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A ~ 8,000-yr record of palaeohydrology and environmental change in fluvial-influenced sediments from Arles-Piton core, upper Rhône Delta, France

by

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with 8 figures and 1 table

Summary. This paper presents new data on Holocene palaeohydrology and environmental history of the Rhône Delta. Derived from integrated study of a 18.3 m Arles-Piton core drilled immediately to the south of the present delta apex, sediments were investigated for sedimentology, micropalaeontology, palynology, magnetic susceptibility and microcharcoal contents. ^{14}C dates, archaeological/historical data and palyno-correlation provided chrono-stratigraphic control. Sedimentary and micropalaeontological analyses show the following palaeoenvironmental succession: the top of a distributary-channel infilling (before 6157–5843 BC), doubtless very close to the palaeocoastline; a brackish- or freshwater swamp (5719–5530/4796–4463 BC) partially disconnected from the Rhône channel; a distal flood plain (5719–5530/4796–4463 BC) in which phenomenon of rapid aggradation is linked to abundant flood supplies of the Rhône River; a high-energy palaeochannel (4796–4463/2900–2503 BC) with a gravel-sand material load; a proximal flood plain (2900–2503 BC/AD 270–290) in which pedosedimentary processes and occupation levels indicate discontinuous aggradation and exundation; a crevasse splay (after AD 270–290) that covers the present floodplain surface. Channel avulsion is a very important process in the high delta-plain construction of the Rhône River. Avulsion process controls 43 % of the alluvial fill studied. The alluvium arriving in the upper Rhône Delta was derived mainly from proximal source areas (Massif Central, southern Alps) during the last 8,000 years, except during for the Rhodanian hydrological change of the Roman antiquity during which detrital inputs were derived firstly from the northern and southern Alps, and secondly from the Massif Central. Finally, the interference between biomass-burning tracks, wildfires and anthropogenic impact is discussed to the regional (catchment) and local (delta) scales.

Zusammenfassung. *8000 Jahre Geschichte der Veränderungen der Hydrologie und der Umwelt in den Flussablagerungen des Bohrkerns Arles-Piton, oberhalb (apex) des Rhône Deltas, Frankreich.* – Dieser Artikel ist ein neuer Beitrag zur holozänen Paläohydrologie und zur Umweltgeschichte des Rhône Deltas. Der Bohrkern Arles-Pitons (18,3 m lang), der direkt südlich des heutigen Apex Deltas entnommen worden ist, stellt den Gegenstand einer umfassenden Studie dar (Sedimentologie, Paläontologiemikroanalyse, Palynologie, Reaktion auf das Magnetfeld, Inhalt in Mikrokohle). Die Chronologie der Ablagerungen beruht auf mehreren C14-Datierungen, archäologischen Datierungen und der palynologischen Wechselbeziehung. Das Ergebnis der Sediment- und Paläontologiemikroanalysen zeigt die folgende Paläo-

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umweltreihenfolge: Die Obersedimentschicht des Ausfüllens einer Flussfahrrinne (jünger als 6157–5843 vor Christus), wahrscheinlich sehr nah bei seiner Mündung; ein zwischen weichem Wasser und Brackwasser wechselnder Sumpf (datiert von 5719–5530 bis 4796–4463 vor Christus), der von der Fahrrinne Rhônes teilweise getrennt ist; eine entfernte Überschwemmungsfläche (datiert von 5719–5530 bis 4796–4463 vor Christus), wo die hohe Sedimentationsrate durch ausgiebige Ablagerungen verstärkt ist; eine kraftvolle Paläoflussfahrrinne mit einer sandigen und kieselhaltigen Schuttlast (datiert von 4796–4463 bis 2900–2503 vor Christus); eine nahe Überschwemmungsfläche (datiert von 2900–2503 vor Christus bis 270–290 nach Christus), wo mehrere Böden und Siedlungsebenen eine zeitlich und räumlich diskontinuierliche Verfüllung mit einigen aufsteigenden Sedimenten darstellen; ein Delta umfasst als Ergebnis des Deichbruches (jünger als 270–290 nach Christus) die Oberfläche des neuzeitlichen Überschwemmungsgebiets. Also scheint der Prozess des Verzichts auf die Flussfahrrinne zugunsten einer neuen Fahrrinne den Hauptfaktor für den Aufbau des Hochdeltas darzustellen. Dieser Prozess hat 43 % des untersuchten Flussausfüllens zur Folge. Während der acht letzten Jahrtausende kommen die oberhalb des Deltas deponierten Alluvionen aus zwei mineralogisch ähnlichen Gebieten (Massif central, Alpes du Sud), außer während der hydrologischen Krise des Rhônes in der römischen Antike, in der Sedimente in großer Menge aus den Nordalpen Frankreichs und den Südalpen Frankreichs, und auch in einer niedrigeren Menge aus dem Massif central kommen. Zum Schluss werden die Beziehungen zwischen der Kohle, den Waldbränden und den anthropogenen Eingriffen auf der regionalen Ebene (Entwässerungsgebiet) und lokalen Ebene (Delta) diskutiert.

Résumé. *8000 ans d'histoire hydrologique et de changements environnementaux dans les sédiments fluviatiles de la carotte Arles-Piton, apex du delta du Rhône, France.* – Cet article est une contribution nouvelle sur la paléohydrologie et l'histoire environnementale holocènes du delta du Rhône. Prélevée immédiatement au sud de l'apex actuel du delta, la carotte Arles-Piton (longueur 18,3 m) a fait l'objet d'une étude intégrée (sédimentologie, micro-paléontologie, palynologie, susceptibilité magnétique, contenu en micro-charbons). La chronologie des dépôts repose sur de nombreuses datations ^{14}C et archéologiques ainsi que sur la palyno-corrélation. Les résultats des analyses sédimentologique et micro-paléontologique montrent la succession paléoenvironnementale suivante: le sommet du remblaiement d'un chenal fluviatile (antérieur à 6157–5843 av. J.-C.), sans doute très proche ici de son embouchure; un marais d'eau douce à saumâtre (de 5719–5530 à 4796–4463 av. J.-C.) partiellement déconnecté du chenal du Rhône; une plaine d'inondation distale (de 5719–5530 à 4796–4463 av. J.-C.) où les taux de sédimentation importants sont corroborés par d'abondants apports détritiques; un paléochenal de haute énergie (de 4796–4463 à 2900–2503 av. J.-C.) à charge gravelo-sableuse; une plaine d'inondation proximale (de 2900–2503 av. J.-C. à 270–290 ap. J.-C.) où plusieurs sols pédologiques et niveaux d'occupation indiquent une aggradation discontinue, ponctuée par des phases d'émersion; un delta de rupture de levée (postérieur à 270–290 ap. J.-C.) qui sous-tend la surface de la plaine d'inondation moderne. Ainsi, le processus de défluviation apparaît comme le principal facteur de la construction de l'édifice deltaïque supérieur. Les défluviations contrôlent 43 % du remblaiement alluvial étudié. Au cours des huit derniers millénaires, les alluvions déposées à l'apex du delta dérivent de deux provinces minéralogiques proches (Massif Central, Alpes du Sud), excepté durant la crise hydrologique rhodanienne de l'Antiquité romaine, durant laquelle les apports détritiques proviennent surtout des Alpes du Nord et du Sud, et secondairement du Massif Central. Finalement, les relations entre charbons, incendies de forêt et action anthropique sont discutées aux échelles régionale (bassin-versant) et locale (delta).

1 *Introduction*

A marine alluvial delta, resulting from the interaction of the river and coastal processes, can be defined as a complex sedimentary accumulation (coastal prism) built by a terrestrial feeder (distributary) system into or against a body of seawater (GALLOWAY & HOBDAY 1996). In the upstream part of the deltaic plain, which is sometimes situated upstream of the maximum coastal onlap (OOMKENS 1970), river processes are dominant and the lateral instability of distributary channels is mainly dependent on several key parameters, including: relief of the floodplain, channel and lateral gradients, degree of sinuosity, variations of discharge/sediment yield ratio, increase of flood peaks, avulsion thresholds, crevassing process, and rates of floodplain aggradation (JONES & SCHUMM 1999). Located at the apex of the Rhône Delta, the site of Arles can serve as support to highlight processes of Holocene deltaic construction controlled mainly by hydrosedimentary variability and lateral channel instability.

In fact, the site of Arles is interesting in many respects. Holocene palaeohydrology of the Rhône River was described in detail for the upper valley (BRAVARD et al. 1997), but few data concern the lower valley. Palaeohydrology of the Lower Rhône was described in the central/lower part of the delta (ARNAUD-FASSETTA & PROVANSAL 1999, ARNAUD-FASSETTA & LANDURÉ 2003). It was also described in Arles city and in Arles plain (ARCELIN et al. 1999, BRUNETON 1999) only for the last 3,500 years, but, even if the sedimentary records are longer, the data relative to the river are often indirect and do not always concern the Rhône channel strictly speaking. Furthermore, extensive geomorphological studies have investigated the lower Rhône delta plain (GENSOUS et al. 1993, ARNAUD-FASSETTA 1998, VELLA 1999), but the upper part of the delta and transition zone between uppermost delta plain and the continental alluvial plain have received little investigation.

The principal objectives of this current research are:

- To describe the sedimentological, palaeontological and palynological characteristics of the alluvial infilling preserved in the lowermost Rhône Valley, with the aim to reconstruct the environmental conditions of the Rhône Delta and the hydrological functioning of the Rhône River during the Holocene.
- To clarify the control factors of the fluvial hydrology, sediment yield and the geometry of the deltaic plain;
- To discuss the results with previous works in both the Rhône Valley and the Rhône Delta.

2 *Environmental and human setting*

The Rhône catchment (97,800 km^2) extends from the western Alps to the northwestern Mediterranean basin (fig. 1A and 1B). It encompasses a large and complex area, different in rock types, climate and hydrology. From the Langres Plateau to the Lower Languedoc, the rivers Saône and Rhône flow across numerous plains and basins oriented parallel to a north-south axis mainly composed of limestones, conglomerates and Quaternary glacial, fluvial and lacustrine deposits. To the east and to the northeast, the Alpine mountains, which occupy the majority of the catchment,

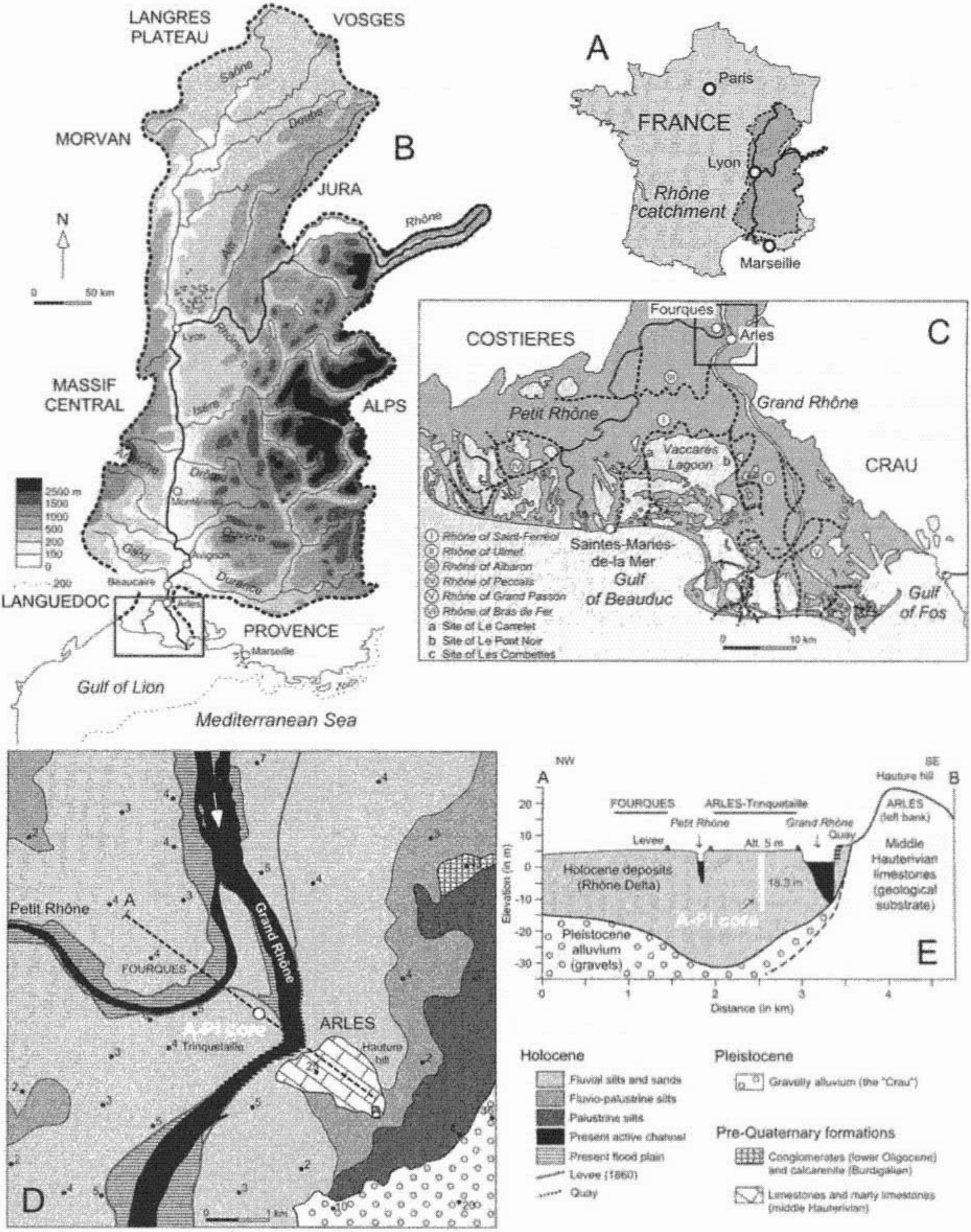


Fig. 1. (A) Location of the Rhône catchment. (B) Physiography and hydrography of the Rhône catchment. (C) Map showing the geometry and the (palaeo)hydrography of the Rhône Delta. (D) Geomorphological map of the Rhône floodplain around the Arles city. (E) Stratigraphic cross-section of the Holocene alluvial infilling at Arles and location of the A-PI core.

are composed mainly by plutonic, metamorphic and sedimentary rocks. To the northeast, the mountains and plateau of the Jura are composed mainly by sedimentary rocks. To the northwest and to the west, the lithology of the Massif Central consists mainly of plutonic, metamorphic, extrusive and sedimentary rocks.

The present Rhône Delta (1,740 km^2) forms a 55-km long, 70-km wide complex of Holocene sediments deposited by the Rhône River in lagoonal or marine basins (fig. 1C). The main part of the Holocene delta plain consists of several overlapping sedimentary sequences that began developing since the last post-glacial eustatic sea-level rise (GENSOUS et al. 1993). Under Trinquetaille's district of Arles (fig. 1E), 20–30 m of Holocene alluvium accumulated there (L'HOMER 1987). During the Holocene, this complex river/shelf hydrosystem was subject to forcing from different sources, including: the variations of flood regime of the river and the characteristics of the detrital inputs (ARNAUD-FASSETTA 1998); and the vertical and lateral evolutions of the coastline (VELLA 1999). These parameters are strictly dependent on the climate variability and on the increasing effects of human activities along the Rhône River and its valley (PROVANSAL et al. 1999).

The Rhône River (812-km long) has a mean annual water discharge of 1,700 m^3/s in the delta (CNR data), but its hydrological regime is characterised by intra- and interannual variability because of various influences (glacial, nival, pluvial; PARDÉ 1925). Today, two main distributary channels carry the bulk of the fluvial water to the Gulf of Lion. The largest (Grand Rhône) is directed towards the southeast and receives 85–90 % of the annual water discharge. The secondary branch (Petit Rhône) drains 10–15 % of the water discharge towards the southwest. The site of Arles corresponds to a hydrodynamic threshold where the river passes from a "high" gradient (0.00025) in the Beaucaire alluvial plain to a low gradient (0.00004) in the delta. The bed-material load consists essentially of cobbles-pebbles and coarse to medium sands (ARNAUD-FASSETTA et al. 2003). The washload (fine sands and silts) constitutes the main part (~ 8–9 million t/yr) of the sediment yield of the Rhône River (PONT et al. 2002). Furthermore, the Rhône River is a key element of the history and the development of Arles city (ARCELIN et al. 1999). From 540–530 BC, an important city developed on the calcareous hill of L'Hauture (fig. 1D). In 46–44 BC, the veterans of the 6th legion settled down in Arles as colonists. From this moment, the Roman city knew a widespread development, including, from the end of the 1st century BC, the district of Trinquetaille (fig. 1D), where the core sampling presented here was sampled. Then, progressive management of the margins of the Rhône River since antiquity induced the narrowing of the active channel and restricting of the flood plain (ARNAUD-FASSETTA 2003).

3 *Materials, methods and proxies*

During July 1998, one sediment coring (so-called "Piton", abbreviated A-PI in the text; lat. 43°41′00″ N, long. 4°37′25″ E, alt. 5 m above m. s. l.) was carried out under the supervision of G. ARNAUD-FASSETTA in the Arles-Trinquetaille area (fig. 1D and 1E), at 2 km downstream of the diffluence of the Rhône River, at 300 m west of the Grand Rhône and at 750 m southeast of the Petit Rhône. The selected site is located in the urban proximal flood plain of the Rhône River, just to the south of the present apex of the delta plain, at 25 km north-northeast of the actual coastal fringe (Gulf of

Beauduc). The sediment core was taken with a 8 cm-diametre stationary piston corer. Coring of overlapping sediments from defined depths, and their correlation on the basis of core description and analytical data, allowed us to obtain 18.3 m sediment sequence, with a core recovery of *c*. 82%. The bottom of the Holocene deposits, situated between –20 and –30 m (L'HOMER 1987), was not reached (fig. 1E). Following core opening, description and photographic documentation for structures analysis, one half core was sampled for grain-size, geochemical, heavy-mineral, ostracofauna and chronologic analyses. The other half was used for the pollen/biocorrelation analysis and for thin sections. All the measurements presented both in the text and the figures are expressed in m above or below present m. s. l., in comparison with the present Mediterranean sea level.

3.1 *Grain-size, geochemical and heavy-mineral analyses*

Two hundred twenty-six samples were collected in intervals of ~ 5 cm for the grain-size analysis. The granulometry was measured by a laser particle analyser Coulter Counter LS100 on the fraction <1 mm. Occasional coarse (e. g., coarse sand and gravel) material was analysed by sieving. Numerical parameters for mean grain size $[(Q_{16}+Q_{50}+Q_{84})/3]$ and maximal grain size (Q_{99}) were derived from the grain-size frequency distribution graphs of each sample.

Geochemical analyses were conducted in intervals of 5–10 cm. Calcium carbonate content of 244 samples was measured on the fraction <0.1 mm using a Bernard calcimetre. Furthermore, total organic carbon content of 168 samples was determined by loss on ignition (NF ISO 10694). The values were transformed to total organic matter content using the factor 1.724.

Heavy-mineral analysis was lead in order to discriminate the contribution of the different source areas in the Rhône catchment. Heavy-mineral analysis was made for the fine sand fraction (0.16–0.05 mm) of 25 sand sequences sub-sampled in intervals of 30 cm. Two heavy-mineral associations were used as indicators of two distinct sediment-source areas. The first association (green hornblende-epidote-glaucophane-chloritoid-piemontite) is indicative of Alps provenance. In this association, glaucophane and piemontite originate from the southern Alps (Durance basin) and the northern Alps (Isère basin), respectively. The second association (hypersthene-augite-brown hornblende-andalusite) indicates Massif Central provenance. Moreover, high amounts of fragile or easily alterable minerals (garnet-amphibole-epidote) reflect high burying ratio whereas the presence of resistant or more stable minerals (rutile-staurolite-tourmaline-zircon) reflects low burying ratio and some reworking (PETIT et al. 1996). All the results are presented on fig. 2.

3.2 *Ostracodes analysis*

Ostracodes and occasional foraminifers of 49 samples (fig. 3) were extracted using a 0.2-mm sieve. Holocene associations were compared to the present Rhône Delta pools (KRUIT 1955, BODERGAT 1983, BRUNETON 1999).

Changes in salinity of marine origin were evaluated through the amount and part of the brackish-waters species *Cyprideis torrosa* and *Cytheromorpha fuscata*. The following freshwater species show a wide tolerance for salinity variations: *Can-*

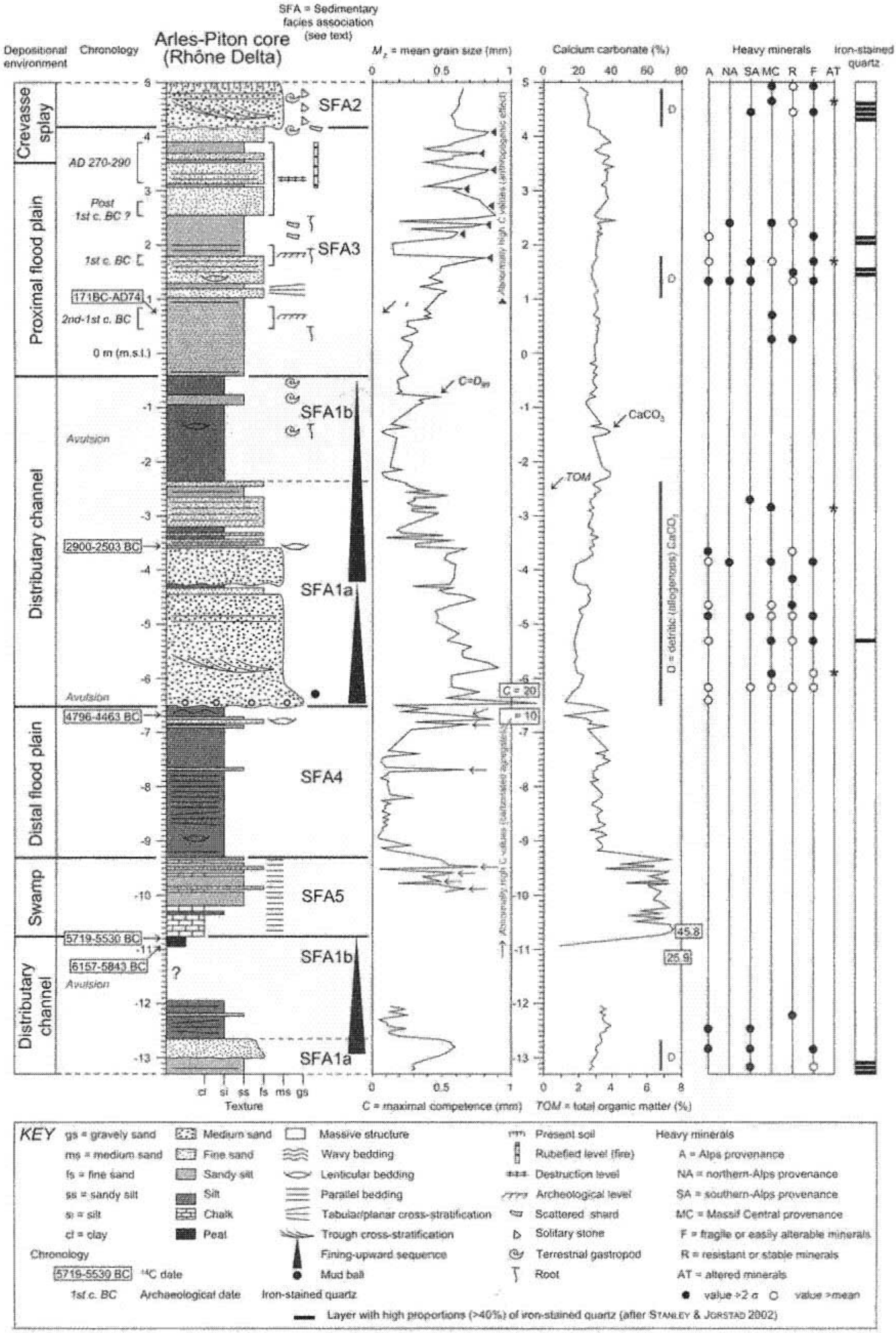


Fig. 2. Sedimentological, geochemical and mineralogical analyses of A-PI core, upper Rhône Delta.

dona neglecta, *Darwinula stevensoni* and *Pseudocandona compressa*. Other variations of salinity rate are also registered through *Paralimnocythere psammophila*, *Limnocythere sancti-patricii* and *Limnocythere inopinata* that live in carbonate-rich waters. The last two also show a greater tolerance for NaCl rich waters. In present associations, *Ilyocypridinae* and *Cypridinae* such as *Herpetocypris reptans*, *Eucypris virens*, *Cypridopsis vidua* or *Heterocypris* sp., live in freshwaters but show a good salinity tolerance and dominate in nitrate- and organic-rich waters. Evidences of the biotopes vegetalisation and eutrophication are shown by the presence of the macrophyte-dwelling species as *Ilyocypridinae*, *H. reptans*, *C. vidua*, *Cyclocypris ovum*. Shifts

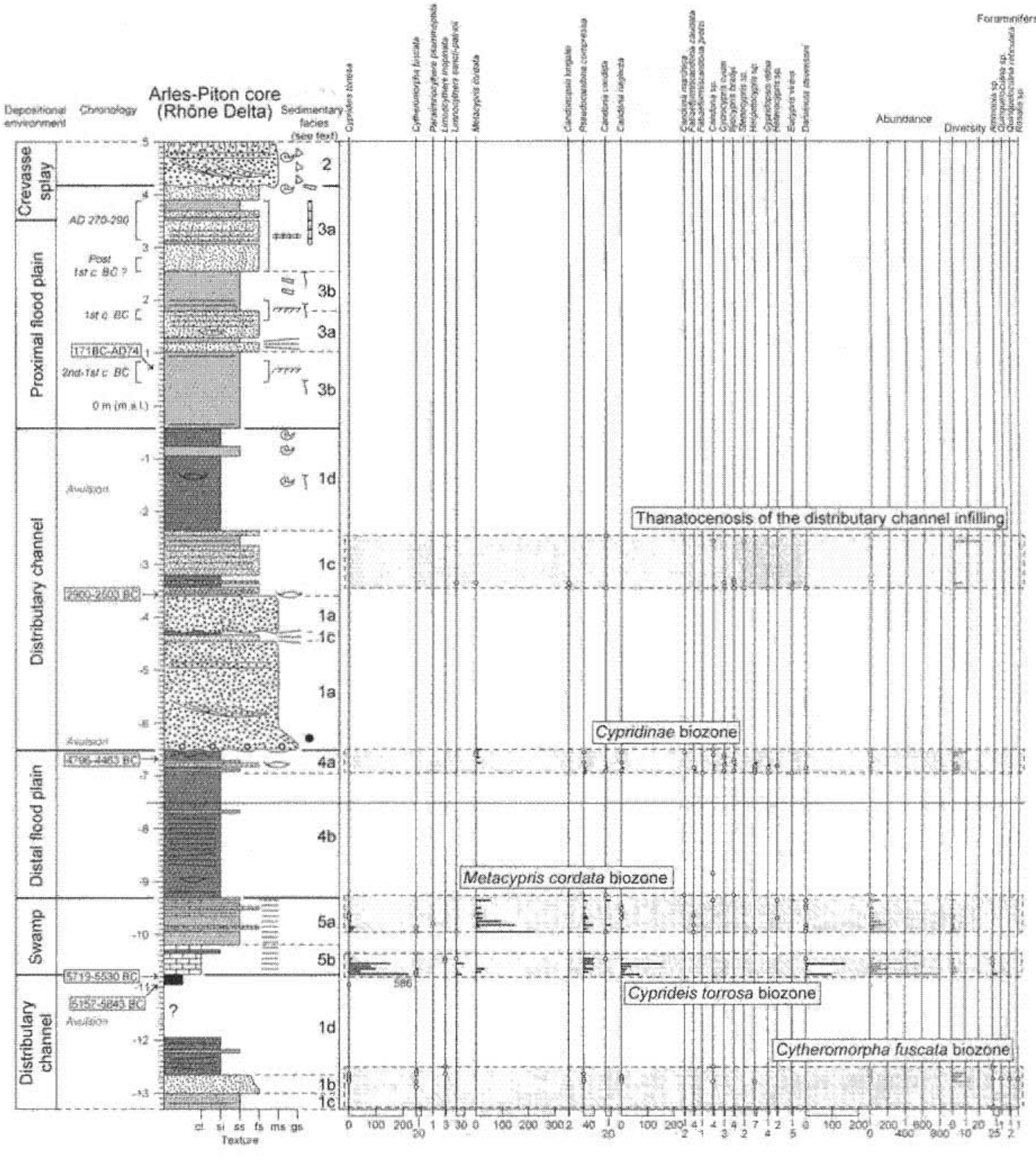


Fig. 3. Ostracodes and microcharcoals analyses of A-PI core, upper Rhône Delta. See also Fig. 2 for details of the legend.

from temporary (seasonal) to permanent water could be observed through the presence and number of permanent freshwaters species, especially *Metacypris cordata* and also *D. stevensoni* and the *Limnocytherinae*, respect to *Cyprididae* and especially *Candoninae*. *C. fuscata*, an estuary species, accepts high turbidity and even a sandy sediment load. On the opposite, the "spring species" *D. stevensoni* needs clear waters to dwell in.

Other chemical and physical water changes are eventually conveyed by the presence/absence of some species. Relatively cold-water temperatures could be suggested by the presence of *L. sancti-patricii*, which dwells best in waters under 14 °C. On the opposite, the presence of two subtropical species (*Stenocypris* sp., and *Candonopsis kingslei*) could convey warmer water temperatures.

3.3 *Palynology*

Fifty-seven samples were taken on the Piton core. Sandy levels were avoided because of their poor pollen content. Palynomorphs were extracted with a standard chemical treatment using HCl (33 %) and HF (70 %) to remove the carbonates and silica, respectively. Heavy liquid separation ($ZnCl_2$, d = 2) was applied, and residues were sieved at 0.2 mm and at 0.01 mm. KOH (at 80 °C for 10 minutes) and a Lüber's mixture were applied when organic matter was abundant. Fifty-four samples were rich enough to be analysed. One hundred fifty pollen grains per sample were counted (the two prevalent pollen types being retrieved from this sum). A detailed pollen diagram was drawn using the software Gpalwin (fig. 4). It is compared with those obtained from other sites of the region (TRIAT-LAVAL 1978). Dinoflagellate cysts and reworked palynomorphs were also counted. It is the first time that such indicators are counted in the deltaic area. All taken together, they help to characterise the environment and to interpret the pollen signal.

3.4 *Microcharcoals and magnetic susceptibility*

Microcharcoal fluxes, derived from forest fires and soil erosion in the Rhône catchment, were studied in thin sections (40 samples). To evaluate quickly microcharcoal densities, the abundance tables of black objects under microscope (BULLOCK et al. 1985) were used in homogeneous facies. Micro-charcoals (particles < 0.2 mm) were discriminated from vegetal humified debris or iron-manganese accumulations by using reflectance microscopy. Results of microcharcoals analysis are presented on fig. 5.

Magnetic susceptibility measurements were used to detect the presence of pedogenic ferrimagnetic minerals (THOMPSON & OLDFIELD 1986). Measurements were made on 10 ml samples and $0.1.10^{-8}$ SI frequencies in a MS2E1 Bartington instrument. Samplings were made at every 10 cm in average (130 samples), except between −6.5 and −4.5 m where coarse material was unsuitable for the measures (fig. 5).

3.5 *Dating methods*

Five ^{14}C dates, archaeological/historical data and palyno-correlation provided chrono-stratigraphic control. Radiocarbon dating (Centre de Datation par le Radio-

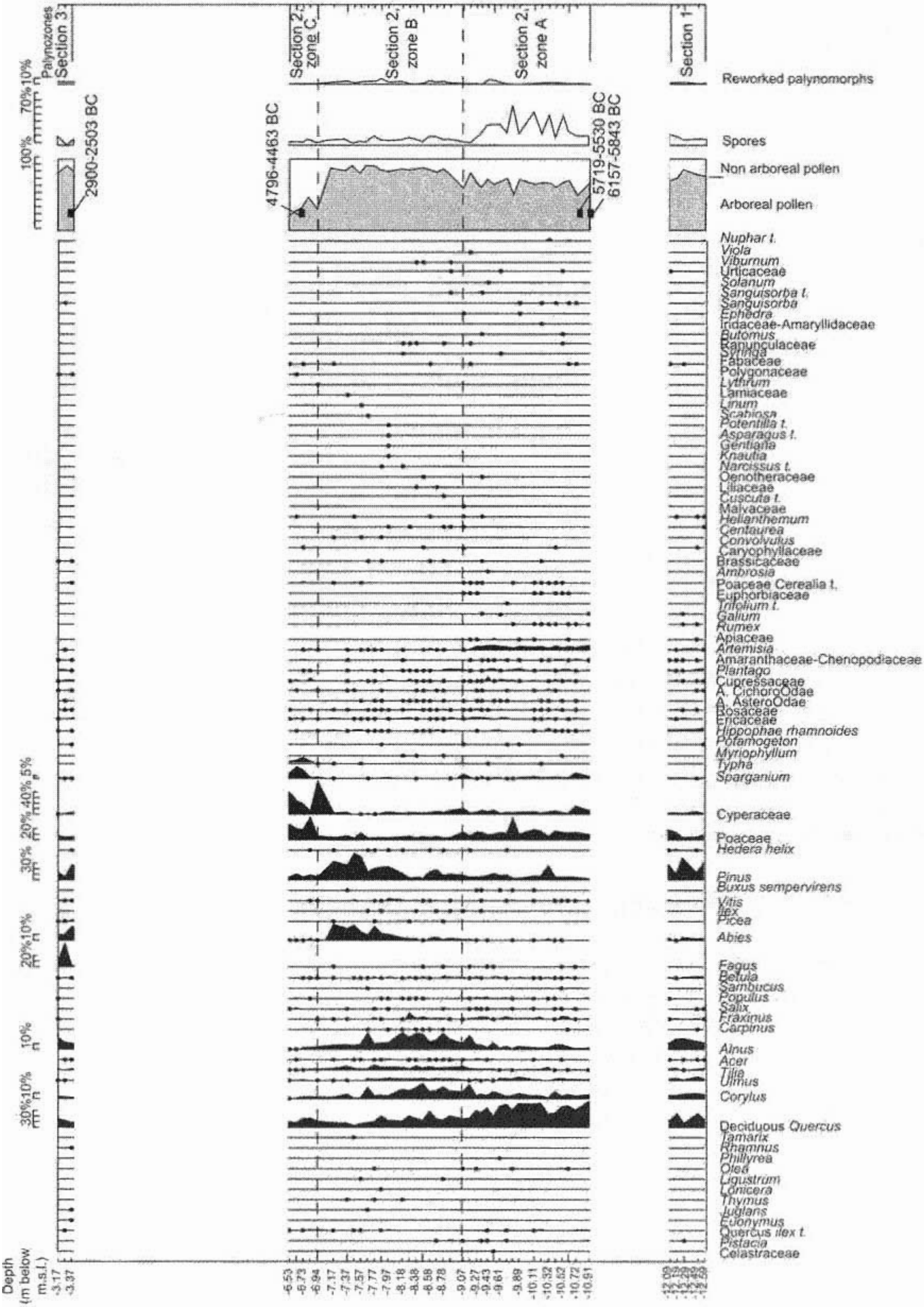


Fig. 4. Detailed pollen diagram of A-Pi core, upper Rhône Delta.

Table 1 List of conventional/AMS ^{14}C ages and archaeological/historical data used for chronology of the sections of A-PI core, upper Rhône Delta.

Elevation (in m) relative to present m.s.l.	Laboratory no.	Material dated	Dating method	$\delta^{13/12}C$ (‰)	Age (^{14}C yr BP)	Cal. yr BC/AD (2σ)	Maximum probabilities
3.17/3.88	IRPA Arles	Rubefied silt (fire)	Historical data	-	-	AD 270	-
2.55/2.8	SRA DRAC-PACA	Italic amphora (reworked)	Archaeology	-	-	Post 1st c. BC?	-
1.65/1.82	SRA DRAC-PACA	Italic amphora	Archaeology	-	-	1st c. BC	-
0.46/0.84	SRA DRAC-PACA	Italic amphora	Archaeology	-	-	2nd-1st c. BC	-
0.69/0.7	LYON-1038 (OXA)	Charcoal	^{14}C (AMS)	-26.65	2035 ± 50	171 BC-AD 74	41-3-25-85 BC
-3.46/-3.47	LYON-1039 (OXA)	Peat	^{14}C (AMS)	-28.03	4170 ± 85	2900-2503 BC	2719-2773-2863-2759 BC
-6.67/-6.68	LYON-1040 (OXA)	Peat	^{14}C (AMS)	-27.67	5795 ± 70	4796-4463 BC	4631-4622-4687-4675 BC
-10.79/-10.8	LY-9559	Peat	^{14}C (conventional)	-27.62	6715 ± 60	5719-5530 BC	5628-5655-5565-5695 BC
-10.94/-10.95	LY-9558	Peat	^{14}C (conventional)	-27.76	7130 ± 65	6157-5843 BC	5993-6005-5935-6045 BC

carbone, univ. Lyon I) of organic matter (ligneous macroremains, charcoal) accumulated syndepositionally in fine-grained sediments was carried out by conventional method and by accelerator mass spectrometry (AMS). The ^{14}C ages were converted to sidereal years using the curve of Stuiver et al. (1998). Results of radiocarbon dating are listed in Table 1. In addition, dating of the core was supported by archaeological remains (pottery fragments, archaeological level, destruction layers), man-induced lithofacies (burnt sediments of the Roman town), and biostratigraphic correlation based on both radiocarbon dating and pollen trends, which reflect the most important components of the Holocene vegetation.

4 *Results and interpretation of the proxy records*

4.1 *Grain-size, geochemical and mineralogical parameters as indicators of depositional environments, hydrodynamics and sediment provenance*

The reconstruction of the deltaic palaeoenvironment was derived from description of the sedimentary facies and from their interpretation in terms of depositional environments (fig. 2). Five distinct sedimentary facies associations (SFA) were identified in 18.3-m section of the A-PI core:

- SFA1: distributary channel (DC; 51 % of the 18.3 m section of the A-PI core), including active DC (SFA1a), and abandoned DC (SFA1b);
- SFA2: crevasse splay (5 %);
- SFA3: proximal flood plain (25 %);
- SFA4: distal flood plain (11 %);
- SFA5: swamp (8 %).

Textural and structural characteristics of each sedimentary facies association were described by Arnaud-Fassetta (2004a), in which we refer the reader.

Besides, we present below (in ascending order) the succession of the 6 depositional environments underlying the present Rhône delta plain at Arles-Trinquetaille, completed by the analysis of sediment provenance (fig. 2).

- From –13 to –10.76 m, an upward-fining sequence (SFA1a to SFA1b) indicates the presence of a first distributary channel of the Rhône River. This latter is characterised by a fine sand-dominated load between –13 and –12.65 m (SFA1a). Heavy-mineral analysis shows the flood supply mainly from the Alps (among which the

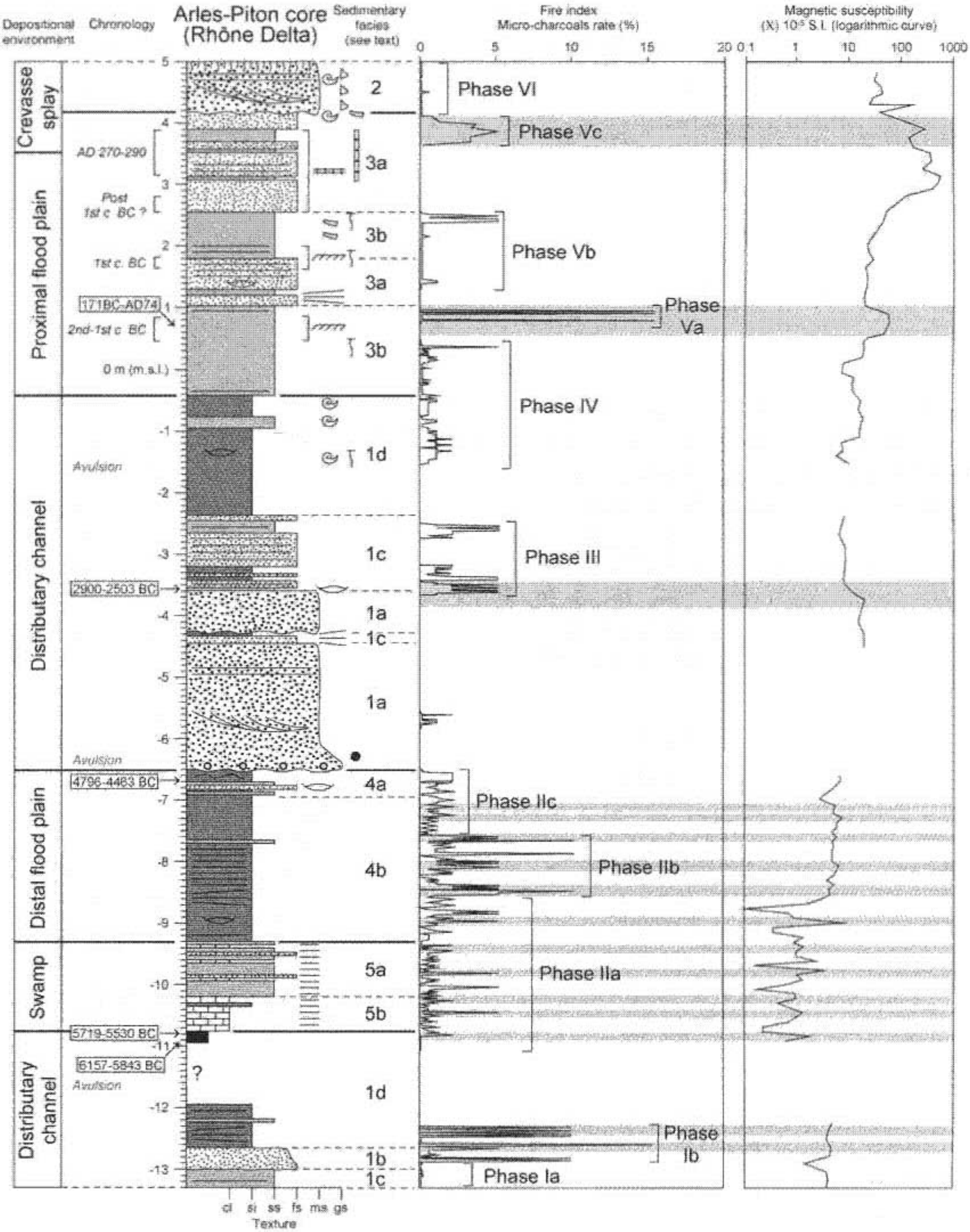


Fig. 5. Microcharcoal and magnetic susceptibility analyses of A-PI core, upper Rhône Delta. See also Fig. 2 for details of the legend.

southern Alps). The burying ratio is high, what, besides, is correlated to the high percentages of iron-stained quartz (ISQ). Then this distributary channel disconnected gradually from −12.65 to −10.56 m. The increase of resistant minerals, reflecting the reworking of old sedimentary material, is correlated to the reduction of Alpine flood supplies. Burying ratio is slower in agreement with reduction of the flood supplies. Then this palaeochannel is abandoned, as a result of an avulsion.

- From −10.76 to −9.3 m, a swamp (SFA5) develops and from −9.3 to −6.51 m, a distal flood plain (SFA4) is evidenced.
- From −6.51 to −0.42 m, a second distributary channel is characterised by two upward-fining sequences. (1) The first one, from −6.51 to −4.27 m, is associated with a very active fluviatile channel between −6.51 and −4.45 m (SFA1a), characterised by a gravely-sand bed-material load. Heavy minerals reveal that flood supplies mainly come from Alps (among which the southern Alps) and Massif Central, both sources zones functioning in antiphase. There is a close correlation between the presence of sediments originated from Massif Central, high values of ISQ, and high percentages of fragile minerals. Furthermore, increasing participation of the Alps is correlated with increasing burying ratio. At the top (from −4.45 to −4.27 m), the short decrease of channel competence is associated with the reworking of old sedimentary material and slow deposition. (2) The second one, from −4.27 to −0.41 m, corresponds to the reactivation (e. g., the increase of competence) of the channel between −4.27 and −3.6 m. It is correlated with the Alps supplies (among which the northern Alps supplies) and sedimentary contributions of the Massif Central. These latter are more in phase with the northern Alps supplies. The significant decrease of the contributions of the Massif Central is followed generally by an increase of resistant minerals, giving evidence of the importance of the Massif Central supplies in the renewal of the alluvial deposits of the Rhône Delta. Then, a channel infilling by fine-grained sediments began between −3.6 and −2.37 m. The flood supplies alternately come from the southern Alps and Massif Central. Low percentages of fragile minerals and high values of altered grains reflect slow deposition. Very fine-grained sediments from −2.37 to −0.42 m (SFA1b) indicate that the distributary channel was abandoned certainly as a result of an avulsion.
- From −0.42 to 4.17 m, a proximal flood plain (SFA3) develops. At the base (from −0.41 to 0.98 m), sediment is originated from Massif Central, that it is positively correlated with high percentages of ISQ, and negatively correlated with resistant minerals (old sedimentary material). This confirms the importance of the contributions of the Massif Central in the renewal of the alluvial deposits, not only in the channel but also in the flood plain. The low percentages of fragile minerals indicate slow burying ratio. Then, between 0.98 and 1.8 m, a flood plain influenced by crevassing process is correlated with the increase of the burying ratio. In certain cases, we note a functioning in antiphase concerning the supplies of resistant (old sedimentary material) and fragile (sedimentary material quickly constituted) minerals. The dominant flood supplies are those resulting from both the southern and northern Alps. The high values in ISQ are in phase with the resistant minerals (reworking of old sedimentary material). From 1.8 to 2.55 m, the slowing down of the sedimentation rates observed in the fine-grained deposits of the proximal

flood plain is synchronous of the increase of resistant minerals. We observe the decrease of the south-Alpine supplies but those coming from the northern Alps and Massif Central are still important. At the top (from 2.55 to 4.17 m), a reinforcement of the hydrodynamics is shown by the presence of a proximal flood plain influenced by crevassing process.

- From 4.17 to 5 m, a crevasse-splay deposit (SFA2) covers the flood-plain surface. Heavy-mineral analysis shows dominant supplies result from the Massif Central and southern Alps (at the base). High percentages of fragile minerals reflect rapid deposition that is correlated to high values of ISQ.

4.2 *Ostracodes analysis as records of biotope conditions*

Five biozones, corresponding to relatively homogeneous biotope conditions, were separated in the A-PI core (fig. 3).

4.2.1 *The Cytheromorpha fuscata biozone (from −13.27 to −12.5 m)*

The sandy levels of the core base reveal a scarce ostracofauna where the only frequent species is *C. fuscata*. The scarcity is here explained by a high sedimentation rate, which dilutes the biocenoses, and by high-energy conditions, unfavourable for ostracodes. Only the turbidity-tolerant *C. fuscata* was in living position (see sample at −13.27 m); other ostracodes and foraminifers should be considered as a thanatocoenosis moved from other biotopes of the Rhône mouth. This is proved at −12.78 and −12.73 m by the associations of marine faunas (*Quinqueloculina*, *Rosalia*), brackish ones (*C. torrosa*, *C. fuscata*, *Ammonia*) eventually in living position, and freshwaters ones (*Candoninae*, *Herpetocypris*). The environment reconstituted through these faunas corresponds to an estuary with brackish water (salt wedge of the Rhône River) and high-energy flows. The ostracodes totally disappear in the silty upper part of A-PI core (over −12.5 m), corresponding maybe to the abandoning of the distributary channel associated with too frequent exundations of the site.

4.2.2 *The Cyprideis torrosa biozone (from −10.8 and −10.55 m)*

Most species are brackish-water or tolerant to brackish-water ones. *C. torrosa* dominates, associated with *C. neglecta* and *D. stevensoni* in some levels. These secondary species indicate that the salinity rate was never over 10–15‰. Variations in abundance correspond to variations in salinity. The fall in number and part of *C. fuscata* among brackish species marks a lowering in energy and turbidity. The salinity is likely to be of marine origin as shown by *C. torrosa* and *Ammonia* sp. Nonetheless there might be other water origins, maybe from close springs as suggested by *D. stevensoni*. The dissolved carbonates that caused the chalk precipitation allow the presence of *L. sancti-patricii*, which suggests also that the water temperature was not too high. The significant numbers of *Limnocytherinae*, *D. stevensoni*, *M. cordata* indicate permanent waters. No macrophyte species are found, conveying a poorly vegetalized, maybe oligotrophic environment with free and clear waters.

4.2.3 *The Metacypris cordata biozone (from −10.55 to −7 m)*

M. cordata-rich levels abruptly follow the *C. torrosa*-dominant ones, indicating a quick transition to a freshwater environment. There still were occasionally rises in salinity, as shown by the remaining presence of *C. torrosa*. A short-time fall of the water level could nonetheless occur during the transition between the brackish- and freshwater pool (−10.5 to −10.35 m), marked by the dominance of candoninae. Only in the last levels (−9.35 and −9.25 m) can be observed a few macrophyte-living species (*I. bradyi*, juvenile forms of *Heterocypris* and *Eucypris*). They might indicate that the littoral vegetation ring draws nearer as a consequence of the drying up (or infilling) of the pool. Variations in abundance correspond here to fluctuations in the fluvial flooding frequency of the pool and in amounts of sediment load then deposited. The incoming of fluvial floods brings turbid waters that could have inhibited the growth of some species (*M. cordata*, *Candoninae* and especially *P. compressa*). These flooding events seem more frequent in the upper levels. This biozone ends again with the disappearance of the ostracofauna between −9 and −7 m, so confirming the hypothesis of a progressive infilling of the pool leading to a partial drying.

4.2.4 *The Cypridinae biozone (from −7 to −6.5 m)*

The last fifty centimetres of the fluvial silty sedimentation, interstratified with occasional peat levels, contain a scarce but diversified ostracofauna, in which the macrophyte and eutrophicated-water species are frequent. The most fragile ostracode shells (especially the *Candoninae*) look very thin or dissolved, conveying processes of carbonates dissolving, as is frequent in eutrophised waters. Pons et al. (1979) proposed to interpret this as a natural phenomenon, linked with the beginning of the present-day's regime of the oligohaline ponds. The strong summer evapotranspiration and the seasonal oscillations of the groundwater table through the dense silty deposits would have lead to summer rises of the salinity, allowing only the most tolerant "freshwater" ostracode species to survive. This ostracofauna (*Ilyocypridinae*, *Cypridinae*) also the nearest to the present one. There are, although, some differences, as the *Cypridinae* never dominate. In the first part of the biozone (−6.95 to −6.8 m), the association is dominated by *Candoninae*, and contains only seasonal-water species. In the upper levels (−6.75 to −6.5 m) the seasonal species become more rare and regular numbers of *M. cordata* are found, revealing a deepening pond with less mineralised and permanent waters.

4.2.5 *The thanatocoenosis of the distributary channel infilling (from −3.4 to −2.5 m)*

There are no ostracodes in the overlying channel coarse sands. Only a few individuals were found in the finer levels of the channel infilling upper part. As there were often broken shells, these individuals could correspond to a thanatocoenosis from close areas of the fluvial environments, deposited here by low-energy floods. However, the association (*C. ovum*, *I. Bradyi* and *Cypridinae*) has a certain coherence. It suggests that in other parts of the delta, the environment reconstituted from the underlying biozone still lasts. The only new element is the occurrence of the tropical

Stenocypris sp. and *Candonopsis kingslei*, conveying year-long warm waters. This could correspond with the stagnant hot waters of an abandoned channel.

The ostracofauna totally disappears in upper levels, together with the appearing of strong bioturbation and pedogenic features.

4.3 *Pollen analytical evidence for land-cover change*

Pollen concentration fluctuates from 1,000 to 14,000 pollen grains per gram of dry sediment. The whole core evidences seven dominant taxa (deciduous *Quercus*, *Corylus*, *Alnus*, *Abies*, *Pinus*, Poaceae and Cyperaceae). Percentages of arboreal pollen (AP) fluctuate from 20 to 91%. Only four spectra contain less than 50% of tree pollen grains. A spectrum characterised by more than 80% of herbs generally represents an open environment; between 20 and 80% of herbs, it corresponds to forests with grasslands; and less than 20% of herbs, it represents the dominance of forests (TRIAT-LAVAL 1978, PONS et al. 1979).

The detailed pollen diagram of the A-PI core is composed of three sections (fig. 4).

- Section 1 (from −12.59 to −12.09 m) corresponds to high values of *Pinus*, low values of deciduous *Quercus* and *Corylus*, and a high value of *Alnus*. Palaeoenvironment is difficult to interpret from such a short sequence. Nevertheless, the abundance of *Pinus* and *Alnus* contrary to pollen of herbs reflecting a local pollen rain (such as Cyperaceae or *Sparganium*), and the presence of reworked palynomorphs remind present-day spectra found at the Rhône river mouth (BEAUDOUIN et al. 2005). They tend to indicate a fluvial influence probably due to floods.
- Section 2, zone A (from −10.91 to −9.07 m) corresponds to high values of deciduous *Quercus*, Poaceae, and relatively high values of *Artemisia* and *Sparganium*. *Corylus*, *Tilia*, *Alnus*, *Abies* and *Pinus* are present but not so abundant. Several herbs increase or appear during this zone: Amaranthaceae-Chenopodiaceae, *Plantago*, Apiaceae, *Rumex* and Poaceae t. *Cerealia*. This is interpreted as the impact of human activities near the site.
- Section 2, zone B (from −9.07 to −6.94 m) is characterised by the decrease of deciduous *Quercus* and the increase *Corylus* and *Alnus* (heliophilous trees).
- Section 2, zone C (from −6.94 to −6.53 m) corresponds to the increase of herbs (Poaceae, Cyperaceae and water plants like *Sparganium* and *Typha*). It characterises the setting of a freshwater marsh or the transition between a marsh and dry soil. Reworked dinocysts decrease to disappear, indicating that the site is not flooded by the Rhône River.
- Section 3 (from −3.37 to −3.17 m) is characterised by the highest values of *Fagus*, *Alnus* and *Pinus* are abundant and reworked dinocysts are present. It tends to indicate an increase of fluvial transport influence.

To conclude, the presence of reworked elements all along the core suggests an influence of the Rhône River on the site (excepted in section 2, zone C). This interpretation is supported by sedimentary data (fig. 2). Indeed, they reflect a marsh more or less flooded by the Rhône River (at least for sections 1 and 2).

4.4 *Microcharcoals and magnetic susceptibility as records of fire history*

The diagram (fig. 5) is subdivided in 6 main phases:

- Phase I: from –13.3 to –12.8 m (Ia), the very low values of fires index suggest that local or regional fires did not occur. From –12.8 to –12.3 m (Ib), the biomass-burning tracks indicate a most pronounced flare-up period, giving evidences of numerous forest fires in the catchment. Charcoals influxes appear in phase with small oscillations of magnetic susceptibility.
- Phase II: from –11.1 to –9 m (IIa), the diagram shows strong charcoal peaks (2–5 %) with a high repetitiveness, and two secondary smaller peaks (1 %) between each of them. The ferrimagnetic minerals content is low and correlated with charcoal densities. From –9 to –7.55 m (IIb), higher values include several large peaks (5–10 %). One dozen charcoal peaks are registered during this phase. This phase could be interpreted as a change in fire regime. From –7.55 to –6.5 m (IIc), the fire regime is similar to that detected in IIa.
- Phase III (from –3.6 to –2.5 m): numerous, higher (~ 5 %) and closely spaced charcoal peaks occur.
- Phase IV (from –1.5 to 0.45 m): the registration of fire events is minimal. Small peaks (1–2 %) of microcharcoals are identified. In the same time, the magnetic curve show important variations in intensity and a long period of high values between –0.9 and –0.1 m. This phase could correspond to a hydromorphic soil evolution.
- Phase V: from 0.45 m to 1 m (Va), values of both microcharcoals and magnetic susceptibility strongly rise. A first important peak of charcoal is identified around 0.45 m, just under the first archaeological level. It could correspond to a clearance phase of the river forest by fire, to prepare the human settlement on the right bank of the Rhône River at Arles. In the same time, the ferrimagnetic signal shows a first stronger peak, which indicates an *in situ* fire event. A second major peak of charcoals of big size (5–10 mm) is identified at around 0.8 m, into a thick archaeological layer with a lot of Roman ceramics. It is clear these macrocharcoals accumulation has an anthropogenic origin. From 1.3 to 2.55 m (Vb), strong decrease of charcoal content and magnetic values indicates the fire signal is very low. From 2.55 to 4.1 m (Vc), the very high values of magnetic susceptibility, observed on one metre thick, correspond to the Trinquetaille district's burning.
- Phase VI (from 4.1 to 5 m) is associated with an abrupt decrease of both microcharcoals and ferrimagnetic minerals, corresponding to the reworking of burnt material aggregates by flood events.

5 *Discussion*

5.1 *Palaeohydrology and environmental change*

Before 6,157–5,843 BC, a distributary channel (so called "Palaeochannel A" on fig. 7A) of the Rhône River took place and it was characterised by a fine sand-dominated load. Ostracodes analysis shows the channel waters were brackish (salt wedge) and associated with high-energy flows, allowing us to localize the distributary channel close to mouth (fig. 6). At this moment, the mean sea level is supposed

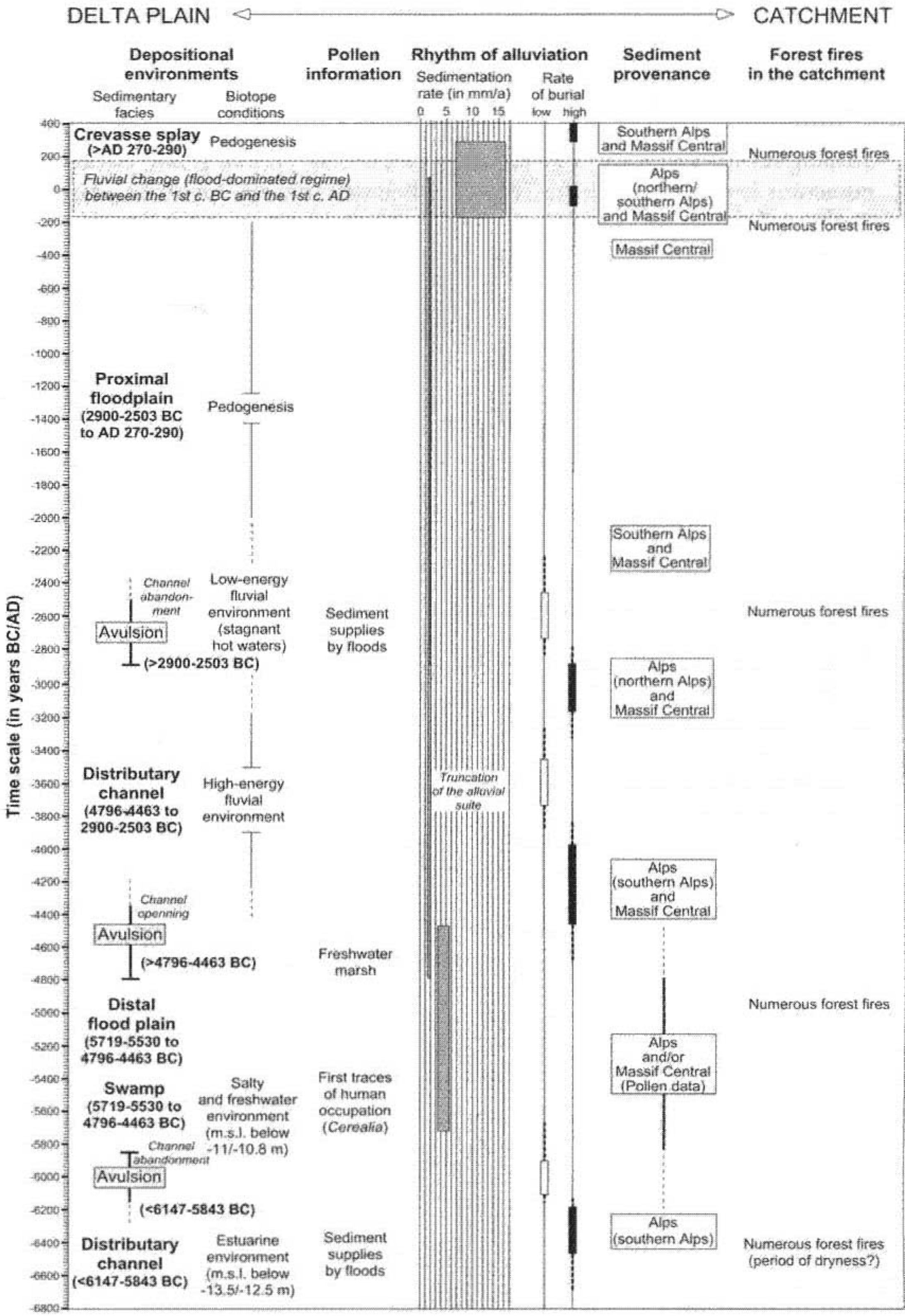


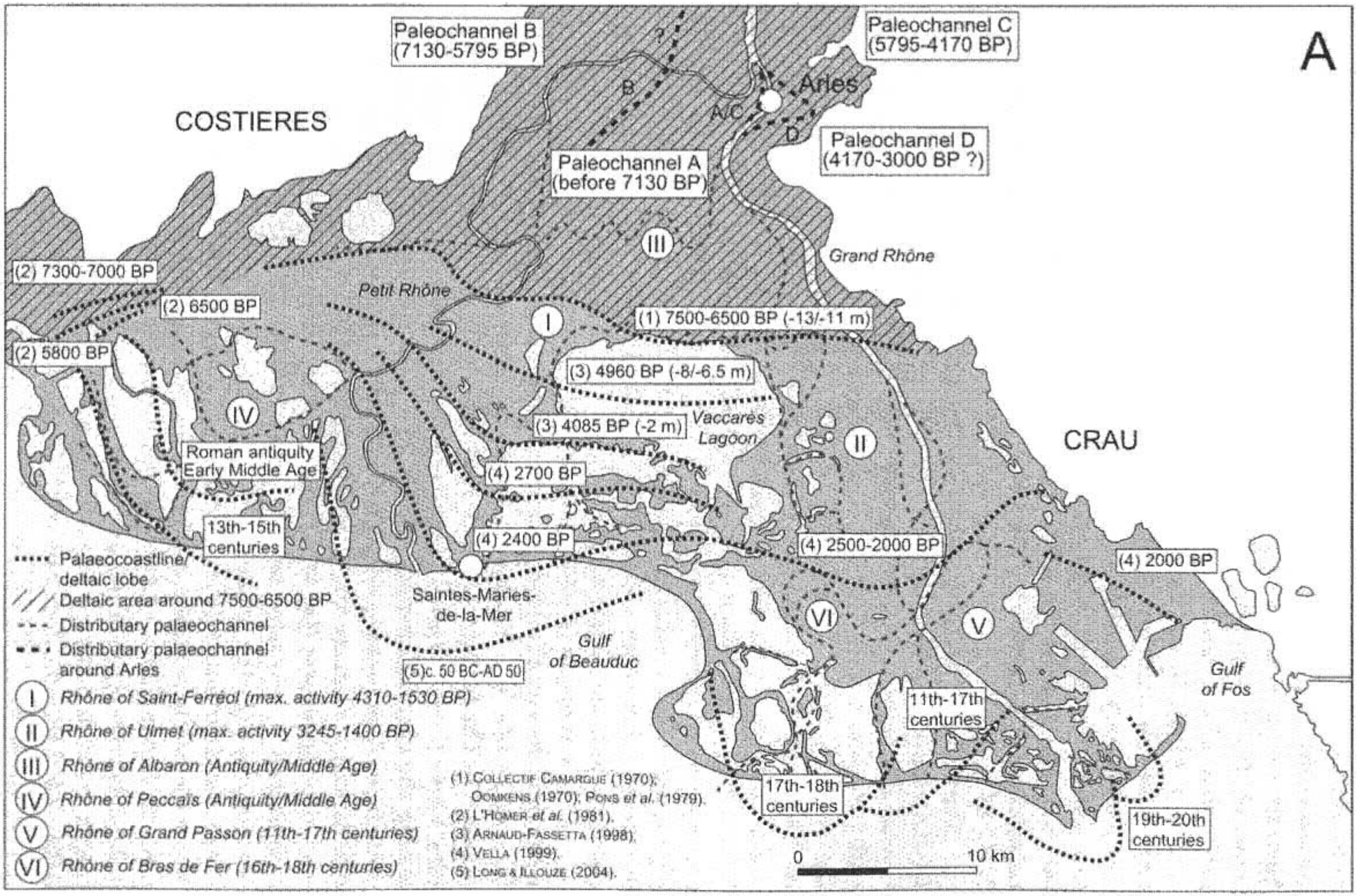
Fig. 6. Palaeohydrology and environmental change in the upper Rhône Delta since the last 8,000 years, deduced from A-PI core.

to be situated at –13.5/–12.5 m below the present Mediterranean sea level, and the palaeocoastline immediately north of Vaccarès Lagoon (fig. 7A). Around Arles-Trinquetaille site, pollen data indicate a fluvial-dominated environment influenced by frequent flood supplies. Heavy-minerals indicate high burying ratio in the palaeochannel and flood supplies resulting mainly from the Alps (among which the southern Alps). In the catchment (Alps?), a possible wave of dryness could be responsible for numerous forest fires, as shown by the microcharcoal analysis. Then this distributary channel disconnected gradually. At the top of the infilling, the increase of resistant minerals reflect the reworking of old sedimentary material and burying ratio is slower, in agreement with reduction of the flood supplies. Then this palaeochannel is abandoned, as a result of an avulsion which occurs before 6,157–5,843 BC.

From 5,719–5,530 to 4,796–4,463 BC, a swamp environment (brackish to freshwater) is associated with the deposit of laminated chalk and silty clay (fig. 6). Ostracodes analysis suggests a poorly vegetalized, maybe oligotrophic environment, with permanent, free, clear and cold waters. This swamp developed above the mean sea level, which was situated at this time below –11/–10.8 m. At this moment, the main Rhône palaeochannel ("Palaeochannel B") is supposed to be west to the site, as indicated by fig. 7A. In Arles-Trinquetaille, pollen analysis records the first traces of human occupation. Then a distal flood plain took place before 4,796–4,463 BC. It corresponds the infilling of a pool by frequent flood supplies, that is confirmed by high sedimentation rates (3.3–5.6 mm/a). Pollen data record the increase of mountainous supplies (Alps and/or Massif Central) whereas high percentages of microcharcoals indicate numerous forest fires in the catchment.

A new avulsion (post 4,796–4,463 BC) induces the displacement of the Rhône River and the rapid implementation of a new distributary channel ("Palaeochannel C") on the site. The functioning of this palaeochannel can be decomposed into two phases. (1) The first one (from 4,796–4,463 to 2,900–2,503 BC) is associated with a very active fluvial channel, characterised by a gravely-sand bed-material load. Following the channel opening, the burying ratio was high and flood supplies mainly came from Alps (among which the southern Alps) or Massif Central. However, the sedimentation rates are low (1.3–1.9 mm/a), indicating a probable reworking/erosion of channel sequences (fig. 6). At the end of this period, the short decrease of channel competence is associated with the reworking of old sedimentary material and low burying ratio. (2) The second one occurred previous to 2,900–2,503 BC. After a brief break, the distributary channel was reactivated by abundant Alps supplies (among which the northern Alps supplies) and by hydrosedimentary contributions of Massif Central. Around 2,900–2,503 BC, the palaeochannel begun to infill by fine-grained sediments coming from the southern Alps and Massif Central. Low percentages of fragile minerals and high values of altered grains confirm low burying ratio. After 2,900–2,503 BC, the distributary channel avulsed (fig. 6).

From 2,900–2,503 BC to AD 270–290, a proximal flood plain was dominated by flood supplies derived from the Massif Central, confirming the importance of this sediment source area in the renewal of the alluvial deposits, not only in the channel but also in the flood plain. The low percentages of fragile minerals indicate low burying ratio whereas sedimentation rates are low (1.4–1.8 mm/a). The presence of a flood plain on the site supposes that the Rhône channel ("Palaeochannel D") is somewhere


A
COSTIERES
CRAU
Paleochannel B
(7130-5795 BP)
Paleochannel C
(5795-4170 BP)
Arles
A/C
B
D
?
Paleochannel A
(before 7130 BP)
Paleochannel D
(4170-3000 BP ?)
III
Grand Rhône
Petit Rhône
(2) 7300-7000 BP
(2) 6500 BP
(2) 5800 BP
I
(1) 7500-6500 BP (-13/-11 m)
(3) 4960 BP (-8/-6.5 m)
IV
(3) 4085 BP (-2 m)
Vaccarès
Lagoon
II
Roman antiquity
Early Middle Age
(4) 2700 BP
13th-15th
centuries
(4) 2400 BP
(4) 2500-2000 BP
(4) 2000 BP
Saintes-Maries-
de-la-Mer
Gulf
of Beauduc
VI
V
Gulf
of Fos
(5)c. 50 BC-AD 50
11th-17th
centuries
17th-18th
centuries
19th-20th
centuries
0
10 km
Palaeocoastline/
deltaic lobe
Deltaic area around 7500-6500 BP
Distributary palaeochannel
Distributary palaeochannel
around Arles
I Rhône of Saint-Ferréol (max. activity 4310-1530 BP)
II Rhône of Ulmet (max. activity 3245-1400 BP)
III Rhône of Albaron (Antiquity/Middle Age)
IV Rhône of Peccais (Antiquity/Middle Age)
V Rhône of Grand Passon (11th-17th centuries)
VI Rhône of Bras de Fer (16th-18th centuries)
(1) Collectif Camargue (1970);
Oomkens (1970); Pons et al. (1979).
(2) L'Homer et al. (1981).
(3) Arnaud-Fassetta (1998).
(4) Vella (1999).
(5) Long & Illouze (2004).

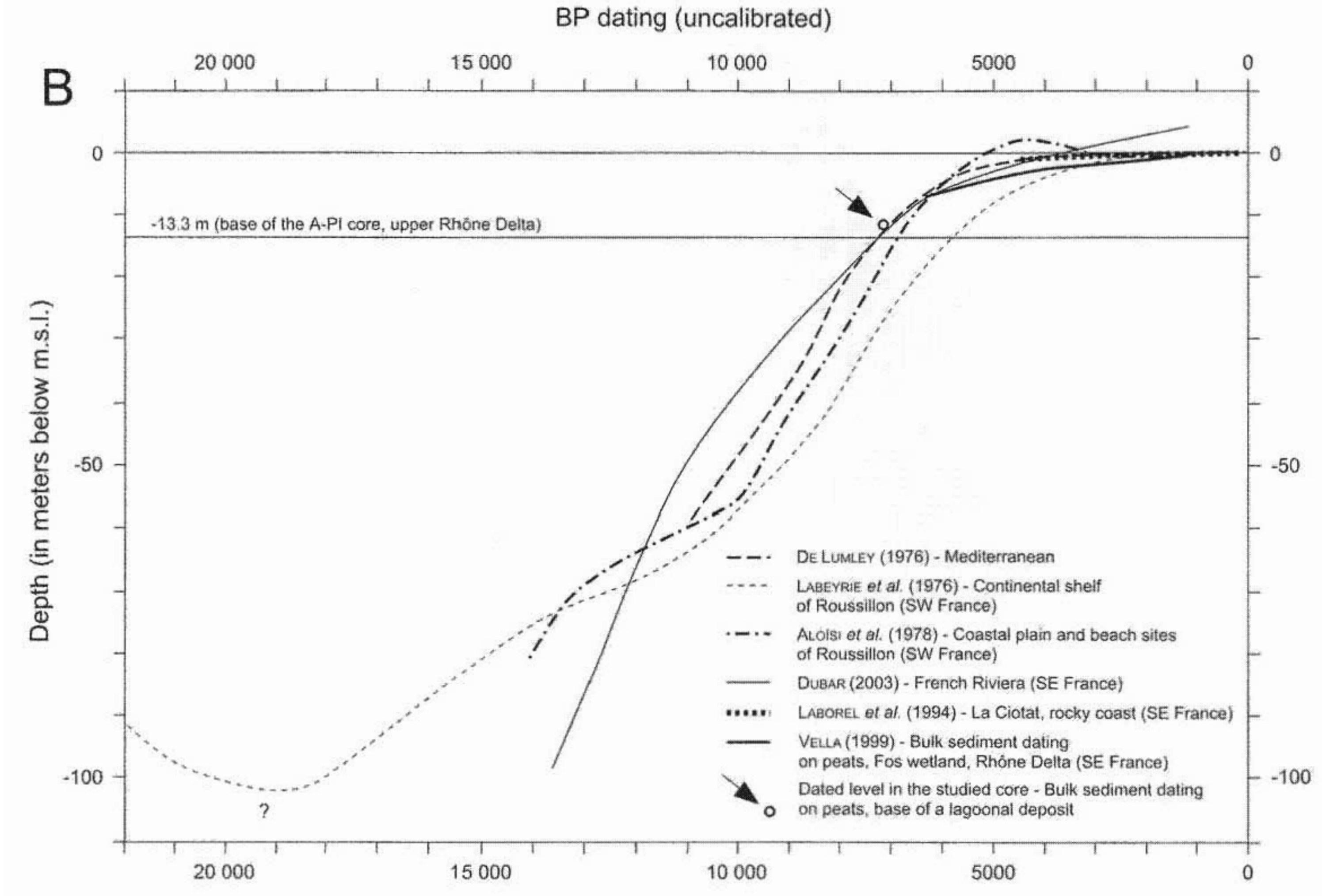


Fig. 7. (A) Geomorphological map of the Rhône Delta showing Holocene distributary channels and shorelines. (B) Relationships between regional sea-level curves (see Pirazzoli 1996) and brackish deposits levels in A-PI core, upper Rhône Delta.

else, probably east of the Hauture hill between the Bronze Age and the first Iron Age (fig. 7A), as suggested by BRUNETON (1999). At this time, the palaeocoastline was situated south of Vaccarès Lagoon (fig. 7A). From 171 BC-AD 74 to AD 270–290, the development of a flood plain influenced by crevassing process is correlated with the increase of the burying ratio and sedimentation rates were 6.8–16.1 mm/a, which are high values, compared to those obtained in the proximal flood plains of the delta (0.5–2 mm/a; ARNAUD-FASSETTA 2000). The dominant flood supplies are those resulting from both the southern and northern Alps and Massif Central. This period corresponds to the fluvial change that occurred in the Rhône Valley during the Roman antiquity (fig. 6). Indeed, from Avignon to Arles, this period of "flood-dominated regime" was characterised by more powerful flood events in the channel and its flood plain, higher flooding frequencies, higher sedimentation rates and rises in groundwater levels in the flood plain (ARCELIN et al. 1999, BRUNETON et al. 2001). It comes true also in the delta plain where phenomena of avulsion, major crevassing and coastal progradation came to add (ARNAUD-FASSETTA 1998, 2002 and 2004b).

After AD 290, a crevasse-splay deposit covers the flood-plain surface (fig. 6). Heavy-mineral analysis indicates high burying ratio and supplies mainly resulting from the Massif Central and southern Alps. Such an event was already described in Arles city (Brossolette site; BRAVARD 1988) and hypothetically associated to the end of the antiquity.

To conclude, the abrupt sedimentary facies superposition clearly indicates several substantial changes in hydrodynamics and environmental conditions, linked to channel avulsions. Based on an estimated thickness of 7.8 m, the deposits directly linked to a channel avulsion represent a significant proportion (c. 43 %) in the uppermost 18.3 m of the alluvial fill of the upper Rhône Delta. Therefore, the present study confirms that channel avulsion is a very important process in the deltaic-plain construction, as suggested by ARNAUD-FASSETTA (2004a) in the Rhône Delta, by TÖRNQVIST et al. (1996) and ROBERTS (1997) in the Mississippi Delta, and by STOUTHAMER & BERENDSEN (2001) in the Rhine-Meuse Delta.

5.2 *Sea level* versus *Holocene delta geometry*

Both palaeoecological proxies characterise coherent changes in salinity for channels and pools environments in the bottom of the core. They convey a variable position of the coring site in altitude and distance from the sea shoreline. The brackish ostracode fauna makes it clear that the open sea did not attain the site during the studied period. Therefore, the maximum coastal onlap since the last 8,000 years was downstream to the site. Nonetheless, there are evident marine influences. A fluvial salt-wedge environment is identified before 6,157–5,843 BC. It conveys an estuarine landscape, with marine waters coming up to the present apex of the delta, more or less using the Pleistocene palaeovalley of the Rhône River. The height (from −13.3 to −13 m) of the deposits can be put in correspondence with the point of maximum coastal onlap drawn by OOMSKENS (1970) immediately upstream of the Vaccarès Lagoon. Therefore, A-PI core would allow us to date the point of the maximum coastal onlap before 6,157 BC in the Rhône Delta, what is coherent with the kinematics proposed by PONS et al. (1979). Furthermore, the sediments were then deposited under the modern sea level, which was then below −13.5 to −12.5 m. This elevation is coherent with the known sea-level curves for the western Mediterranean (fig. 7B). The brackish marsh levels that follow between –11 and –10 m can be interpreted as a lagoon environment, where sediments still deposited under the sea level. The dated peat level between –11 and –10.8 m was formed near the water surface, as humidity was sufficient to conserve the organic matter but insufficient to allow an ostracofauna to develop. This provided dating of the sea level is again coherent with the known curves. The transition between an estuarine and a lagoon environment is caused by the first identified channel avulsion. The fact that the sea does not invade the abandoned channel illustrates the deltaic progradation, beginning together with the slowing of sea-level rise. Deltaic progradation and aggradation further explain the transition towards a freshwater marsh at –10 m. From this level on, the coring site is too far north from the seashore to record any important marine influence (fig. 7A). The flood silts fill the marshes quicker than the sea-level rise, which explains the progressive drying up of the site.

5.3 *Anthropogenic impact on the environment, from catchment to the delta*

On the regional scale (Rhône catchment), the microcharcoal analysis has shown the occurrence of fires since the last 8,000 years. It is in accordance with what was observed in the middle Rhône basin where fires have been regularly identified since the Lateglacial in colluvial, paludal and alluvial environments (Berger 2003). But no consensus is still established concerning the origin of these fires. Changes in frequency of fire occurrences could be interpreted in terms of ecological, climatic or human activity fluctuations (Berger & Thiébault 2002). The A-PI core has evidenced 4 main phases (Ib, IIa/IIb/IIc, III and Va/Vc) of fire. They correspond to different fire regimes, and to different geographical locations of fire (signal more or less distal from the site).

It seems difficult to associate the first phase (Ib) with clearance fires of human origin, because only few contemporary Late Mesolithic (Castelnovian culture) and Early Neolithic settlements (associated with the Impressa culture) are known today in the southern France (Richard 2000). We suppose that charcoal influxes identified in the upper Rhône Delta correspond to a strong detrital signal from the Alps, and particularly from the southern Alps (see heavy minerals, fig. 2) and to fluctuations in the oak-forest cover, without association with anthropogenic manipulation of the canopy. Moreover, there are no pollen grains of Poaceae *Cerealia* type (section 1 on fig. 4). Furthermore, fires are identified in numerous sites of the middle Rhône valley and in the Vidourle Delta (lower Languedoc) at the same period. Fire signals registered in the Rhône Delta seem to correspond to a period of general fires in the southern France, concentrated around 8,200 cal. BP (Blanchemanche et al. 2003), associated with a pronounced hydrological activity and erosion in the Rhône catchment. These macro-regional signatures appear to be more like a climatic event (period of dryness) than cultural pressure on the Mediterranean forest. In the ice-core GISP2 (Groenland), Alley et al. (1997) observed a major phase of fires in the North Atlantic and North America at the same period, interpreted as a generally dry and cold period in the northern hemisphere.

The phase II brings more information concerning fire regime, cycles and vegetation changes (fig. 8). The pedosedimentary environmental succession seems to prove that fire signatures appear more local than regional. Between the Mesolithic to Ne-

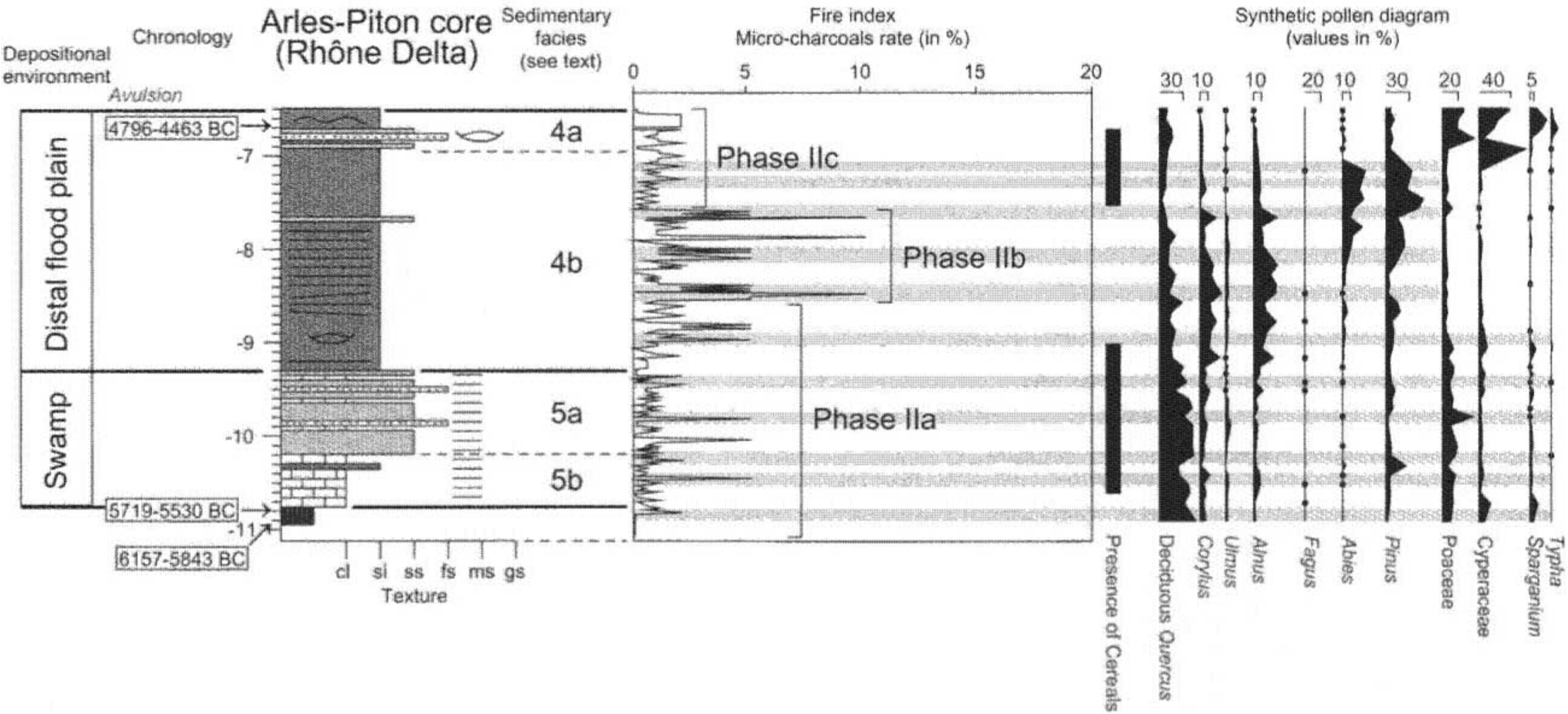


Fig. 8. Correlations between sedimentary facies, microcharcoal content and pollen data in the lower part of A-PI core, upper Rhône Delta. See also fig. 2 for details of the legend.

olithic transition (5,719–5,530 BC) until the beginning of the Middle Neolithic (4,796–4,463 BC), three different fire regimes are recognized. Charcoals peaks (above –9 m) coincide with a decrease in deciduous *Quercus* pollen grains and the increase of heliophilous trees (*Corylus* and *Alnus*). When the fire regime becomes higher between –9 and –7.5 m, a significant peak (1) in heliophilous trees followed by a significant peak (2) in conifers (*Pinus* and *Abies*) is observed. Palynology is not able to determine the species of *Pinus*. Nevertheless, some species of *Pinus* are known to be favoured by disturbances such as fires and colonize the open spaces. Therefore we can suggest that when fire events are closer in time, conifers could substitute to oak deciduous forest, because they are better adapted to periods of fires regime dominance. In particular, pines are considered as pyrophilous species, which colonise the open spaces created by fires. When fire regimes decrease, they tend to decrease as well (BRADSHAW 1993). Nevertheless, the decrease in *Pinus* and *Abies* pollen grain is strongly correlated to the installation of a marsh (section 2, zone C). Furthermore, the phase IIa shows a lower regime of fires, with small fluctuations in charcoal contents, contemporaneous with the first signs of agriculture (appearance of cereals) in a flood plain. In fact, the first farming activities disappear when fires become more frequent. To conclude, the phase II, which represents one millennium in calibrated age, seems to illustrate a modification of the natural wildfire regime by the first farming activities.

The major fire peaks characterising the phase III (around 2,900–2,503 BC and after) correspond on a regional scale to a fire period also identified in numerous sites in the middle Rhône Valley (BERGER 2003) and in the Vidourle Delta (BLANCHEMANCHE et al. 2003) associated with strong human pressure on the environment and a period of a great hydrological fluctuation.

The antic Rhodanian detrital crisis (1st c. BC – 1st c. AD; BRUNETON et al. 2001, ARNAUD-FASSETTA 2002) is associated with a very low fire regime (phase Vb). This signature can be explained by an artificial reduction of the fire regime, associated with large-scale anthropogenic actions identified in the entire Rhône catchment (Roman colonisation effects). The fixing of agricultural soils, permanently exploited for intensive crop production decreases the wood reserves and increases the soil sensitivity to erosion (BERGER 2003).

Finally, on the local scale (Rhône Delta), presence of Cerealia has been detected in Arles-Trinquetaille (A-PI core) since 5,719–5,530 BC. Modern pollen rain of *Cerealia* reaches less than 1% at 100 meters away from the studied site (DE BEAULIEU 1977). So, the percentage encountered in the A-PI core could be due to the neighbouring of a cultivated area. There are some evidences of ancient agro-pastoral activities in the Rhône Delta as already proposed by TRIAT-LAVAL (1978) for Neolithic civilizations. These activities are then continuous and found everywhere in the Rhône Delta (TRIAT-LAVAL 1978, ARNAUD-FASSETTA et al. 2000). We hypothesize agro-pastoral activities could have begun earlier in the Rhône catchment, because of edaphic constraints less strong than those existing in the delta.

6 *Conclusions*

The detailed study of the 18.3-m-long A-PI core reveals for the first time the depositional history and hydrological functioning of the upper Rhône Delta over the past 8,000 years. Sedimentary-facies succession of the A-PI core allowed us to characterise the hydrosedimentary dynamics and the degree of lateral instability of the Rhône River in the upper part of the delta. So, the lithostratigraphy deduced from A-PI core can constitute a model of sedimentation ("fluvial-dominated sequence") for the upper part of the Holocene delta plain.

Several specific points concerning the Rhône Delta and its catchment, or more general points on the construction of deltas, were cleared up:

(1) *Environmental and palaeohydrological changes in the upper Rhône Delta.* During the studied period (6,157–5,843 BC/AD 270–290), the abrupt change of environmental conditions is correlated to several substantial variations in hydrodynamics and lateral channel instability. One of the most important factors controlling lateral channel instability is avulsion process. This working hypothesis is in agreement with the conclusions brought by previous delta studies (Törnqvist et al. 1996, Roberts 1997, Stouthamer & Berendsen 2001). Furthermore, there is a significant correlation between the Rhône floodplain palaeohydrology, the channel avulsions and the geomorphological evolution of the delta plain.

(2) *Mediterranean sea-level change and Rhône Delta geometry.* Stratigraphic records have shown the site of Arles has not been reached by the sea, and the maximum coastal onlap was downstream to the site since the last 8,000 years. About the point of maximum coastal onlap in the Rhône Delta, A-PI core allowed us (1) to localize it immediately upstream of the Vaccarès Lagoon, (2) to identify it at −13.5 to −12.5 m below the present Mediterranean sea level, and (3) to date it before 6,157–5,843 BC. Deltaic progradation and aggradation further explain the transition between brackish to freshwater marsh at −10 m.

(3) *Geographical origin of flood supplies in the Rhône Delta.* In a general way, the heavy-mineral analysis confirms that the sedimentary fluxes arriving in the Rhône Delta during the last 8,000 years were derived from several possible source areas. Among these sources, the Massif Central arrives in head, with 52 % of occurrence in sediments. The Alpine contributions (48 %) arrive in second position, and those resulting from the northern Alps (12 %) are minor. In fact, the Alpine contributions seem to result first and foremost from the southern Alps (36 %). On the whole, this study brings so again the proofs that the Rhône Delta was mainly built by sediments derived from proximal source areas (Massif Central and southern Alps), as suggested by Van Andel (1955) and Stanley & Jorstad (2002).

(4) *Antropogenic impacts from Rhône catchment to deltaic plain.* On the scale of Rhône catchment, microcharcoals analysis has shown the occurrence of 4 main phases of fires. Before 6,157–5,843 BC (phase I), erosion process in the catchment seems strictly correlated with a high wildfires regime, in the context of a possible period of climatic dryness. This phenomenon was not able to be appreciated from 5,719–5,530 to 4,796–4,463 BC (phase II). After 2,900–2,503 BC (phase III) then around 2nd–1st centuries BC (phase III), sediment/charcoal yield coming from the Rhône catchment occurred in the context of major human expansion. Therefore, both climate and human activities could be considered as main factors responsible for phenomena of intense erosion in the catchment during the late Neolithic, what would have had for consequence the rapid progradation of the Rhône Delta. Furthermore, on the scale of the delta, presence of *Cerealia* has been detected in Arles-Trinquetaille since 5,719–5,530 BC, attesting the presence of cultivated areas. However, agro-pastoral activities could have begun earlier in the Rhône catchment, because of edaphic constraints less strong than those existing in the delta.

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