ELSEVIER

Geomorphology 33 (2000) 183–207

GEOMORPHOLOGY

Long-term fluvial archives in NW France: response of the Seine and Somme rivers to tectonic movements, climatic variations and sea-level changes

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Accepted 18 July 1999

Abstract

The Seine and the Somme are the two main rivers flowing from northwestern France into the Channel. During the Pleistocene cold stages both rivers were tributaries of the River Manche which was exporting sediments into the central deeps of the Channel. The River Seine has a very well developed terrace system recording incision that began at around 1 Ma. The same age is proposed for the beginning of the main incision in the Somme Valley on the basis of morphostratigraphy, pedostratigraphy, palaeontology, palaeomagnetism and ESR datings. The uplift rate deduced from analysis of the Seine and Somme terrace systems is of 55 to 60 m/Ma since the end of the Lower Pleistocene. The response of the two rivers to climatic variations, uplift and sea-level changes is complex and variable in the different parts of the river courses. For example, the evolution of the lower Seine system is influenced by uplift and climate changes but dominated by sea-level changes. In the middle Seine the system is beyond the impact of sea-level variations and shows a very detailed response to climatic variations during the Middle and Upper Pleistocene in a context of uplift. The Somme Valley response appears to be more homogeneous, especially in the middle valley, where the terrace system shows a regular pattern in which incision occurs at the beginning of each glacial period against a general background of uplift. Nevertheless, the lower Somme Valley and the Palaeo-Somme in the Channel area indicate some strong differences compared with the middle valley: influence of sea-level variations and probably differences in rates of tectonic uplift between the Channel and the present continent. The differences in the responses of the two river valleys during the Pleistocene are related to differences in the size of the fluvial basins, to the local tectonic characteristics, to the geometry of the platform connected to the lower parts of the valleys and to

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PII: S0169-555X(99)00122-1

the hydrodynamic characteristics of each river. Finally, it is shown from these examples that the multidisciplinary study of Pleistocene rivers is a very efficient tool for the investigation of neotectonic activity.

Keywords: River Seine; River Somme; Quaternary; neotectonics

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1. Introduction: location and background

Today, the Seine and the Somme are two of the major rivers flowing from northwestern France into the Channel. During the Quaternary cold stages they were the main tributaries of the ‘‘Channel River’’ (Auffret et al., 1980, 1982; Gibbard, 1988; Lericolais, 1997) and accounted for a very important part of the drainage system of the present-day eastern Channel area (Fig. 1A). Both rivers are characterised by very well developed terrace systems, especially in their middle parts and are mainly incised into Cretaceous and Jurassic calcareous bedrock (Fig. 1B).

Nevertheless, in the area submerged beneath the Channel at the present-day, the Seine Valley is incised into Jurassic calcareous bed-rock, while the Somme is incised into Tertiary sands and clays (Fig. 1B). Both rivers are located in the same climatic area and share the same tectonic background, characterised by slow uplift of the northwestern part of the Paris Basin (Pommerol, 1978; Founiguet, 1987). Local ‘‘bloc tectonic’’ activity during the Pleistocene has been demonstrated for the northern part of the area (Colbeaux et al., 1977, 1978, 1979, 1980). The whole area is also characterised by a very clear adaptation of the river courses to the geological structure, which is mainly dominated by NW–SW features.

Nevertheless these two rivers show some strong differences: the Seine Valley is characterised by very large meanders while the Somme Valley is straighter, especially in its central part, and the sizes of the fluvial basins are very different (Seine: 76,000 km^2; Somme: 5,800 km^2).

The aim of this paper is to attempt a comparison between the responses of the Seine and Somme rivers to tectonic movements, climatic variations and sea-level changes during the Pleistocene, based on new data concerning the Pleistocene evolution of these river systems (Lautridou, 1982, 1985, Lautridou et al., 1984, 1999; Lefebvre et al., 1994; Antoine, 1990, 1993, 1994a,b, 1997a,b, 1998; Antoine et al., 1995, 1998, 1999; Laurent, 1993, Laurent et al., 1994; Lericolais, 1997).

2. The fluvial system of the River Seine from the end of the Pliocene to the Weichselian Lateglacial

2.1. The Pliocene–Lower Pleistocene history of the Seine–Loire

The first stage of Seine–Loire Pliocene–Lower Pleistocene history is represented by the ‘‘Sables de Lozère’’ (Lozère Sands). They are plateau deposits and are characterised by granules and fine sands derived from the Massif Central. At that time the River Loire was a tributary of the Seine. Downstream of Rouen these sands are fluvio-marine and their age is about 3.5 My (Lautridou, 1985).

The second stage concerns the ‘‘very high terraces’’ (+120 m) of the River Seine (Figs. 2 and 3). After deposition of the Sables de Lozère, the Upper Normandy plateau was covered by the marine Saint-Eustache sands (Fig. 3) and locally, near Rouen, by the lagoonal Reuverian and Praetiglian La Londe Clay (Kuntz and Lautridou, 1974; Clet-Pellerin, 1983; Lautridou, 1985).

The ‘‘very high terraces’’ are the first witnesses of the incision by the rivers into the Cretaceous chalk plateau (30 to 40 m). The gravels of these very high terraces contain augite, derived from volcanoes of the Massif Central, that has been dated at 1 Ma (Tourenq and Pomerol, 1995). It is probable that the River Loire continued to be a tributary of the Seine at this time. Based on the record of the long sequences of La Londe, the tectonic events (graben formation) had largely finished by the end of the Lower Pleistocene (Lautridou, 1985).

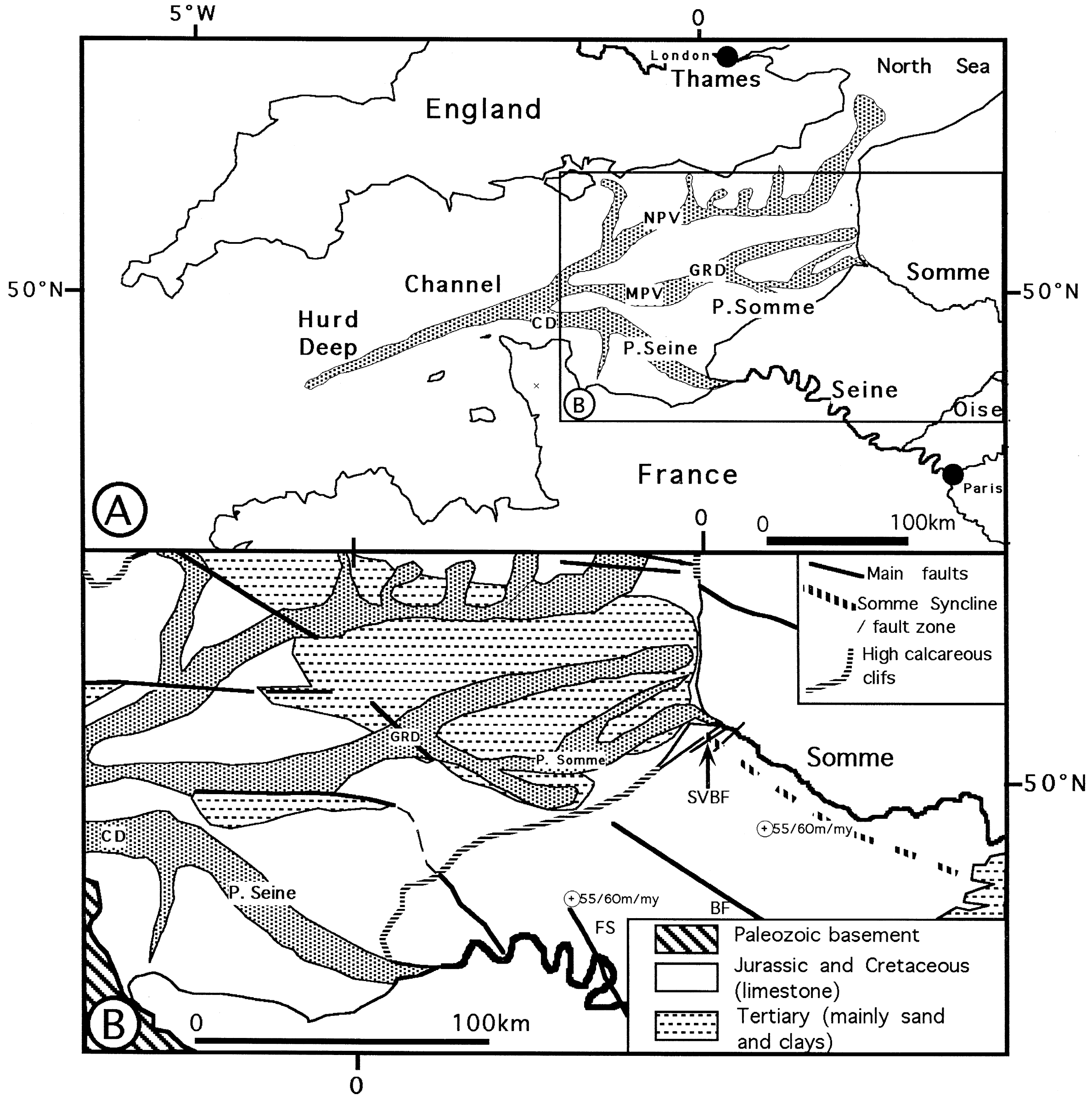

Fig. 1. (A) Location of the Seine and Somme river valleys and of their extension beneath the present-day English Channel ; (B) Simplified geology and structure of the Eastern Channel (according to Lericolais, 1997 modified, and to the Carte Géologique de la France, BRGM, 1996). NPV: Northern Palaeovalley, MPV: Median Palaeovalley, GRD: Greenwich Deep, CD: Cotentin Deep, BF: Bray Fault, FS: Seine Fault, SVBF: St. Valery–Boismont faults).

2.2. Middle and Upper Pleistocene in the lower Seine Valley (Rouen–Le Havre)

In this area there are relatively few terraces (7 large bedrock steps) in comparison to those of the River Somme (10 bed-rock steps), but in a system of very wide meanders the record of the fluvial estuarine sediments is very well preserved (Fig. 3). For example, at the famous site of Tourville (Lautridou, 1982), near Rouen, the erosion step of the low

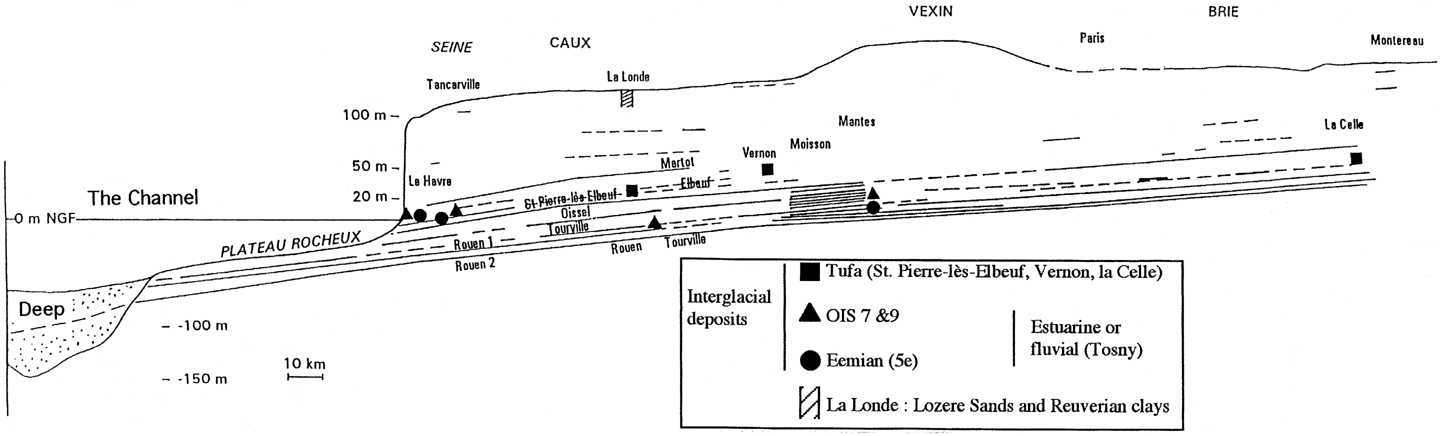

Fig. 2. Longitudinal profiles of the Seine valley from the upper course to the Channel deeps.

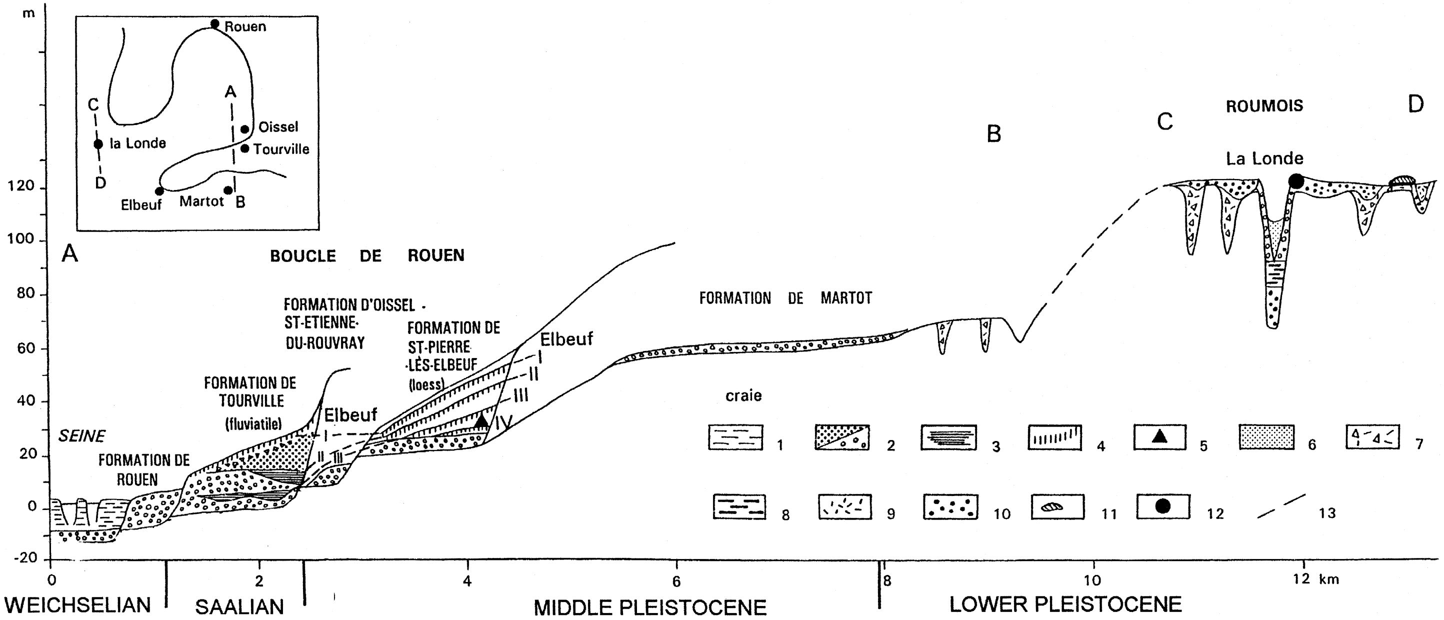

Fig. 3. Synthetic cross-section of the lower Seine terrace system near Rouen. (1) Holocene (2) Periglacial sands and gravels (3) Estuarine beds of Tourville (200 and 300 ky) (4) Brown leached soils (5) Calcareous tufa (Saint–Pierre) (6) Lower Pleistocene loess of La Londe (7) Clay with flints (8) Reuverian clay of La Londe (9) Saint–Eustache Sands (Pliocene) (10) Lozère Sands (11) Oligocene (12) Tertiary sandstone (13) Location of the cross-section.

terrace (+2 m) is covered by three periglacial alluvial sediment bodies separated by two interglacial estuarine silt beds, including a typical Saalian mammal fauna (macrofauna and rodents) (Lautridou, 1982, 1985). The upper one has been dated at 200 Ka by ESR–OSL, and the lower at 300 Ka by OSL (Balescu et al., 1991, 1997). The other periglacial gravels in this area are the Oissel Formation lying at 10 m above the bedrock of the Tourville terrace, and then the Elbeuf Formation, 15 m higher, which is covered by the famous loessic Saint Pierre-Formation (Lautridou, 1985), which contains four palaeosols, and a tufa on the top of the Elbeuf IV soil (Fig. 3).

The molluscan fauna from this tufa, as at Vernon (between Rouen and Paris) and at La Celle-sous-Moret (upstream of Paris), indicates a forested interglacial environment warmer than the Holocene. The fauna, dated at 350–400 Ka using U/Th (from Vernon, Lécolle et al., 1990), has also been described in Britain from the Hoxnian tufa sites of Hitchin and Icklingham (Rousseau, 1987; Rousseau et al., 1992). Above this Saint-Pierre-les-Elbeuf terrace, at 30 m O.D. near Rouen, there is an older, very weathered terrace (Martot) that can be traced downstream to Le Havre, but is very discontinuous upstream (Fig. 2). Below the Tourville terrace (low terrace), there are the two Weichselian valley-bottom gravels: Rouen 1 and Rouen 2 (Figs. 2 and 3). These gravel beds, like the Tourville Formation, continue below the English Channel (Fig. 2), as far as the large depression of the Hurd Deep (Fig. 1A) (Alduc et al., 1979; Auffret et al., 1980, 1982; Lericolais, 1997).

2.3. The Middle Pleistocene fluvial system of the middle Seine Valley in the ''Region Mantaise'' (From Elbeuf to Paris)

Fifteen kilometres upstream of Elbeuf–Les Andelys, characterised by a straight and narrow channel without terraces (Fig. 2), there is a characteristic system of meanders, smaller than downstream and more stable, with many steps eroded into the chalk bedrock. Dating from 600 to about 20 Ka there are 16 bedrock-steps, many more than downstream, perhaps because of differences in the longitudinal gradient, which is lower upstream (0.2%), and in the pattern of the meanders (stable meanders in the middle valley/migrating meanders in the lower valley).

Each bedrock step is covered by the same kind of alluvial sequence (Fig. 4), (Lécolle, 1989):

1. Deposition of fluvial loams and clays in a cold environment (first phase of the cycle beginning after an interglacial).
2. Deposition of gravels and coarse sands in a periglacial environment (fluvial activity with high seasonal contrasts in water and sediment supply, braided river channel).
3. Deposition of sandy to silty fluvial sediments (reduction of the lateral solifluncted sediment input into the valley in a drier environment).

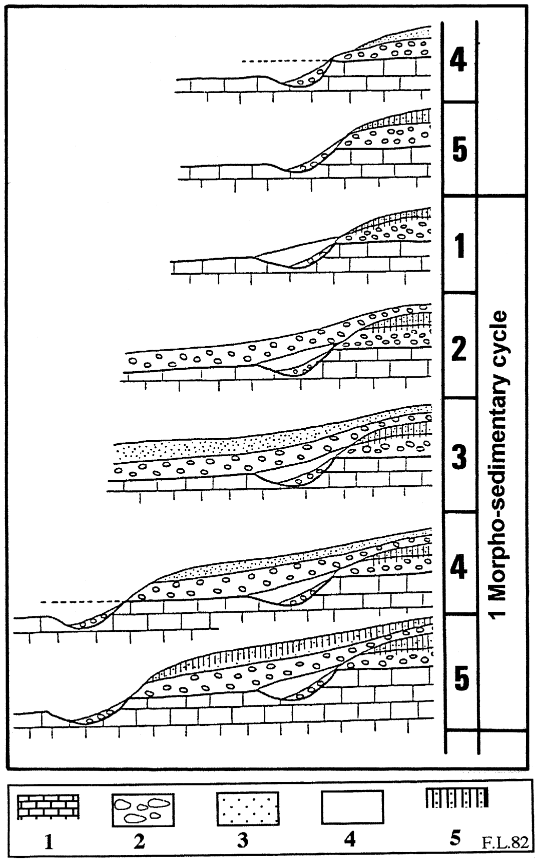

Fig. 4. Model of morpho-sedimentary cycle of the middle Seine area, Région Mantaise (according to Lécolle, 1989) (see text for explanation). (1) Chalk bedrock (2) Fluvial gravels (3) Fluvial sands (4) Fluvial loams (5) Pedogenesis (brown soil).

4. End of the cold period, climatic improvement and vegetation colonisation: major erosion and lateral incision creating a new step into the bedrock (1–2 m maximum.).
5. Climatic Optimum (interstadial, rarely interglacial): pedogenesis and soil formation at the top of the previous deposits (brown soil), deposition of overbank silts (final phase of the cycle).

The cycle then returns to stage 1 at the beginning of a new cold period.

Attempts to correlate the middle Seine sequence with the lower Seine system, and especially with the Tourville Formation, have used altimetry of the main bedrock steps, large mammal remains and the position of the interglacial deposits in the various sequences (Lautridou et al., 1984).

2.4. The upper Seine Valley (from Paris to Montereau)

In the city of Paris there are again several large meanders incised into soft Tertiary sediments (mainly sands and clays) and a stepped terrace system similar to that of the lower Seine (Fig. 2). Upstream, the system, with only few meanders is characterised by a few terraces separated by well developed bedrock steps (5 to 10 m), especially near Montereau at the confluence with the River Yonne. It seems that the main terraces defined at Rouen can be correlated with those of the region of Paris and Montereau. For example, at Paris mammal remains discovered in a silty bed included in the alluvial formation of the low terrace have been dated to 162 ± 9 to 206 ± 18 ka by U/Th technique (Durbet et al., 1997). These dates are in agreement with that of the upper part of the Tourville Formation near Rouen (Balescu et al., 1997).

Finally, the upper Seine valley is also characterised by well preserved Lateglacial silty sediments. These sediments have been dated using ^{14}C from many Magdalenian archaeological settlements (11.9–13 ky BP, Roblin-Jouve and Rodriguez, 1997). In this area a first incision phase is identified between the end of the Upper Pleniglacial and the Lateglacial (Roblin-Jouve and Rodriguez, 1997), as has been demonstrated in the Somme valley (Antoine, 1997a,b) and in other northern European Rivers (Vandenberghe et al., 1994). As regards the Upper Pleistocene, there is good correlation between the two younger alluvial formations of the lower Seine (Rouen 1 and Rouen 2) and the Weichselian Pleniglacial and Lateglacial gravel accumulations in the upper Seine.

Finally, the absence of Lateglacial sediments in the lower Seine may be related to the occurrence of strong fluvial erosion during the Holocene, especially at the beginning of the Preboreal, the impact of which was stronger downstream (Antoine, 1997a).

3. The terrace system of the middle Somme Valley

3.1. General context

The Somme Valley is a small, NW–SE orientated valley in northern France (Fig. 1B), developed upon homogeneous Chalk bedrock of Upper Cretaceous age. In the whole area the main fluvial systems are parallel to the NW–SE structural features (i.e., the Somme syncline, Fig. 1B). The area where the terraces are best developed is the middle Somme valley (about 70 km long). In the lower valley all the terraces are preserved on the left bank and the occurrence of faults crossing the valley (SW–NE) makes upstream correlations very difficult (Figs. 1B and 5).

The Somme Valley is well known for its important prehistoric archaeology (Prestwich, 1859; Commont, 1909, 1910, 1911; Breuil and Koslowsky, 1931; Bordes, 1954; Tuffreau, 1987, Tuffreau and Antoine, 1995) and its complex Quaternary terrace system (Bourdier, 1969, 1984; Bourdier et al., 1974a,b; Sommé and Tuffreau, 1978; Sommé et al., 1984; Haesaerts and Dupuis, 1986; Antoine, 1989, 1990, 1994a).

New research, based on field surveys combined with environmental studies (palynology, palaeontology, malacology, micromammal: Munaut, 1988, Munaut and Defgné 1997; Moigne, 1989; Auguste, 1995; Rousseau et al, 1992; Antoine et al., 1995), have allowed the proposal of a reference sequence for Pleistocene river development in northern France that is summarised by Figs. 5–7 (Antoine, 1990, 1993, 1994a). The chronostratigraphical interpretation of this sequence is controlled by magneto-

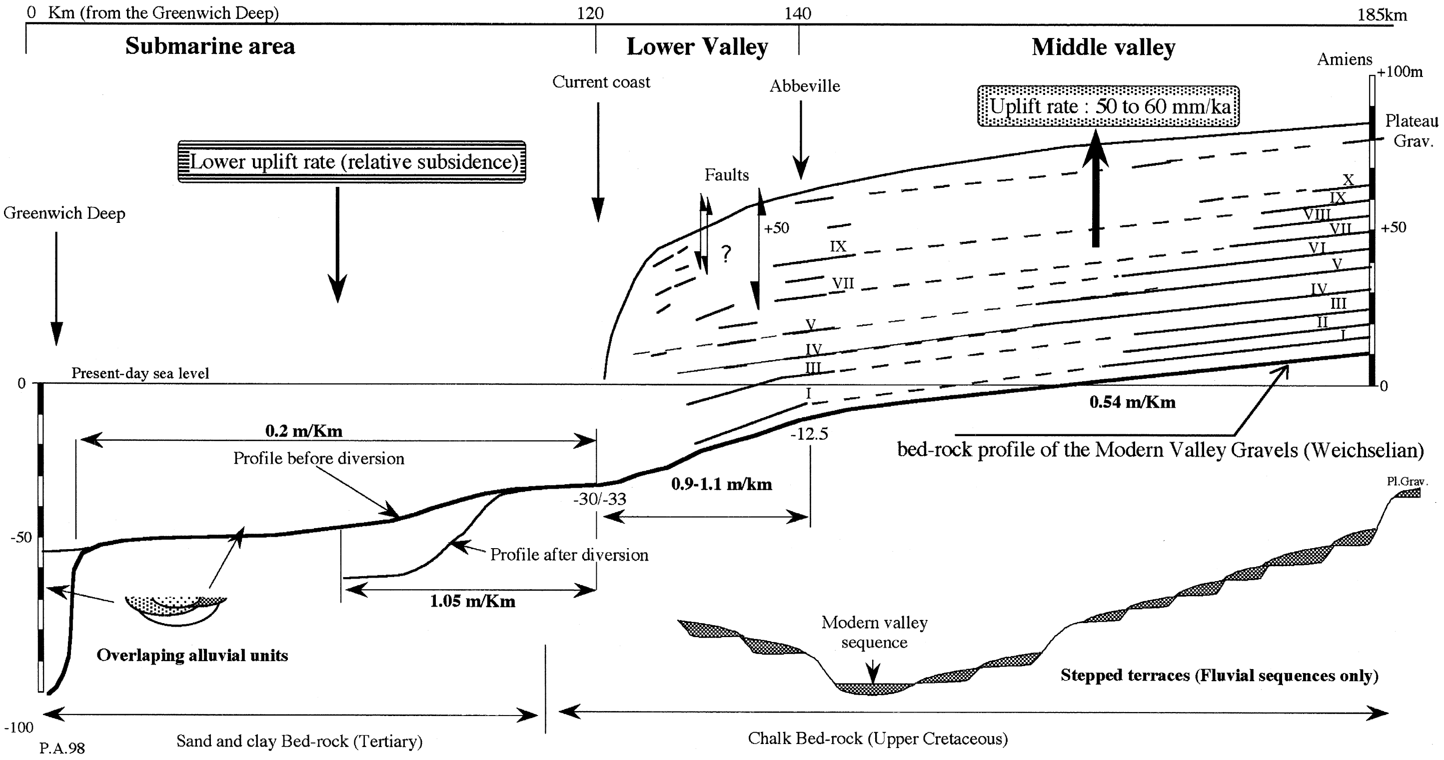

Fig. 5. Longitudinal profile of the river Somme terraces and maximum incision (Weichselian), from the beginning of the middle valley to the submerged Palaeovalley then to the Greenwich Deep (according to Auffret et al., 1982 for the submerged area).

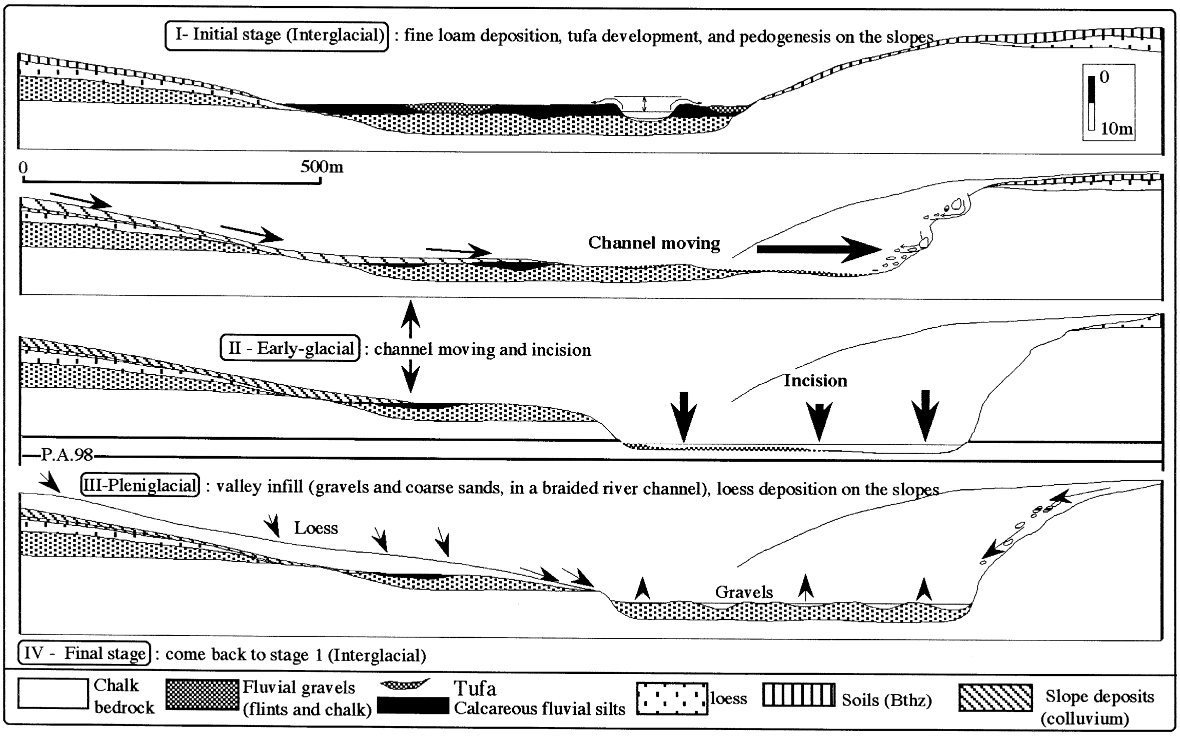

Fig. 6. Simplified model of terrace formation for one Interglacial–Glacial cycle in the Somme valley.

stratigraphy (Biquand, 1974; Laurent et al., 1994), U/Th series (Laurent, 1993), ESR on fluvial Quartz grains (Laurent, 1993; Laurent et al., 1994, see Appendix and Table 1), TL and IRSL on loess (Balescu, 1988; Engelmann and Frechen, 1998), large mammal material (Auguste, 1995), and amino-acid racemisation of molluscs (Bates, 1993).

Moreover, recent results concerning the Lateglacial and Early Holocene evolution of the valley provide a detailed model for the interpretation of the Pleistocene fluvial sequences of the terraces (Antoine, 1997a).

3.2. *Alluvial sequences and terraces*

In the new studies on the Somme Valley, the term terrace is used for the ‘‘morpho-stratigraphical’’ pattern resulting from overlapping of one incision surface in bedrock by one alluvial sequence, then by an unconformable loess and palaeosol succession (slope sequence) (Figs. 6 and 7). The longitudinal profiles of the bedrock surface beneath each of the alluvial sequences are identified on the basis of their height above the basal contact of the alluvial sequence of the modern valley. Within the middle valley it is now possible to describe 10 stepped alluvial formations from +5/6 m to 55 m relative height above the modern valley bedrock (Antoine, 1994a). The oldest, named Grâce-Autoroute Formation, was discovered and studied in 1994 during the excavations for a motorway, and lies at a relative height of +55 m in the Montières area (Antoine, 1994b, 1998) (Fig. 7).

The longitudinal profiles of the basal contacts of all the alluvial formations are sub-parallel to the modern bedrock floor beneath the modern valley gravels and show a general gradient of 0.54‰ (Fig. 5). The succession of alluvial formations of the Somme Valley results from the combination of two different and asynchronous types of erosion: lateral erosion linked to channel migration (0 to 500 m) and vertical erosion or incision (5 to 6 m), which results in the separation of each alluvial formation (Fig. 6). Studies of the Somme terrace alluvial sequences never show the superposition of more than one cli-

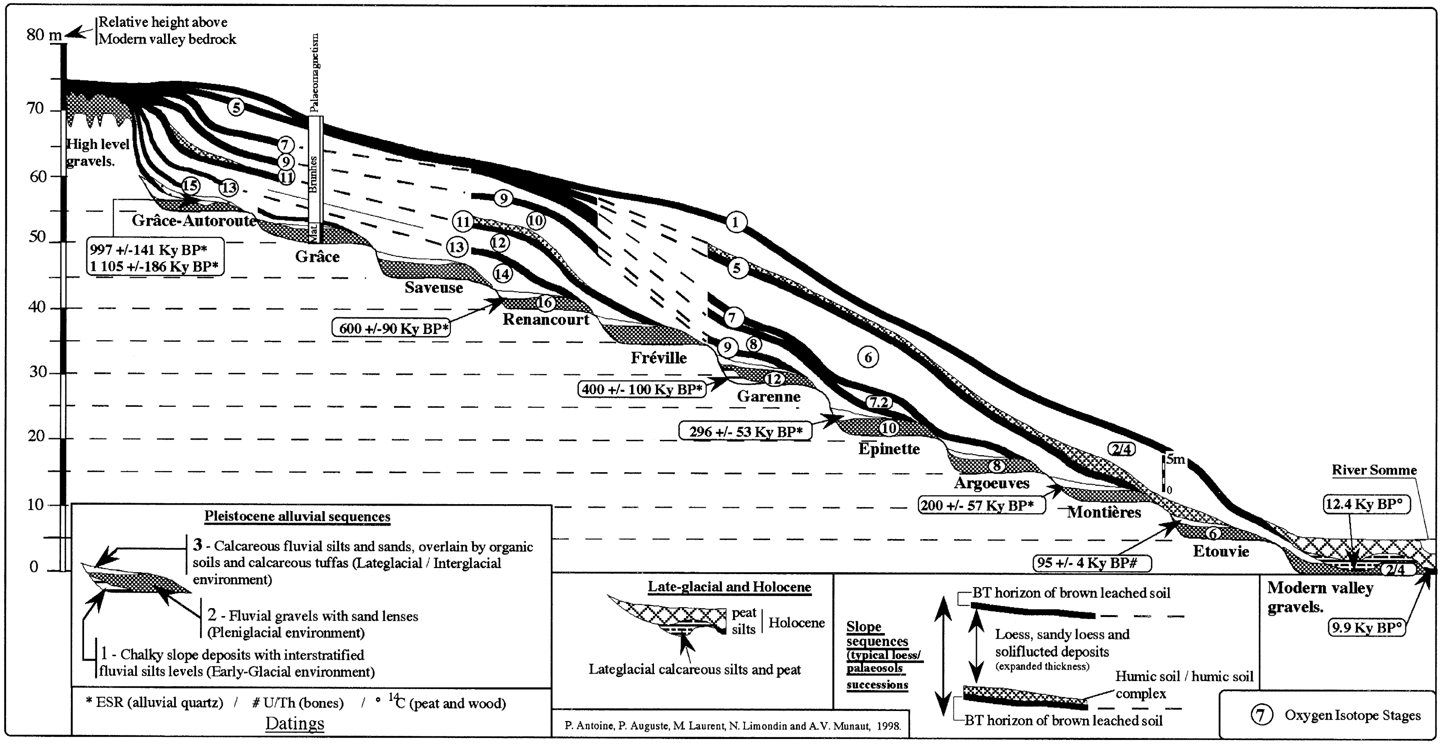

Fig. 7. Synthetic cross-section throughout the middle Somme terrace system (geometry, stratigraphy, geochronology and chronostratigraphical interpretation).

Table 1
ESR data from fluvial Quartz grains from some alluvial formations of the middle Somme (according to Laurent, 1993, modified)
Da: Annual dose, DR: Palaeodose.

Site/Alluv. Form./Rel. height above the modern valley bedrock	Sediment	P (Gy)	Error (Gy)	DR (Gy)	Error (Gy)	Da (mGy/y)	Error (m Gy/y)	Age Ky	Error (Ky)
Boutmy (Montières Formation, +12 m)	Fluvial loam	3120.0	861.0	290.0	80.029	1450.0	103.248	200	57
Cambron Montières Formation, +12 m)	Fluvial loam	4333.0	439.0	390.0	39.513	1921.18	303.402	203	38
Cagny–Epinette. (Epinette Formation, +21m)	Fluvial loam	2250.0	250.0	270.0	30.0	912.162	128.076	296	53
Cagny–Garenne. (Garenne Formation, +27 m)	Fluvial sand	2666.0	214.0	240.0	19.265	600.0	143.641	400	101
Abbeville–Carpentier (Renancourt Formation, +40 m)	Fluvial sand	2500.0	326.0	230.0	29.992	383.333	28.418	600	90
Ferme de Grâce (Grâce–Autoroute Formation, +55 m)	Fluvial sand	2312.0	231.0	370.0	36,968	456,790	64,423	810	140

matic succession (glacial–interglacial or glacial–lateglacial). The same type of simple fluvial sequence is common in other river valleys of northern France such as Scarpe at Biache–Saint-Vaast (Sommé et al., 1988) or in northwestern Europe such as at Maastricht–Belvédère (Vandenberghe et al., 1985) and the Haine Valley (Haesaerts, 1984; Haesaerts and Dupuis, 1986), but it does not occur with the same regularity in these terrace systems.

From stratigraphic, sedimentological and bioclimatic studies, the alluvial sequences appear to represent a simplified budget of fluvial sedimentation during a glacial–Interglacial cycle (Figs. 6–9):

1. Slope deposits with interstratified fluvial silts (Early-glacial, at the bottom and at the valley margins near the slope; rarely preserved)
2. Coarse fluvial gravels and sands: budget of the pleniglacial sedimentation, well preserved, and corresponding to the most important and the thickest part of the fluvial sequence in all the valley (Fig. 8 no.1).
3. Fine grained fluvial silts, humic soils, tufas: Late-glacial to Interglacial budget, well preserved near the slopes, rarely in the central part of the valley (Figs. 8 and 9, nos.2, 3, 4)

3.2.1. Incision and Early-glacial sedimentation

Locally a sequence of slope and fluvial deposits (chalk debris and unrolled flints in a calcareous silty matrix interstratified with thin beds of fluvial calcareous silts) is described for the first part of the cycle (Garenne, Fig. 7) and provides evidence of the earliest sedimentation phase in the terrace (Antoine, 1990).

Palynological data from the fluvial silts of the Garenne profile indicate a succession of temperate continental climatic phases which can be attributed to an Early-glacial context in comparison to the Early Weichselian (Munaut, 1989; Antoine, 1994b,

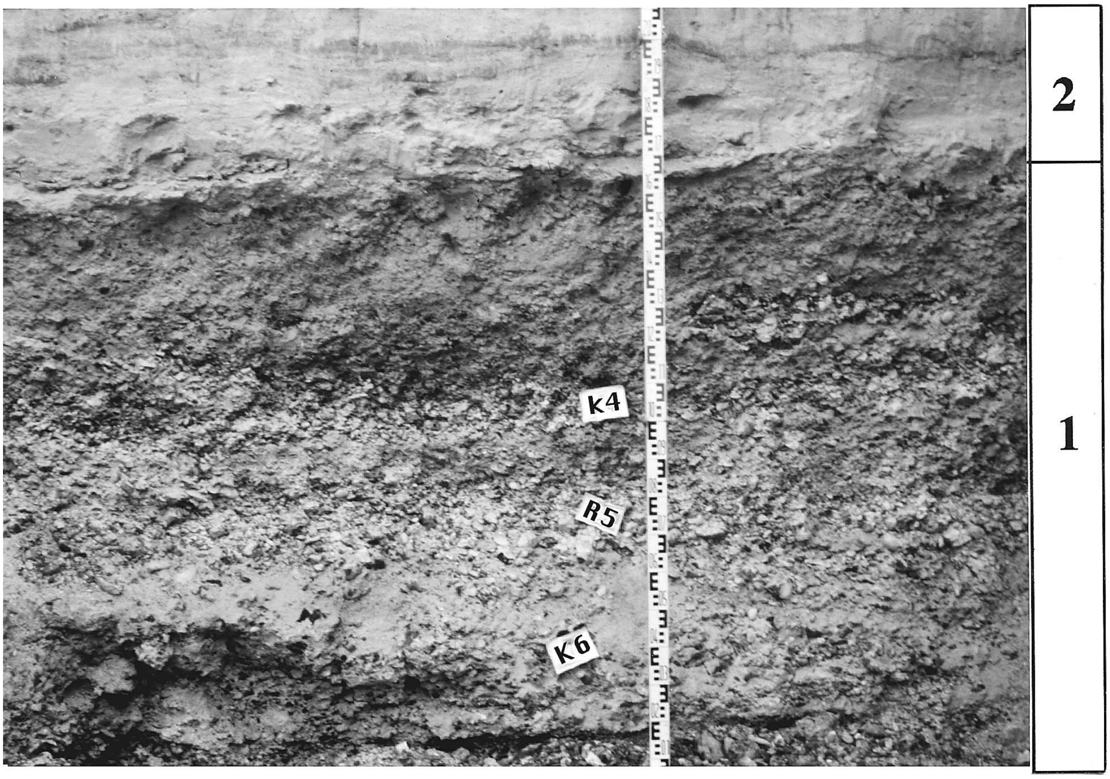

Fig. 8. Example of alluvial sequence in the middle Somme valley: Cagny-Cimetière near Amiens (Garenne Formation, Fig. 7). (1) Coarse calcareous flint gravels (2) Fine grained calcareous overbank silts.

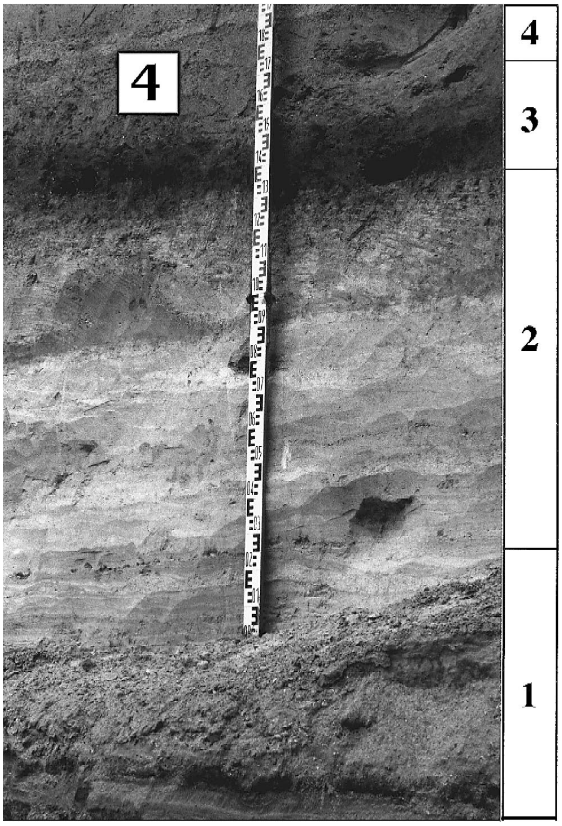

Fig. 9. Upper part of the alluvial sequence at Longprès-les-Corps-Saints (Argoeuve Formation, Fig. 7). (1) Coarse calcareous gravels with sand lenses, (2) Bedded calcareous fluvial silts, (3) Grey-green organic clayey soil horizon, (4) Calcareous tufa with molluscs.

Antoine et al., 1994, 1999). This interpretation is reinforced by the large vertebrate remains obtained from these beds (*Cervus elaphus, Equus caballus mosbachensis*, Bos and Megaceros, Moigne, 1989; Antoine and Tuffreau, 1993).

This observation implies that the incision of the bedrock occured before the full-glacial climatic phase. The same interpretation can be derived from the multi-disciplinary study of the Saint–Sauveur sequence in the Etouvie Formation (Antoine et al., 1995). All the available data show, therefore, that incision occured probably very quickly at the beginning of a glacial stage in a transitional context, as proposed by Vandenberghe (1993, 1995).

This interpretation is also consistent with the results of the study of northwestern European river morphology and sedimentological modifications at the end of the Pleniglacial, which show clearly that incision phases occur during a short period and in a transitional climate and environment (Vandenberghe, 1995; Vandenberghe et al., 1994). Indeed, in the Somme basin a strong incision into the Weichselian Pleniglacial deposits (gravels and loess) has also been demonstrated at the beginning of the Lateglacial, between the end of the Pleniglacial and 12,400 BP ^{14}C (from the oldest peat layers infilling the channels; Antoine, 1997a,b). This incision is coupled with a progressive change in the channel pattern from a braided river system to a transitional system during the Bølling (two or three stable channels), then to a single large meandering channel during the Allerød.

3.2.2. Pleniglacial sedimentation

The main unit of the alluvial formation always comprises coarse fluvial gravels, mainly composed of rolled flints, reworked Tertiary pebbles and chalk blocks, in a calcareous sandy matrix (Figs. 6–8, no.1). The gravels are generally crudely stratified and locally include calcareous sand lenses and some large ice-rafted Tertiary sandstone blocks (lag-deposits). Several sections show a succession of coarse gravel beds, sand and gravely sand lenses (1–5 m wide) with cross-bedded stratification indicating abrupt changes in energy characteristics of a braided river system with very unstable channels.

The palynology of sand and silt lenses contained in the gravels of the Garenne Formation shows that during the gravel deposition the environment was an open landscape (non-arboreal pollen $> 70\%$).The malacology of the Argoeuves Formation also gives similar results (T. van Kolfschoten, personal communication). According to all the available data these sediments can be related to a periglacial environment and to deposition in braided channels separated by gravely channel bars. The gravel sedimentation took place during the full-glacial under a severe climate, where the absence of vegetation and strong seasonal changes caused significant hillside erosion by gelifraction and solifluction. Regarding the duration of the complete Pleniglacial phase, the gravels of the lower unit represent probably the budget of the strongest peaks in sediment discharge (typical thickness: 4 to 5 m).

3.2.3. Lateglacial to interglacial sedimentation

The fine fluvial deposits of the upper unit correspond to the final phase of alluvial sedimentation within the terrace formation and are characterised by low energy facies (Figs. 8, 9 no.2), deposited in an interglacial context (maximal thickness 1.5 m). Indeed, during this phase the hillsides were stabilised by vegetation. They represent the last phase of alluvial sedimentation and are contemporaneous with the infilling of the valley and its stabilisation. This sequence ends with the development of immature humic soils and calcareous tufas (Fig. 9, no.3, 4).

The correspondence between the palynology (Munaut, 1988, 1989), small mammal remains (Cordy, 1989) and the sedimentology (Antoine, 1990) demonstrates that these fine fluvial deposits accumulated during a continental temperate climatic phase (forested-steppe landscape, arboreal pollen: 60–80%). The same results have been obtained in the Scarpe Valley sequence, northern France, at Biache-Saint-Vaast (Sommé et al., 1988; Munaut, 1998).

Nevertheless, in the Somme Valley sequences, the absence of ‘‘typical full interglacial conditions’’ comparable to the Holocene or to the Eemian optimum, such as have been found in the peat of the Lys Valley (Sommé et al., 1996), is a problem. Previously, it was thought that this observation could be explained by assuming the occurrence of more continental conditions during interglacials in the chalk valleys of NW France (Munaut, 1988). New investigations on the modern valley sequence show that the geomorphological and sedimentological characteristics of the sediments preserved at the top of the fluvial sequences of the terraces are locally very similar to those of the Weichselian Lateglacial, and especially to the Allerød and Younger Dryas overbank silts (Antoine, 1997b; Limondin, 1995; Munaut and Defgnée, 1997). Moreover the fine-grained sedi-

Fig. 10. General view of the slope sequence overlying the Grâce-Autoroute Formation (Fig. 7), and of its contact with the chalk talus (maximum thickness: 11 m).

ments of the terraces apparently always represent overbank facies while typical channel sediments have never been found.

From these observations it is possible to infer that during a full interglacial, sedimentation only takes place in a narrow channel, as it has been demonstrated for the Holocene (Antoine, 1997a). Then, at the beginning of the next Early-glacial, erosion during migration of the channel followed by incision, has removed all the full interglacial sediments.

On the other hand, the occurrence of full interglacial conditions is demonstrated from the malacological study of the tufa sequence at Arrest in a small tributary of the lower Somme (Rousseau et al., 1992). In this sequence, the malacological assemblage shows about 53% of forest and semi-forest species (36% in individuals) and is comparable to the faunas of the oxygen isotope stage 11 interglacial tufas of Normandy, the Paris Basin and southern England (Rousseau et al., 1992).

Finally, full Interglacial deposits are also known in the lower Somme Valley at Menchecourt, where periglacial fluvial gravels (relative height above the modern valley bedrock : 15 m; Antoine, 1990) are covered by fluvio-marine beds, including marine and fluvial interglacial molluscs (Commont, 1910). New investigations are planned to determine more clearly the relations between marine and fluvial systems during interglacial periods in the lower part of the Somme.

3.3. Slope deposits sequences and age-control of the terrace system

One important characteristic of the Somme valley is the presence of well developed loess and palaeosol sequences, which provide good age-control for the whole fluvial system. Generally speaking, the comparison of the various loess and palaeosols sequences overlying the succession of fluvial units in the Somme valley shows that terrace formation is characterised by a cyclic pattern (Antoine, 1990, 1994a,b). This pattern is illustrated by the progressive increase of the number of fossil soils and associated loess and colluvial deposits, with the increasing antiquity of alluvial formations (Fig. 7).

For example, the analysis of the slope sequence of the Garenne Formation shows that this alluvial unit is overlain by at least five climato-sedimentary cycles whereas the Epinette Formation, at Mautort near Abbeville, is covered by only four cycles. In addition, the pedosedimentary analysis of the new Grâce slope sequence (Antoine, 1994b; Fig. 10), demonstrates a minimum of eight climatic cycles overlying the oldest alluvial formation of the middle Somme area dated at around 1 Ma (Grâce-Autoroute Formation, Fig. 7). Moreover, the study of slope deposit sequences provides correlations between the Somme Valley long loess sequences (Garenne and Grâce) and the reference loess sequences at Saint-Pierre-les-Elbeuf in Normandy (Lautridou, 1985) and at Ariendorf in the middle Rhine valley (Brunnacker et al., 1975, 1982).

Finally, the chronostratigraphical interpretation of the system is based on the correlation between the climatic signal deduced from the multidisciplinary study of the Somme terrace system, and the global Marine Isotope Stratigraphy (Martinson et al., 1987). This interpretation is reinforced by the study of the remains of large mammals (Auguste, 1995), the negative polarity determined for the Grâce Formation (Biquand, 1974; Laurent et al., 1994), aminochronology (Bates, 1993) and ESR and U/Th dates (Laurent, 1993; Laurent et al., 1994; Table 1).

4. Comparison between the Somme and the Seine River responses to climatic variations, tectonic movements and sea-level changes since about 1 My ago.

Even if internal factors can produce terraces (Schumm, 1977), it is generally admitted that climatic variations, tectonic movements and sea-level changes have worked together during terrace formation (Lowe and Walker, 1984; Vandenberghe, 1995; Veldkamp and Van Den Berg, 1993; Van Den Berg, 1996; Maddy, 1997). Nevertheless, these factors have operated at different time scales and their relative impact is variable in time and is linked to the location of the area within the whole fluvial system. This variability is well illustrated by the comparison between the pattern of the different river systems, or between the different parts of one river system, such as the Seine (Fig. 11).

Finally, it is also possible that, in northwestern France tectonic uplift has been enhanced during glacial stages by glacio-isostatic crustal rebound,

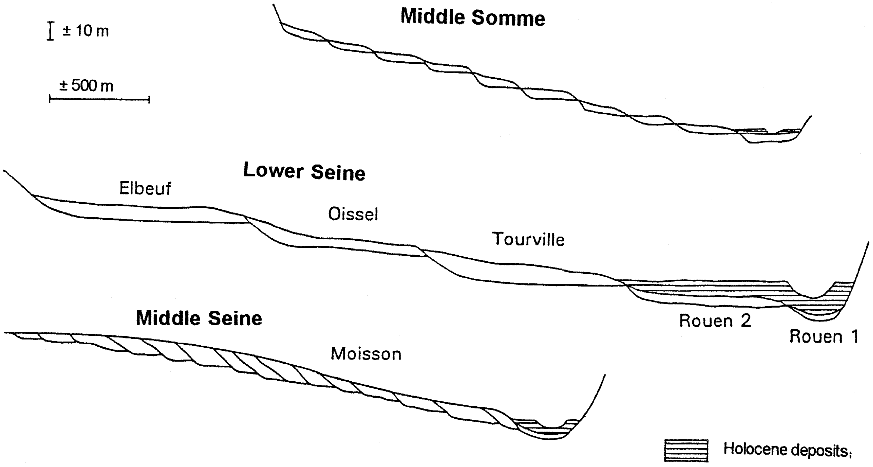

Fig. 11. General pattern of the bedrock steps and of the alluvial formations in the middle Somme and in the lower and middle Seine.

with the development of a forebulge (Dawson, 1992; Devoy, 1996). This phenomenon was discussed by Boulton (1990), but its importance with regard to tectonic uplift in northern France is difficult to evaluate, and probably not very significant compared to uplift of tectonic origin (Lericolais, 1997). In the same way, it is very difficult to differentiate the real impact of the ''isostatic adjustment'' in response to the effects of sediment transfer from the areas of erosion to areas of accumulation, as proposed by Bridgland (1994), as an explanation for the incision process.

4.1. Climatic variations

As elsewhere in NW Europe, the climatic factor seems to be the major control on the formation of the northern French river terrace systems (Haesaerts, 1984; Lautridou, 1985; Lautridou et al., 1984; Sommé et al., 1984; Antoine, 1989, 1994a; Lécolle, 1989). Within the valleys, climate is the principal control in the middle and upper courses in which sea-level changes do not influence the dynamics of the fluvial systems (Vandenberghe, 1995; Bonnet, 1998). For example, in the middle Somme area the evolution of the structure and of the sedimentology of the alluvial sequences, as well as the incision process, are clearly controlled by climate variations (Antoine, 1990, 1994a). In the Seine Valley the climatic impact is also very clear in the middle valley (Lécolle, 1989) and in the lower valley where it is superimposed upon the effects of sea-level change (Lautridou et al., 1984; Lefebvre et al., 1994).

The fact that incision is probably a very short event or a succession of very short events compared with the duration of a single glacial–interglacial cycle is one important problem for the discussion of the relative impact of climate, tectonic and sea-level changes on a fluvial system. Moreover, it is very difficult to evaluate the effects of slow tectonic movements and sea-level changes and rapid climatic variations such as those which have been demonstrated in ice or deep sea records (Bond and Lotti, 1995; Stuiver et al, 1995) upon this type of record.

Indeed, investigations on the Weichselian Pleniglacial/Late-glacial transition, which has been well dated by ^{14}C, have demonstrated that strong incision occurs over a very short time span ($<$ 1ka), during transitional climatic and environmental conditions (Vandenberghe, 1995; Antoine, 1997a,b). These incisions, in the upper and middle courses, are totally independent of sea-level variations and could occur during a period of sea-level rise, as has been observed during the Weichselian Late-glacial in the Somme Basin (Antoine, 1997a).

4.2. Tectonic movements

Uplift is generally and increasingly considered to be a fundamental factor in the development of a stepped terrace system as in the middle and lower Seine and middle Somme Rivers (cf. Veldkamp and Van Den Berg, 1993; Van Den Berg, 1996).

Indeed, in the Somme valley, the progressive and discontinuous downcutting throughout the whole system of the middle valley since the end of the Lower Pleistocene has taken place in the context of the general uplift of the northwestern part of the Paris Basin (Pommerol, 1978, Colbeaux et al, 1977, 1980, Antone, 1994a,b). The whole middle Somme valley is located in an area where uplift rates are uniform (Founiguet, 1987). All the substantial asymmetrical aggradations of alluvial formations, such as in Amiens-Montières (Somme/Selle confluence), show no particular orientation and their development appears to be linked to hydrodynamic processes (i.e., preferential accumulation of fluvial deposits in confluence zones).

In addition, despite numerous observations, no clear Pleistocene tectonic effects have been recorded in the terrace sediments of the middle Somme (e.g., clear faults continuing into the chalk bedrock). Indeed, all the fault systems observed until now in the fluvial and slope sequences of this area clearly result from dissolution features in the underlying chalk bedrock (Fig. 12), and are related to weathering and pedogenesis during interglacial and Early-glacial phases (Antoine, 1990)

On the other hand, in the lower Somme valley the terraces are preserved only on the left bank of the valley. This observation could indicate a tilting of the left bank of the Somme area and a relative lower rate of uplift of the right bank. Nevertheless, the profiles of the alluvial formations are very difficult to establish in this area because of the small number of outcrops and of the occurrence of faults crossing the system (N50° to N70°; Fig. 1B), which could have been active during the Pleistocene (Dupuis et al., 1977).

Moreover, in the Somme valley the strong difference between the continental area, with a stepped terrace system, and the submarine extension with

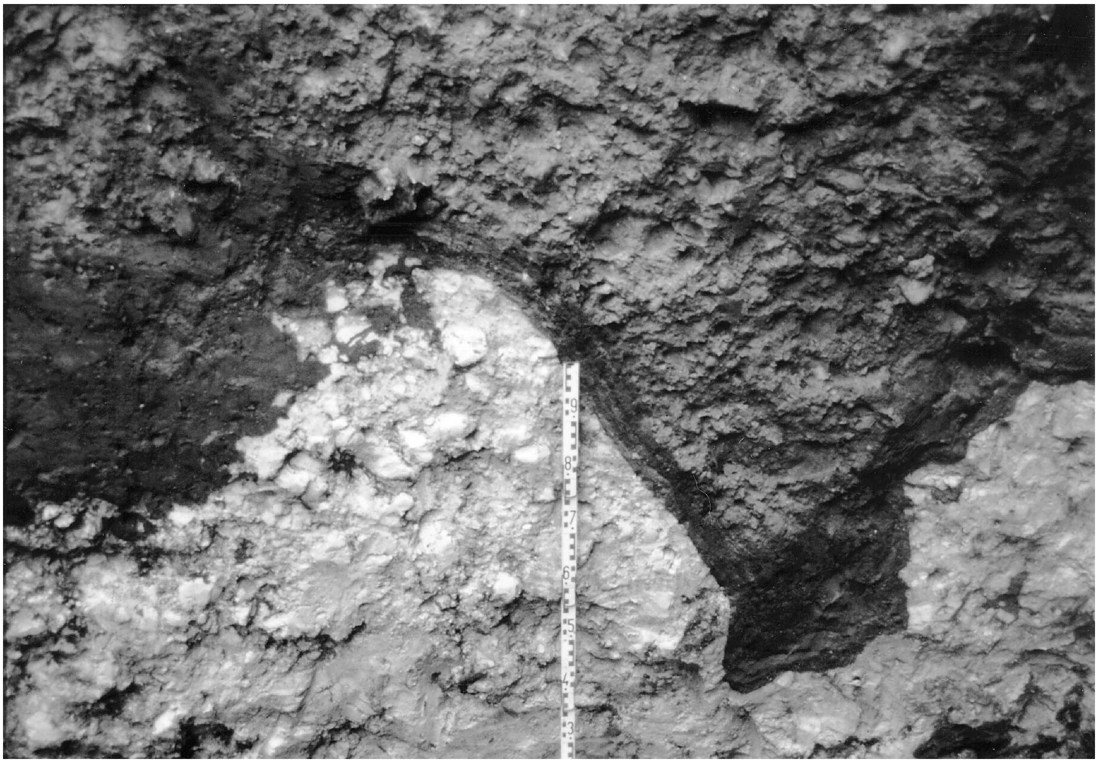

Fig. 12. Dissolution features in the chalk bedrock at the base of weathered coarse alluvial deposits (Mautort, area of Abbeville).

overlapping alluvial formations, probably indicates a difference in the absolute values of uplift between the present-day continental chalk plateau and the Channel area (Fig. 5). This difference could also explain the preservation of thick Tertiary beds in the Channel area while they are eroded elsewhere. According to Auffret et al. (1980, 1982), the lower part of the Somme valley, today submerged beneath the Channel, shows a very different pattern. Indeed, in this area, the longitudinal profile is characterised by a lower gradient (0.2 m/km) and the occurrence of a thick sequence of superimposed alluvial bodies (4 to 5) in the Palaeo-Somme (Fig. 5), before the diversion (Auffret et al., 1980, 1982). In addition, the longitudinal profile of the valley floor shows a short segment with a higher gradient (0.9 to 1.1 m/km, Fig. 5), between the lower part of the middle valley (0.54m/km), and the submarine area (0.2 m/km).

According to these observations, it is proposed that these important changes in the gradient and in the fluvial pattern result from differences in the absolute uplift rates between the continental and the submarine area (relative subsidence in the submarine area, Fig. 5).

The short segment of the lower Somme (20 km, between Abbeville and the current shore), which is characterised by the highest gradient (1.1 m/km) and the occurrence of faults (N50 to N70, Fig. 1B), appears therefore as a transitional area in which the uplift rate is higher than upstream (SE). In the same way the high chalk cliffs (height : 80 to 90 m) that characterise the coast at the south–west of the Somme bay (Fig. 1B), and which are parallel to the direction of the faults (N50°), could also result from a difference in uplift rates between the Channel and the continental area, and thus have a tectonic origin (Fig. 5).

Nevertheless, the lithological composition of the bedrock could also be an important factor. Indeed, the submarine Seine valley shows the extension of a stepped system on hard Jurassic calcareous bedrock (Figs. 1B and 3), while the submarine Somme, incised in a sandy bedrock, is characterised by overlapping alluvial formations (Figs. 1B and 5). This kind of relation between stepped terrace systems on a hard bedrock and stacked alluvial formations on soft bedrock is also described from the Oise valley (Paris Basin, Fig. 1B) or in the Lys Valley (northern France) (Sommé, 1975, Sommé et al., 1996; Colbeaux et al., 1979). In the latter, the modification in the fluvial pattern from stepped terraces to superimposed alluvial bodies, between the chalky ‘‘Haut Pays’’ and the sandy ‘‘Plaine de la Lys’’, is clearly linked to tectonics (Colbeaux et al., 1977). Therefore, in NW France where the bedrock is characterised by sandy soft Tertiary beds overlying Cretaceous Chalk, the effect of a relative subsidence is the preservation of soft bedrock area and the development of fluvial patterns characterised by superimposed alluvial bodies.

In the Seine valley, the River Seine fault (Faille de la Seine, Fig. 1B), which is a very ancient feature, has apparently not been active during the Middle and the Upper Pleistocene, according to the record in this area and downstream. This contrasts with the Lower Pleistocene, where there are several indications of tectonic activity, e.g., faults at La Londe (Fig. 3). But at the same time during the Lower Pleistocene, in the very high terraces, which are contemporaneous with the sediments of the graben structures, like at La Londe, no tectonic sensitivity has been identified because the gravels are too weathered, too discontinuous, and unsuited for the preservation of faults. On the other hand, in the Seine valley, uplift is clearly, demonstrated by the occurrence of Pliocene estuarine sediments on the plateau, around 150 m, before the incision of the valley (Formation of la Londe; Kuntz and Lautridou, 1974; Lautridou, 1985).

Finally, the comparison between the evolution of the Seine and the Somme shows that the absolute value of uplift is of 55 to 60 m for 1 Ma in both valleys (Fig. 1B). In addition this result demonstrates that uplift is a fundamental parameter in the terrace formation process and that there are no strong differences in the tectonic background throughout the area. These values are also in good accordance with those given by Veldkamp and Van Den Berg (1993) for the Meuse valley near Maastricht for the same period (about 70 m/1 Ma).

4.3. Sea-level changes

In the Seine it has been suggested that sea-level changes have influenced incision in the lower valley (Lefebvre et al., 1994). Indeed, in this area it is possible to describe more than one glacial–interglacial cycle overlying a single bedrock step, such as at Tourville (Lautridou, 1985; Lautridou et al., 1984). This pattern indicates that strong incision in the chalk bedrock does not always occur during each glacial or Early-glacial phase.

The interpretation proposed by Lefebvre et al. (1994) is that the main bedrock steps result from regressive erosion during the strongest sea-level falls. It has been suggested that the main incision phases in this area may occur during the coldest stages (OIS 2, 6 , 12, 16 and 22).

Nevertheless, the problem with determining the effect of sea-level change lies with the identification of the section of the river that has been controlled by this factor, especially during sea-level fall. Moreover, the change in fluvial pattern in response to sea-level fall also depends on the gradient of the platform exposed by the regression.

In the Seine valley, the boundary between the lower valley, controlled by sea-level changes, and the middle valley, characterised principally by climatic control is marked in the longitudinal profiles gradients by a knick point (Fig. 2), and a change in the longitudinal profile from 0.3–0.5 m/km in the lower valley to 0.2 m/km in the middle and upper courses (Lautridou et al., 1984).

In the Somme Valley, a clear difference is also seen between the middle and lower courses (Fig. 5). In the middle course, where the terraces are best preserved, the slope of the longitudinal profile is of 0.5–0.54 m/km, whilst in the lower valley, after a very pronounced knick-point near Abbeville, the longitudinal profile of the modern valley bedrock changes very rapidly and shows a gradient of 1.1 m/km from Abbeville (−12.5 m) to Le Hourdel (−30/−33 m) in the modern estuary (Antoine, 1990). Then, below the Channel, the gradient is very low (0.2 m/km) between the present coast and the Greenwich deep. In this system, where the incision in the middle valley is related to Early-glacial conditions (Antoine, 1989, 1990; Antoine et al., 1995), a strong lowering of sea-level is not necessary to change the profile, which is completely emerged when the sea-level is at −50 m (Fig. 5). This lowering of the sea-level is solely a condition for the exportation of the sediment produced upstream by the incision.

According to the model of early and quick incision described above, the absence of a palaeovalley in the western part of the Channel (west of the Hurd Deep), previously interpreted as the result of marine erosion during sea-level rise (Lericolais, 1997), could therefore be explained only by the absence of fluvial incision. Following this idea, and on the basis of the data from the last climatic cycle, it is suggested that all the incision process takes place at the beginning of the cycle (Early-glacial) when the sea-level falls very quickly to −20/25 m minimum, as after the Eemian (Zagwijn, 1989; Sommé et al., 1994), then to −50 to −60m (at the end of the Weichselian early glacial). When the sea-level was around −50/−60m, incision ended because of the huge increase in coarse sedimentary supply linked to the onset of Pleniglacial conditions (solifluction). Thus during the Pleniglacial, when the sea-level fell up to −130m, the continental area between the Hurd Deep and the ocean (Fig. 1A) is an area of transport or of sedimentation but not of incision. Indeed incision is completed, and during the most important part of the Pleniglacial the area is characterised by transportation and deposition of coarse sediments. Then during sea-level rise, at the beginning of a new interglacial stage, these deposits are reworked and eroded by marine erosion.

Finally, even if it is generally thought that sea-level falls could induce incision in the lower courses of the fluvial systems, the speed of the phenomena (1/5 mm/year) is very low compared with the speed of the incision induced by abrupt climate changes. Therefore, its impact on large fluvial systems is not easy to demonstrate. In addition, in the example of the Somme, the very low gradient of the eastern part of the Channel could also reduce the impact of sea-level fall. In the Somme valley, the changes in the gradient observed in the lower valley are therefore rather linked to differences in the uplift rates as it was proposed previously in the discussion about techtonic movements Section 4.2.

5. Conclusion

According to the evidence for evolution of the Seine and Somme river valleys during the last 1 Ma, it appears that climatic variations, tectonic movements and sea-level changes have worked together at different timescales and that their relative impact is variable in the different areas of the fluvial systems.

Nevertheless, combining the data for a long river system such as the Seine, it is possible to determine the principal controls acting on each of the different parts of the fluvial system. For example, in the Seine Valley, a low rate of tectonic uplift during the Pleistocene is shown in the whole course by the occurrence of Pliocene marine and estuarine sediments on the plateau before the incision of the valley.

According to the data from the Seine and Somme valleys, climatic and tectonic factors are strongly linked in the terrace formation processes but work at very different rates. The slow tectonic uplift (0.05 to 0.06 mm/year) is fundamental to create the potential for incision which is accumulated throughout a climatic cycle. This potential is then quickly released during the incision, the speed of which is about 50 to 100 times faster than the uplift. This short incision process takes place at the beginning of the climatic cycle, in a transitional period (Early-glacial), characterised by strong seasonal increases in water flow, and by a still well developed vegetation (limitation of the colluvial imput into the valley).

In the lower Seine the main factor seems to be sea-level variation and especially sea-level falls during the coldest glacial periods. On the other hand, the pattern of the middle and upper Seine valley fluvial systems is mainly controlled by climatic variations superimposed on an uplifting background.

In the Somme valley, the middle and upper courses are located in the same uplifting area as the Seine. The fluvial pattern of all this area seems to be under climatic control, as is shown by the study of the alluvial sequences.

The very strong changes in the gradient of the bedrock-profiles, observed at the junction between the middle and lower Somme, then between the lower Somme and the submarine area, are not linked to the influence of sea-level variations because of the very low gradient of the submarine profile which is not very sensitive to sea-level fall.

On the other hand, according to the strong differences that appear in the gradient and in the pattern of the fluvial system between the present day continental and submarine area, it is proposed that these two parts of the system are controlled by different rates of uplift:

-relatively high uplift rates in the middle and lower valley characterised by a stepped terrace system and high gradients
-lower uplift rate (relative subsidence) in the submarine area showing stacked alluvial sequences and a lower gradient.

Finally, in the same general climatic and tectonic background, the difference between the Seine and the Somme responses during the Pleistocene seems to be mainly related to:

-differences in the influence of sea-level changes, partly linked to the geometry of the submarine area (gradient of the structural platform, composition of the bedrock, tectonic evolution) and,
-differences in the general pattern of the valley linked to the size of the fluvial basins, and to hydrodynamic parameters (size of the meanders, sinuosity)

The middle Somme valley terrace system represents therefore an intermediate pattern stage between the Middle and the Lower Seine valleys.

It is concluded that the study of the terrace systems appears to be a very good tool for the measurement of general tectonic movements during the Pleistocene.

Acknowledgements

This work is partly supported by the ‘‘Palaeolithic occupations and Pleistocene Palaeoenvironments in the Somme Basin and surrounding areas’’ program (funded by the French National Centre for the Scientific Research).

We thank B. Morin and J.M. Dolo for their help in ESR measurements, and Phil Gibbard and David Bridgland for the review of the English text and their constructive suggestions.

Appendix A. ESR dating of fluvial quartz grains from the Somme Valley alluvial formations

A.1. Introduction

Electron Spin Resonance (ESR) dating of sediments may improve our knowledge of the chronostratigraphy of the Tertiary and Quaternary periods and especially in the case of non-calcareous deposits. Quartz extracted from volcanic materials (Shimokawa et al., 1984) and sediments baked by lava-flows (Yokoyama et al., 1986) or burned by fire (Monnier et al., 1994) have been dated by ESR. Bleaching of quartz has been studied in Quaternary sediments (Yokoyama et al., 1985; Buhay et al., 1988; Li et al., 1993; Brumby and Yoshida, 1994; Laurent et al., 1994), and recently, ESR results have been obtained on bleached quartz extracted from Tertiary formations (Laurent et al., 1998).

ESR dating of bleached quartz is based on the behaviour of the aluminium centre (Al): it is composed of an aluminium atom substituted to a silicium centre (Weil, 1984). The diamagnetic centre $[(AlO_4/M^+)]$ becomes paramagnetic under ionising radiation $[(AlO_4/h)]$ (see details and other references in Ikeya, 1993). Exposure to light releases trapped electrons which will be collected by an aluminium hole centre. This process will induce the bleaching phenomena. However, the energy light scale allows only a part of trapped electrons, which means that the bleaching is incomplete.

In order to date quartz, it is important to determine residual intensity after light bleaching. Modern coast or overbank sands have a constant ESR intensity after a very long exposure under UV-light; fossil sands and irradiated modern sands show decreasing intensity under UV-light. The latter tend to reach their natural intensity. The Al centre in quartz reaches a residual level which corresponds to the maximum of bleaching. Dating of quartz extracted from sediment requires samples that were exposed to sunlight for long times in the range of 6 months.

For fossil quartz, the maximal bleaching intensity is calculated by a least square method fitted by an exponential decay added to a constant value (Walther and Zilles, 1994):

$$f(x) = ae^{-bx} + c$$

The palaeodose, P, is determined by fitting the dose response curve with a simple saturating function and extrapolation to the residual intensity.

Appendix B. Sampling and method

Each sample consists of about 400 g of sediment enclosed in an opaque bag. The water content of each sample was determined by drying the sediment at 40°C.

Quartz was extracted according to the usual chemical methods already described by Yokoyama et al. (1985). Gamma-ray irradiations are made with a cobalt panoramic source (Dolo et al., 1996); ten aliquots were irradiated with the same dose flow. The range of 10 doses were chosen between 1000 G and 15,000 Gy. Palaeodose measurements were calculated using the least squares method equation and error measurement (Yokoyama et al., 1985). The quartz was exposed to UV-light (UV lamp with a wavelength in the range 365–400 nm). The U, Ra, Rn, Th and K activities of the sediments were determined using gamma-ray spectrometry. A k-value of 0.15 ± 0.10 was assumed, alpha and beta attenuations in quartz were estimated from the calculations of Mejdahi (1979) and Bell (1980). Cosmic doses were then calculated using the formula of Yokoyama et al. (1981).

Measurement errors are due to gamma dosimetry, intensity height determination of the Al centre, radioelement content counting and moisture content. The analytical results are given in Table 1.

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