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Jean-Louis Ballais, Marie-Christine Bosc

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THE IGNIFRACTS OF THE SAINTE-VICTOIRE MOUNTAIN (LOWER PROVENCE, FRANCE)

J. L. BALLAIS & M.C. BOSC

*U.F.R. de Géographie, Université d'Aix-Marseille I, 29 Avenue Robert Schuman, 13621
Aix-en-Provence Cédex, France*

ABSTRACT

This paper deals with the first French, even world-wide, survey of ignifracts. A statistical study of 162 objects has shown that the average flattening index ($I_a = 5.6$) is much greater than that of gelifracts. There is no correlation between this index and the lithology of the samples studied. Ignifraction is a specific case of thermoclasty; its main characteristics are its high efficiency (up to $22,500 \text{ g/m}^2$ of ablation in a few minutes) and its high spatial variability, the causes of which have not yet been clearly established.

Key words: Ignifracts, Flattening index, Thermoclasty, Provence.

RESUMEN

Este trabajo es la primera investigación francesa, o incluso mundial, sobre los ignifractos. Un estudio estadístico de 162 objetos ha demostrado que el índice medio de aplanamiento ($I_a = 5.6$) es mucho mayor que el de los gelifractos. No existe correlación entre este índice y la litología de las muestras estudiadas. La ignifración es un caso específico de termoclastia; sus principales características son su alta eficacia (más de $22,500 \text{ g/m}^2$ de ablación en unos pocos minutos) y su elevada variabilidad espacial, cuyas causas no han sido claramente establecidas.

Palabras clave: Ignifractos, Índice de aplanamiento, Termoclastia, Provenza.

On August 28th, 1989, at 11:43 am, on a site of clearing of brush-wood fire broke out on the far westerly tip of the Sainte-Victoire mountain, to the East of Aix-en-Provence (fig. 1). The Mistral wind was blowing at between 70 to 80 km/h with gusts reaching up to 100 km/h. Soil water reserves had already fallen below 10 mm several days prior to the fire. Despite immediate action by the fire department, on standby only 2 km away, conditions were such that it was impossible to prevent the fire from spreading. In little over 3 hours, the entire southern slope was devastated by fire. In all, approximately 5,000 hectares of "garrigue" or scrubland and thinly planted forests of *Pinus halepensis* were burnt to the ground (Baccouche, 1990).

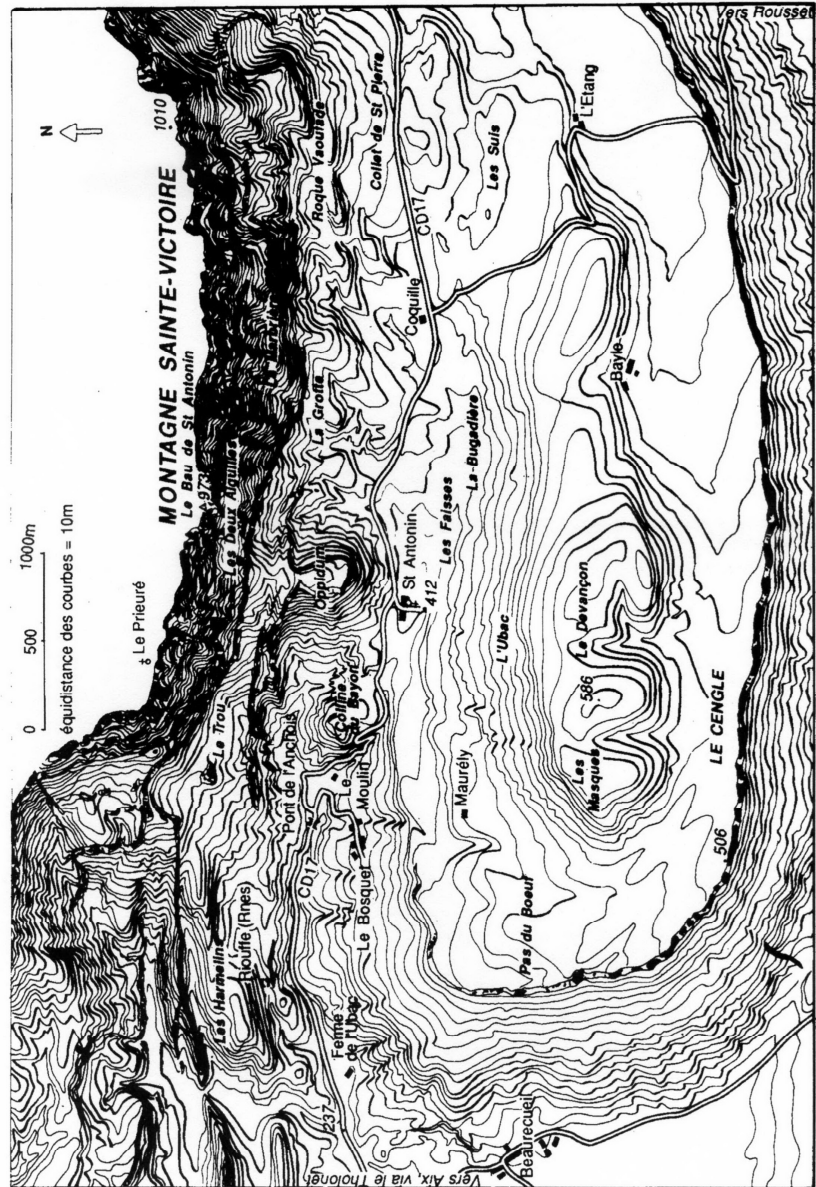
Different studies were immediately performed to precise the morphogenic consequences of this wild fire. As in several cases in the past (for example, Krammes, 1960, Wells, 1981, Vega & Díaz-Fierros, 1987, Puech, Lavabre & Martin, 1991), a measurement plan of pluvial and gully erosion was fitted out (Ballais, Bosc & Sandoz, 1992). But it rapidly appeared that ignifracts, here observed for the first time, were the more important type of ablation.

1. Ignifracts

From early September it became obvious that the rock faces and rock beds (Jurassic limestone, Upper Cretaceous, Eocene and Quaternary breccia and conglomerates, Jorda & Provansal, 1992, Ballais & Crambes, 1992) had started to flake off. At the foot of these rock faces very thin, brittle, sometimes already fragmented spalls, were beginning to accumulate. The external surface of these spalls was blackened by fire whereas the inside surface showed the rock structure. As they were created by fire, we suggest these spalls be termed ignifracts (from the Latin *ignis* : fire), and the process by which they were created (photo 1), ignifraction.

1.1. Statistical characteristics

A preliminary statistical study was carried out so as to designate these objects, and be able to compare them with other spalls (gelifracts or thermoclasts). Particular attention was paid to their flattening index ($I_a = L+1/2e$, where L represents the length, l the width and e the thickness (Tricart & Cailleux, 1955)). 162 ignifract samples were taken from a small area in the small catchment (3.1 km²) of the Deux-Aiguilles stream, slightly to the east of the Saint-Antonin Oppidum (Fig. 1). The average ignifract sample measures 109.2 mm x 77.9 mm x 18.1 mm and its weight approximately 385 g. In fact (table 1) the length of these samples varies from between 41 mm and 188.5 mm, the width from 27 mm to 154 mm and the thickness from 5 mm to 44 mm. It should be noted that sampling does not wholly reflect the heterometry of the ignifracts, as neither the smallest samples, too brittle to be removed, nor the largest, too heavy to be transported, were taken into account.



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The average flattening index is 5.6. This figure is considerably higher than that of gelifracts (2.5 according to Tricart & Cailleux, 1955). Additionally, the minimum index noted for these samples, i.e. 2.88, is already greater than the average flattening caused by gelifraction. From a statistical point of view it is not possible to mistake one for the other : ignifraction provides specific material which can be easily identified from its flattening index.

Table 1. Statistical study of ignifracts

Elementary statistics						
	Mean	STD Dev.	STD Err.	Max.	Min.	Range
2	109.194	33.022	2.594	188.500	41.000	147.500
3	77.917	27.559	2.165	154.000	27.000	127.000
4	18.099	7.535	0.592	44.000	5.000	39.000
5	5.634	1.603	0.126	10.330	2.880	7.450

Factor analysis				
Correlation	coefficients			
	2	3	4	5
2	1.000			
3	0.842	1.000		
4	0.716	0.661	1.000	
5	-0.017	0.020	-0.596	1.000

Eigenvalues	2.5562	1.2107	0.1595	0.0735
2 factors extracted				

Variance		
	1	2
%	63.91	30.27
cum. %	63.91	94.17

Eigenvectors				
	2	3	4	5
1	0.564	0.548	0.577	-0.220
2	0.297	0.342	-0.295	0.841

Factor matrix			Communalities	
	1	2		
2	0.90239	0.32721	2	0.92137
3	0.87599	0.37646	3	0.90908
4	0.92228	-0.32434	4	0.95581
5	-0.35210	0.92561	5	0.98072

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Regressions	coefficients			
	2	3	4	5
1	0.3530	0.3427	0.3608	-0.1377
2	0.2703	0.3109	-0.2679	0.7654

The factorial analysis (table 2) shows that the length, the width and the thickness can be easily correlated: a coefficient of 0.842 between length and width, 0.716 between length and thickness, 0.661 between width and thickness: the longer the ignifract, the wider and thicker it is. It is therefore not surprising that the flattening index cannot be correlated with either the length (a coefficient of -0.017), nor with the width (a coefficient of 0.020). The best correlation can be obtained using the thickness (a coefficient of 0.596) which has the lowest correlation with the length.

These results are effectively confirmed by the Matrix Factor table (table 1). It can be noted that the first extracted factor groups together the three dimensional measurements (0.90239 for the length, 0.87599 for the width and 0.92228 for the thickness), leaving aside the flattening index (-0.35210). The opposite, however, can be said for the second factor: it is clearly linked to the flattening index (0.92561) and only slightly to length (0.32721), to width (0.37646) and to thickness (-0.32424). The difference (1.2%) in the first column of table 1 comes from the fact that there were 82 breccia ignifRACTS as opposed to 80 limestone ignifRACTS.

1.2. The influence of lithology

As there is no link between the dimensions and the flattening of the ignifRACTS, it was necessary to look for the part which could be attributed to the lithological nature of the samples. In order to introduce this new parameter numerically, a second file was drawn up using a Boolean matrix, and the same operations carried out as on the first file (table 2). By extracting only two factors, the first of which grouped together the three dimensional measurements, it was possible to retain only one of three in the new file: this being the length. Moreover, the first results were used as a basis when determining the three length categories (short, average, long) and the three flattening categories (slightly, moderately or considerably). In both cases, the first limiting value was set at $x - 1/2 x$ and the second at $x + 1/2 x$, where x is the average and x the standard deviation. It was thus possible to categorize the objects as short ignifRACTS (28.4%), medium (44.4%) and long (27.2%). The largest category is therefore medium, whilst the remaining objects are divided almost equally between the other two categories. The breakdown, in relation to the medium category, is therefore symmetric.

This is no longer the case when dealing with flattening, as 37.7% of the objects are slightly flattened, 35.2% moderately flattened and 27.2% considerably flattened. It can be seen that the first two categories each comprise just over one third of the objects, whereas the third category contains fewer objects. Furthermore, the slightly flattened category is somewhat larger than the moderately flattened category.

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Table 2. Statistical study of ignifracfs

Elementary statistics

	Mean	STD Dev.	STD Err.	Max.	Min.	Range
2	0.284	0.452	0.036	1	0	1
3	0.444	0.498	0.039	1	0	1
4	0.272	0.446	0.035	1	0	1
5	0.377	0.486	0.038	1	0	1
6	0.352	0.479	0.038	1	0	1
7	0.272	0.446	0.035	1	0	1
8	0.494	0.502	0.039	1	0	1
9	0.506	0.502	0.039	1	0	1

Factor analysis

Correlation

	2	3	4	5	6	7	8	9
2	1,000							
3	-0,563							
4	-0,385	-0,546						
5	-0,037	0,151	-0,131					
6	-0,034	-0,035	0,073	-0,573				
7	0,077	-0,127	0,064	-0,475	-0,450			
8	-0,458	0,110	0,341	-3,1.10 ⁻³	3,8.10 ⁻³	7,5.10 ⁻³	1	
9	0,458	-0,110	-0,341	3,1.10 ⁻³	3,8.10 ⁻³	-7,5.10 ⁻³	-1	1

Eigenvalues

2,5782	1,8291	1,5008	1,2765
0,8154	5,2.10 ⁻¹⁶	-1,4.10 ⁻¹⁶	-3,0.10 ⁻¹⁵

5 factors extrated

Variance

	1	2	3	4	5
%	32,32	22,86	18,76	15,96	10,19
% cumul.	32,32	55,09	73,85	89,81	100,00

Eigenvectors

	2	3	4	5	6	7	8	9
1	0,462	-0,137	-0,316	8,3.10 ⁻³	0,028	0,021	-0,577	0,577
2	0,201	-0,571	0,434	-0,534	0,256	0,307	0,025	-0,025
3	0,126	-0,217	0,114	0,298	-0,762	0,494	0,074	-0,074
4	-0,163	0,456	-0,355	-0,520	-0,031	0,599	-0,015	0,015
5	0,624	-0,104	-0,517	-0,030	0,084	-0,058	0,400	-0,400

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Factor matrix

	1	2	3	4	5
2	0,74193	0,27184	0,15450	-0,18386	0,56389
3	-0,21956	-0,77167	-0,26562	0,52631	-0,09358
4	-0,50686	0,58651	0,14012	-0,40150	-0,46711
5	0,01330	-0,72211	0,36470	-0,58707	-0,02691
6	-0,04445	0,34606	-0,93344	-0,03467	0,07586
7	0,03324	0,41507	0,60492	0,67673	-0,05213
8	-0,92719	0,03378	0,09080	-0,01736	0,36142
9	0,92719	-0,03378	-0,09080	0,01736	-0,36142
% total variance	32,32	22,86	18,76	15,96	10,19

Communalities

2	1,00 000
3	1,00 000
4	1,00 000
5	1,00 000
6	1,00 000
7	1,00 000
8	1,00 000
9	1,00 000

These results suggest that if the average length, calculated using the first file, gives a good idea of this measurement, the same does not apply to the average flattening index. This is shifted to a lower figure, between the calculated indices (2.88; 10.33).

When using this second file, however, the factorial analysis shows far more conclusive results. From the correlation table (table 2), it is clear that there is no link between lithology and flattening. Indeed, the correlative coefficients between the two lithological variables (limestone and limestone cemented breccia) and the three flattening variables vary from between $-7.5 \cdot 10^{-3}$ and $7.5 \cdot 10^{-3}$ (1). These are negligible and there is therefore no link between lithology and flattening. This result is highly unexpected, and contrary to what is accepted for gelifracsts (Tricart & Cailleux, 1955).

In addition to this basic conclusion, this table also reveals a link between lithology and short ignifracsts, a link confirmed by the Factor Matrix and Eigenvector tables (table 2). They show a correlation between the "long" and "considerably flattened" variables on the one hand, and the "average" and "slightly flattened" variables on the other, links which do not appear clearly in the correlation table. In fact, the first factor, which represents approximately one third of the total variance, emphasises the correlation between short material (2) and breccia (9) and the inverse correlation between short material and limestone (8). It is therefore possible to define a category of ignifracsts which is both short and brecciated.

The second factor, which when added to the first represents 55.09% of the total variance, shows the correlation between the moderately flattened (-0.77167) and slightly flattened categories (-0.72211). A second category of ignifracts which is medium in size and slightly flattened can therefore be determined.

1.3. Conclusion

This statistical approach therefore provides considerable knowledge of the sampling structure. It makes it possible to single out two well-defined categories : small ignifracts in breccia and medium, slightly flattened ignifracts. However, all the links between the variables in the second file remain insignificant. Extracting five factors, none of which represents a large part of the total variance, whereas factor 1 of the first factorial analysis amounts to 63% of the total variance and the two factors combined amount to more than 94%, confirms that the structure of the second file is not extremely coherent. The two categories, small ignifracts in breccia and medium slightly flattened ignifracts, in no way differentiate all the 162 samples. They form the two largest groups of statistically identifiable objects, but the other samples remain poorly structured and are difficult to perceive and categorize.

Above all, this statistical approach provides a way of rejecting the hypothesis that the dimensions of the ignifracts influence their flattening index and the influence of lithology on this same index, thus characterizing these objects even further.

2. Ablation by ignifraction

2.1. Progression in time after the fire

Ignifracts were seen to fall during the days which immediately followed the fire. Similarly to other processes of mechanical fragmentation, the time which elapsed between the individualization of the ignifracts and their breaking away from the rock face, followed by their fall, varied considerably.

In the first few weeks of autumn 1989, these falls were accelerated by rains, albeit relatively light (Bosc, 1990). This was most probably helped by the wind, in particular the Mistral, although it is not possible to give more exact details in this respect.

During winter, two further processes appeared; the first being gelifraction. Although this process was extremely moderate, due to the low number of freeze-thaw cycles in the course of a particularly mild winter, this nevertheless encouraged the breaking away of ignifracts as water could easily infiltrate between these ignifracts and the rocky face. The second process is typically anthropic, and combines a voluntary "purge" and an involuntary breaking away caused by climbers, even before the Local Authorities had granted them access to the much-frequented catchment of the Deux-Aiguilles stream (photo 2).

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It would therefore seem that most of the ignifracts were loosened during the winter of 1989-1990. Since then, the breaking away of ignifracts seems highly localised, but the areas from which these ignifracts broke away remain very visible, as the patina has not yet reformed over the rocky outcrops (photo 2).

2.2. Distribution, cause and extent of ignifraction

At first glance the distribution of the ignifracts seems quite uneven. However, density is at a maximum on the subvertical rock faces and in the first few meters above ground level. On a larger scale, the dominant feature is once again variability : a rock face may in one area have been affected by up to 50%, whilst only a few meters away have been affected to a far lesser degree, or not at all.

The most likely explanation for these variations is obviously linked to the fire itself. It should be remembered that, on a macroscopic scale, neither the localisation of surface ignifracts, nor the surface from which they have broken away, which is rugged, with the substratum, appear to have been influenced by the patina or by a possible superficial modification. Ignifraction should therefore be considered as a specific form of thermoclasty.

According to eye-witness accounts given by the firemen, the fire did not advance evenly and the temperature to which the rock walls were superficially subjected must have varied considerably from one place to another, depending in particular on the density of the woodland. Similarly, the time period during which temperatures remained at a high level varied considerably. In certain cases small areas were even left unaffected due to sudden gusts of wind (Mistral). However, further observation, although difficult, will be required as an examination of the rock face several weeks after the fire showed no distinct correlation between, for example, clumps of *Pinus halepensis* and the density of the ignifracts.

Furthermore, the role of coherent rock structures should not be overlooked : lateral changes in facies, particularly in the breccia, but also fragmentation caused by tectonics, which is particularly intense at this thrust-plane edge.

Without an in-depth study, the total weight of these ignifracts cannot be calculated accurately. Maximum densities reach approximately 50% of the rock face surface, and as the average thickness which was removed is 18.1 mm, the maximum volume which broke off could be estimated at 22,500 g/m² (compared to 181.5 g/m² for gelifraction on the Santonian limestone in the hills around La Fare (west of Aix-en-Provence) during the winter of 1969-1970, Gabert *et al.*, 1981). Assuming that 50% of the rock face surface was burnt and that 10% of the rock face surface was ignifRACTED, i.e. 250 ha, and a mean rate of 25% of the surface was affected by the breaking away of ignifracts, ablation by ignifraction could be calculated at approximately 2,800 t of coherent rock, assuming a margin of error to the order of 100%.

3. Conclusions

The main purpose of this short preliminary study of ignifracsts, was to reveal the very specific characteristics of these objects and the considerable volume loosened by ignifraction over a period of only a few hours.

The presence of ignifracsts, as a consequence of fire, has been noted in the Santonian limestone to the West of Aix-en-Provence by Ballais, in limestone on Mount Carmel in Israel (Inbar, oral presentation) and in the sandstone of Montserrat in Spain (Marqués, oral presentation). On the other hand, the gneiss and mica schist found in the Maure Range, in the crystalline area of Provence, do not seem to have been affected (work carried out by Ballais). Is this due to a difference in the temperature of the fire or/and structural factors? Further research should clarify this, particularly by way of experiments dealing with the influence of temperature on the distribution, density and even the thickness of ignifracsts.

Finally, ignifracsts can now provide a means with which to carry out research work into evidence left behind by previous fires, and therefore broaden our knowledge of more recent fires. It should also however be possible to raise the issue, from a historical or holocene standpoint, of the part played by ignifraction in the mechanical fragmentation of rocks, particularly in the Mediterranean area: assuming that ignifraction is 10 to 100 times more effective than gelifraction, could it not be the main source by which spalls are produced? It is this problem which we will attempt to analyse on the Sainte-Victoire Mountain, by undertaking new research work in close collaboration with archeologists.

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