	13-51	41-96	57-166
L2	13	18	28	43	1	10	18	3	7	14	-	6	15
	6-22	14-20	23-34	33-52	0-3	5-18	11-25	0-7	5-9	12-16			
L3	-	3	8	16	-	8	19	0	5	25	-	11	35
		2-4	6-14	10-24		0-19	4-33	0-1	4-6	15-37		5-17	23-48
L4	-	-	2	3	-	1	2	0	0	1	-	0	2
			2-3	2-4		0-1	1-2	0-1	0-1	1-1		0-1	1-2
L5	15	61	109	161	6	62	85	7	34	75	1	38	106
	8-38	34-84	69-173	94-245	2-10	20-101	33-141	2-18	29-42	68-92	0-2	22-59	56-176
L6	7	19	40	98	12	18	46	3	8	34	1	12	42
	0-20	16-22	34-46	60-134	1-28	6-32	11-85	1-7	7-10	19-49	0-6	5-19	25-62
L7	-	31	55	55	4	36	41	4	20	45	3	30	70
		11-52	28-110	35-96	0-10	9-69	13-82	1-11	13-25	39-57	0-7	20-41	47-102
L8	-	4	11	23	-	22	21	-	5	25	-	10	38
		2-5	7-18	13-39		16-32	3-43		4-5	14-38		4-16	22-54
L9	18	10	6	13	8	9	6	5	3	5	3	10	6
	7-30	6-16	4-9	7-26	5-10	4-16	3-10	4-6	3-4	3-7	1-3	4-21	4-8

Table 3 (*continued*)

Code[b]	Storage at +1°C (days)												
	0				7			14			21		
	Postharvest maturation at +20°C (h)												
	0	48	72	168	0	48	72	0	48	72	0	48	72
Terpenic compounds													
T1	11	11	14	13	12	14	15	10	7	14	9	9	15
	5-18	6-19	8-18	4-23	9-18	5-26	7-25	6-16	6-8	9-19	5-13	5-15	12-19
T2	5	5	6	5	4	5	6	4	3	5	4	4	6
	2-9	3-6	4-7	2-8	3-5	1-10	3-9	2-5	3-4	4-7	3-6	2-5	5-7
T3	21	31	36	75	38	40	35	32	42	38	36	42	49
	15-30	15-48	19-61	43-110	10-64	14-63	18-50	21-42	25-62	25-56	21-54	24-62	32-69
Total	2620	2529	2405	2188	2454	2199	1875	1499	1166	1372	1044	1081	1514
	2409-2940	2149-2951	1865-3033	1879-2482	1905-2862	2023-2467	1404-2405	1321-1837	1090-1242	1074-1641	775-1285	820-1352	1176-1972

[a] Average values expressed in µg/kg equivalents of 2-octanol and min-max range on the two experiments ($n = 6$).

[b] See Table 2.

[c] Not detected.

Table 4
Levels of volatiles[a] in the different samples of apricot harvested at maturity stage 5.

Code[b]	Storage at +1°C (days)												
	0				7			14			21		
	Postharvest maturation at +20°C (h)												
	0	48	72	168	0	48	72	0	48	72	0	48	72
Alcohols and carbonyl compounds													
O1	12	27	41	46	5	16	23	5	14	25	10	13	25
	6-21	6-61	1-75	20-79	4-7	12-20	13-38	0-8	9-24	20-31	6-15	8-23	10-39
O2	2	1	1	1	2	2	2	2	2	2	2	1	2
	2-3	0-2	0-2	0-3	1-2	1-2	2-2	1-4	2-2	1-2	1-3	1-1	1-2
O3	179	160	95	23	220	104	61	209	88	69	139	65	73
	53-289	41-352	40-196	10-45	147-297	53-149	15-145	147-284	16-235	12-161	58-249	18-129	24-131
O4	3	4	4	4	3	3	5	3	4	4	4	4	10
	0-7	3-6	2-7	2-6	2-7	2-5	4-6	1-4	4-4	3-6	2-7	3-6	4-23
O5	1	3	4	6	5	4	3	3	4	3	3	3	5
	0-2	2-5	2-6	5-9	3-7	3-5	0-4	0-6	3-6	2-4	2-4	2-4	3-7
C_6 compounds													
C1	90	91	101	66	59	77	59	24	37	40	34	22	42
	65-127	37-184	2-138	55-82	29-79	45-104	43-67	9-32	26-48	23-61	16-53	16-40	25-61
C2	1306	912	650	506	770	599	497	526	370	247	587	299	218
	1062-1768	770-1129	516-753	411-617	641-924	541-668	430-565	482-554	304-468	96-320	368-702	223-382	177-296
C3	4	10	15	13	1	7	9	3	7	7	4	6	8
	3-5	5-19	8-20	9-17	0-3	6-9	7-13	2-4	5-10	6-8	3-6	5-10	6-13
C4	-[c]	2	2	2	1	1	2	0	1	1	1	1	1
		2-5	1-3	1-3	0-1	1-1	1-2	0-1	1-1	1-2	0-1	0-1	1-2
Esters													
E1	30	131	331	740	7	192	209	9	69	201	22	75	335
	16-49	61-210	4-573	484-1120	3-13	90-313	88-413	3-17	40-113	147-273	14-33	52-130	223-438
E2	2	6	11	25	1	6	8	2	4	9	2	5	12
	1-3	3-10	0-18	18-35	1-2	4-8	5-13	0-2	3-6	8-10	1-2	4-7	9-15
E3	7	30	50	127	2	22	34	1	16	30	2	19	33
	0-19	21-43	6-73	64-228	1-3	13-34	21-53	0-3	10-21	25-35	0-4	12-31	21-46
E4	1	2	2	13	-	2	2	-	1	3	-	1	4
	0-2	2-3	0-5	8-20		0-4	0-4		1-2	3-4		1-1	3-6
Lactones													
L1	20	65	120	271	25	64	137	32	81	129	36	72	167
	12-32	55-87	87-192	236-318	5-45	18-116	54-240	17-61	44-123	91-168	17-60	51-94	112-236
L2	14	26	40	63	11	14	24	5	11	17	1	7	18
	11-19	18-40	25-49	48-74	8-19	6-23	16-35	2-8	8-14	14-22	0-2	5-9	14-22
L3	1	8	21	43	0	12	27	0	11	34	-	13	49
	0-1	4-13	6-32	27-65	0-1	1-25	10-54	0-1	7-15	28-42			
L4	-	-	3	5	0	1	2	0	1	2	-	1	2
			2-4	4-6	0-1	0-2	2-3	0-1	0-1	1-2		0-1	2-2
L5	22	105	178	294	21	73	117	6	55	95	2	52	104
	16-30	59-154	86-243	216-443	13-37	35-115	65-175	2-14	38-74	74-104	1-4	39-64	49-162
L6	9	28	55	161	10	20	51	4	13	39	1	12	47
	5-14	23-34	33-82	122-243	6-15	5-35	21-87	1-10	8-18	30-48	0-6	8-16	24-77
L7	-	67	117	153	13	48	71	5	41	69	3	50	75
		26-109	38-172	94-247	5-21	21-85	35-124	1-8	28-56	46-86	0-7	36-59	51-101
L8	-	9	25	67	1	12	30	0	10	33	-	11	46
		5-14	8-38	38-125	0-2	2-24	9-61	0-1	5-14	25-46		7-15	29-68
L9	9	11	11	18	5	12	7	6	6	4	9	9	7
	3-16	7-15	2-19	7-36	2-6	9-15	5-9	4-13	2-11	3-5	2-22	4-14	5-13

Table 4 (*continued*)

Code[b]	Storage at +1°C (days)												
	0				7			14			21		
	Postharvest maturation at +20°C (h)												
	0	48	72	168	0	48	72	0	48	72	0	48	72
Terpenic compounds													
T1	10	11	16	15	10	12	16	8	8	14	8	9	16
	4-17	8-13	12-24	5-27	7-12	5-16	11-23	5-13	6-11	12-16	5-11	6-10	11-19
T2	3	5	7	6	3	4	6	3	4	6	4	4	7
	1-6	3-6	6-10	5-9	3-4	1-6	4-9	2-5	3-4	5-6	3-4	3-5	6-9
T3	33	54	67	111	60	66	55	57	63	56	53	60	62
	17-52	28-87	24-105	75-179	31-97	43-122	28-73	30-113	35-93	30-85	39-69	41-80	46-80
Total	1755	1769	1966	2780	1235	1372	1456	914	921	1139	927	815	1369
	1542-2323	1319-2345	1440-2554	2265-3626	976-1402	1264-1490	1106-1991	843-989	679-1200	914-1400	578-1087	658-1051	1047-1695

[a] Average values expressed in µg/kg equivalents of 2-octanol and min-max range on the two experiments ($n = 6$).
[b] See Table 2.
[c] Not detected.

Table 5
Levels (µg/kg) of the main chemical classes in the different samples of apricot.

Stage of maturity	Post-harvest maturation at 20 °C (h)	Storage at 1 °C (days)												
		0			7			14			21			F (p)^a
		Mean		Range	Mean		Range	Mean		Range	Mean		Range	
Alcohols and carbonyl compounds														
3	0	314	bAB	173–424	400	bB	127–552	229	bAB	179–321	198	bA	40–341	3.3(*)
	48	195	abA	50–373	146	aA	111–184	100	aA	47–206	98	aA	29–172	2.2 (ns)
	72	186	abA	66–389	76	aA	32–158	82	aA	40–147	90	aA	59–131	2.8 (ns)
	168	93	a	61–154										
F (p)		4.7(*)			12.8(***)			13.5(***)			4.3(*)			
5	0	197	aA	68–307	235	bA	159–314	222	bA	155–298	159	aA	74–263	1.5 (ns)
	48	195	aA	56–421	129	aA	81–171	112	aA	43–255	87	aA	40–151	1.5 (ns)
	72	145	aA	68–268	93	aA	36–188	103	aA	41–200	115	aA	56–169	0.8 (ns)
	168	79	a	58–100										
F (p)		2.1 (ns)			10.7(**)			5.9(*)			2.7 (ns)			
C$_6$ compounds														
3	0	2189	cC	1916–2638	1947	cC	1717–2303	1163	bB	1053–1503	752	aA	518–985	56.1(***)
	48	1987	cD	1740–2111	1668	bC	1581–1871	826	aB	780–858	676	aA	537–830	189.4(***)
	72	1587	bC	1353–1897	1252	aB	1004–1482	715	aA	604–865	609	aA	469–755	52.1(***)
	168	1096	a	971–1154										
F (p)		42.3(***)			21.2(***)			25.7(***)			1.3 (ns)			
5	0	1399	cC	1133–1900	831	cB	673–1002	553	cA	517–576	626	bAB	389–754	27.8(***)
	48	1016	bC	884–1203	685	bB	600–765	415	bA	345–505	328	aA	249–432	69.3(***)
	72	768	aC	527–894	566	aB	504–641	295	aA	167–360	269	aA	229–329	51.8(***)
	168	587	a	498–719										
F (p)		22.2(***)			12.3(***)			27.5(***)			26.9(***)			
Esters														
3	0	16	aA	9–43	5	aA	2–13	10	aA	5–22	12	aA	6–19	1.7 (ns)
	48	101	bA	39–174	100	bA	67–154	50	bA	35–64	70	bA	51–82	2.8 (ns)
	72	224	cAB	134–364	155	bA	58–256	168	cA	107–223	313	cB	221–397	5.1(**)
	168	318	d	179–386										
F (p)		23.9(***)			8.4(**)			62.1(***)			97.6(***)			
5	0	40	aB	17–72	10	aA	5–18	12	aA	7–19	25	aAB	16–39	6.1(**)
	48	169	abB	90–262	221	bB	124–331	91	bA	56–140	100	bA	70–169	5.8(**)
	72	393	bAB	10–664	254	bA	115–481	244	cA	184–320	384	cA	256–505	1.6 (ns)
	168	905	cA	612–1403										
F (p)		22.9(***)			12.1(***)			63.6(***)			60.1(***)			
Lactones														
3	0	65	aB	45–80	48	aAB	29–60	51	aAB	31–98	33	aA	17–54	3.5(*)
	48	199	bA	152–241	226	bA	83–374	138	bA	125–150	183	bA	109–258	1.6 (ns)
	72	352	cA	269–502	338	bA	121–598	350	cA	251–449	432	cA	259–630	0.5 (ns)
	168	589	d	414–809										
F (p)		48.1(***)			6.3(*)			50.5(***)			24.5(***)			
5	0	73	aA	51–113	85	aA	61–142	58	aA	37–97	52	aA	31–81	2.3 (ns)
	48	319	bA	206–445	255	aA	113–434	229	bA	144–298	227	bA	166–277	1.2 (ns)
	72	570	cA	295–721	466	bA	223–787	422	cA	356–520	516	cA	356–723	0.9 (ns)
	168	1077	d	860–1533										
F (p)		39.9(***)			8.7(**)			74.5(***)			36.8(***)			

Table 5 (*continued*)

Stage of maturity	Post-harvest maturation at 20 °C (h)	Storage at 1 °C (days)												
		0			7			14			21			*F* (*p*)[a]
		Mean		Range	Mean		Range	Mean		Range	Mean		Range	
Terpenic compounds														
3	0	37	aA	28–41	54	aA	28–77	45	aA	38–58	49	aA	33–63	1.6 (ns)
	48	47	aA	35–60	59	aA	49–71	53	aA	37–73	54	aA	44–71	1.1 (ns)
	72	55	aA	43–80	55	aA	44–69	57	aA	48–69	69	bA	57–87	2.1 (ns)
	168	92	b	68–120										
F (*p*)		18.3(***)			0.2 (ns)			1.6 (ns)			4.9(*)			
5	0	46	aA	37–58	73	aA	46–107	69	aA	48–124	65	aA	53–78	1.8 (ns)
	48	70	abA	43–100	82	aA	65–129	75	aA	49–106	73	abA	55–89	0.3 (ns)
	72	90	bA	42–130	77	aA	52–88	75	aA	52–102	85	bA	73–105	0.7 (ns)
	168	133	c	102–189										
F (*p*)		12.7(***)			0.2 (ns)			0.1 (ns)			4.7(*)			

For a given stage of maturity, means within the same storage time followed by the same small letters are not significantly different ($F_{(0.05;\ 2,15)} = 3.7$; $F_{(0.05;\ 2,15)} = 6.4$; $F_{(0.05;\ 2,15)} = 11.3$ or $F_{(0.05;\ 3,20)} = 3.1$; $F_{(0.01;\ 3,20)} = 4.9$; $F_{(0.001;\ 3,20)} = 8.1$, respectively, for 3 and 4 levels). For a given stage of maturity, means within the same post-harvest maturation time followed by the same capital letters are not significantly different ($F_{(0.05;\ 3,20)} = 3.1$; $F_{(0.01;\ 3,20)} = 4.9$; $F_{(0.001;\ 3,20)} = 8.1$).

[a] ns, not significant.

[*] $p < 0.05$.

[**] $p < 0.01$.

[***] $p < 0.001$.

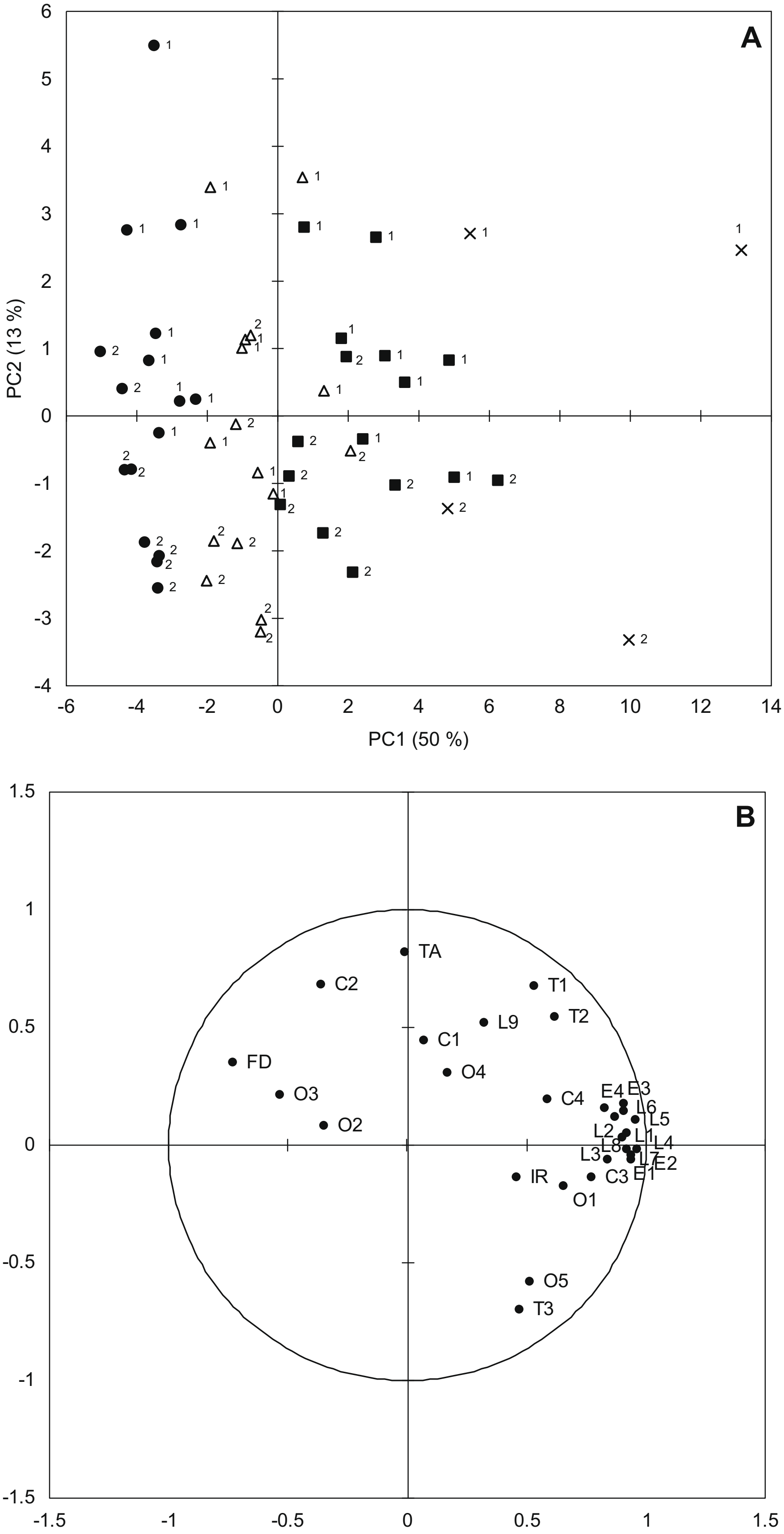

Fig. 1. Results from PCA analysis (A) projection of the samples (1, 1st experiment; 2, 2nd experiment; ●, 0 h; △, 48 h; ■, 72 h; ×, 168 h); (B) factor loadings of variables (for variable codes see Table 2).

eberle, 2007; Tang and Jennings, 1967, 1968), increase mainly during post-harvest maturation, reaching their highest amounts in samples ripened for one week at 20 °C. The same trend was observed for esters, and particularly for butyl and hexyl acetates, pre-

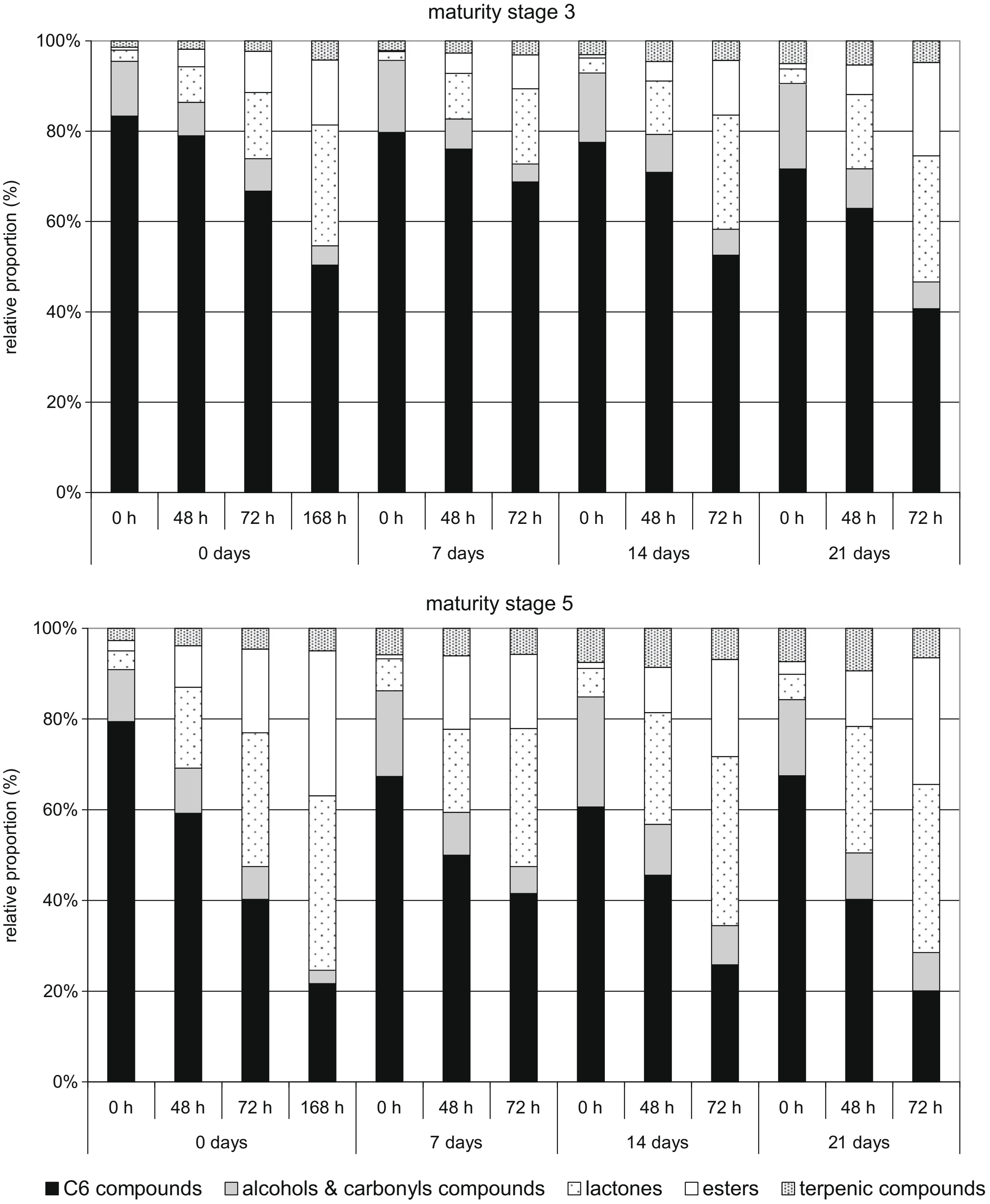

Fig. 2. Relative proportions (percent) of the main classes of volatile compounds in the different samples of apricot in the two experiments according the length of storage at 1 °C (days) and the length of post-harvest maturation at 20 °C (h).

viously reported to be responsible for the banana-like and the nail polish notes of apricot (Chairote et al., 1981; Crouzet et al., 1983; Greger & Schieberle, 2007; Tang and Jennings, 1967, 1968). Regarding storage at 1 °C, the results have shown that, although some results were statistically different between samples, the changes observed for lactones and esters were relatively weak in comparison to those observed during post-harvest maturation. For a given ripening time, their levels were found overall, to be similar to those observed at harvest. To a lesser extent, the same trend was observed for the levels of terpenic compounds previously reported to be responsible for the flowery note of apricot (Chairote et al., 1981; Crouzet et al., 1983; Greger and Schieberle, 2007; Guillot et al., 2003; Tang and Jennings, 1967, 1968). These results are consistent with those previously reported by Aubert and Chanforan (2007). Finally, it is important to note that the results also indicated that, in "ready-to-eat" apricots, the relative proportions of the sum of lactones, esters and terpenic compounds were, on average, 50% higher in samples harvested at stage 5 (~66%) in comparison to those observed in samples harvested at stage 3 (~42%) (Fig. 2).

In this study, great numbers of data, including physicochemical characteristics and volatile constituents, of Bergeron apricot have been obtained under different storage and/or post-harvest maturation conditions. The results showed that the most significant changes, *i.e.*, a significant decrease of firmness and C_6-compounds and a significant increase of esters, lactones and terpenic compounds, mainly took place during post-harvest maturation rather than during storage. The results have also shown that, in the end, qualitative and quantitative differences could be observed between ripened samples according to their initial stages of maturity at harvest. Nevertheless, although the results have demonstrated that, after ripening at 20 °C, the "ready-to-eat" samples, previously harvested at maturity stage 5, have, on average, higher levels of soluble solids, lactones, esters and terpenic compounds, and lower levels of firmness or C_6 compounds than those harvested at maturity stage 3, it would be particularly pertinent, in further investigations, to characterize these samples from a sensory point of view (descriptive analyses, preference tests) in order to determine whether consumers are able, or not, to perceive differences between apricots.

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