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Major palaeohydrographic changes in Alpine foreland during the Pliocene–Pleistocene

CHRISTOPHE PETIT, MICHEL CAMPY, JEAN CHALINE AND JACQUES BONVALOT

BOREAS



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The changing palaeogeographical pattern of Alpine deposits across the European forelands can be traced by identifying mineral assemblages and establishing the chronology of Pliocene–Pleistocene deposits in Alpine foreland. In the late Miocene, the upper courses of the Rhine and the Aar flowed east from the Swiss molasse plain towards the Danube. In the early Pliocene (Brunssumian, 5–3.2 Ma), these same rivers headed northwards towards the Rhine Graben of Alsace. In the early Reuverian, these streams were captured south of the Rhine Graben by the Doubs. They ceased their northward flow and headed west to feed the Bresse Graben. This phase is dated to the Lower and Middle Reuverian (3.2–2.6 Ma). From the Upper Reuverian (2.6 Ma) to the present day, the Rhine has adapted approximately its present course towards the North Sea, south to north along the Rhine Graben and across the Rhine Schist Massif to feed the Dutch Grabens. This changing pattern of capture and alteration of the hydrographic system of the upper reaches of the Rhine and the Aar can be explained by local tectonic movements.

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The present-day pattern of European rivers (Rhône, Rhine, Danube) of the Alpine foreland exhibits certain specific features (Fig. 1). The Danube flows eastwards along the northern boundary of the peri-Alpine molassic plain. The Rhine and its major tributary, the Aar, flow across the molassic plain, the northeast Jura and along the Rhine Graben before cutting through the ancient Eiffel Massif and on to the North Sea. The Rhone rises close to the headwaters of the Aar and the Rhine, crosses the molassic plain and the southern Juran before heading from Lyon towards the Mediterranean Sea. Its tributaries, the Doubs and the Saône, rise in the Jura and the Vosges respectively and cross the Bresse basin before joining the Rhône at Lyon.

The episodic occurrence of Alpine metamorphic material in the Pliocene–Pleistocene deposits of the Alpine foreland basins has been used by various investigators to show that this pattern has changed since late Tertiary times. Delafond & Deperet (1893) and Rollier (1907) reported the occurrence of Alpine cobbles (radiolarites) and Tchimichkian *et al.* (1958) identified Alpine heavy minerals (epidote, garnet, amphibole) in the Pliocene sediments of northern Bresse. These deposits were ascribed to the capture of the Aar by the Doubs in the Cailloutis de Sundgau (south of the Rhine Graben) where the sand fraction exhibits the same mineralogical content (Bonvalot 1974). The advent of Alpine minerals in Bresse is correlated to the late Pliocene and early Pleistocene (Bonvalot *et al.* 1984). Brunnaker *et al.* (1977) showed that the upper course of the Rhine was aligned towards the Danube across the molassic plain until the early Pliocene. Geissert *et al.* (1976) demonstrated that Alpine sediments were laid down in the Rhine

Graben in the early Pliocene (Brunssumian) and that these deposits discontinued into the Reuverian. The first minerals from the Alps to reach The Netherlands' basin are dated to the end of the Reuverian (Boenigk *et al.* 1974; Schnütgen *et al.* 1975; Zagwijn 1989).

On the basis of a recent review of the infilling and dynamics of Bresse and the Alpine foreland (Petit 1993), a synthesis can now be provided of the distribution of Alpine deposits in the area throughout the Pliocene–Pleistocene. To provide a uniform stratigraphical terminology, The Netherlands' Neogene stratigraphical terminology has been adopted (Zagwijn & Doppler 1978). In this scheme, the Pliocene–Pleistocene boundary is placed at the base of the Praetiglian stage (2.4 Ma) and the Pliocene–Pleistocene Bresse infilling dealt with in this article dates back to the early Pliocene up to the early Pleistocene inclusive.

The Pliocene–Pleistocene deposits of Bresse

The Bresse Graben is part of the major West European distensive system (Bergerat 1985). It is a rift valley filled mainly with Oligocene sediments to a depth of over 1000 m (Lefavrais-Raymond 1962). The Pliocene–Pleistocene deposits form the upper part of the infilling, which is irregular in thickness and seldom exceeds 100 m. Bresse is a gentle plain of some 200 m altitude, which is drained southwards by the Saône (Fig. 2). It is bounded to the north by the plateaux of Seuil de Bourgogne and stretches southwards to the Lyon area.

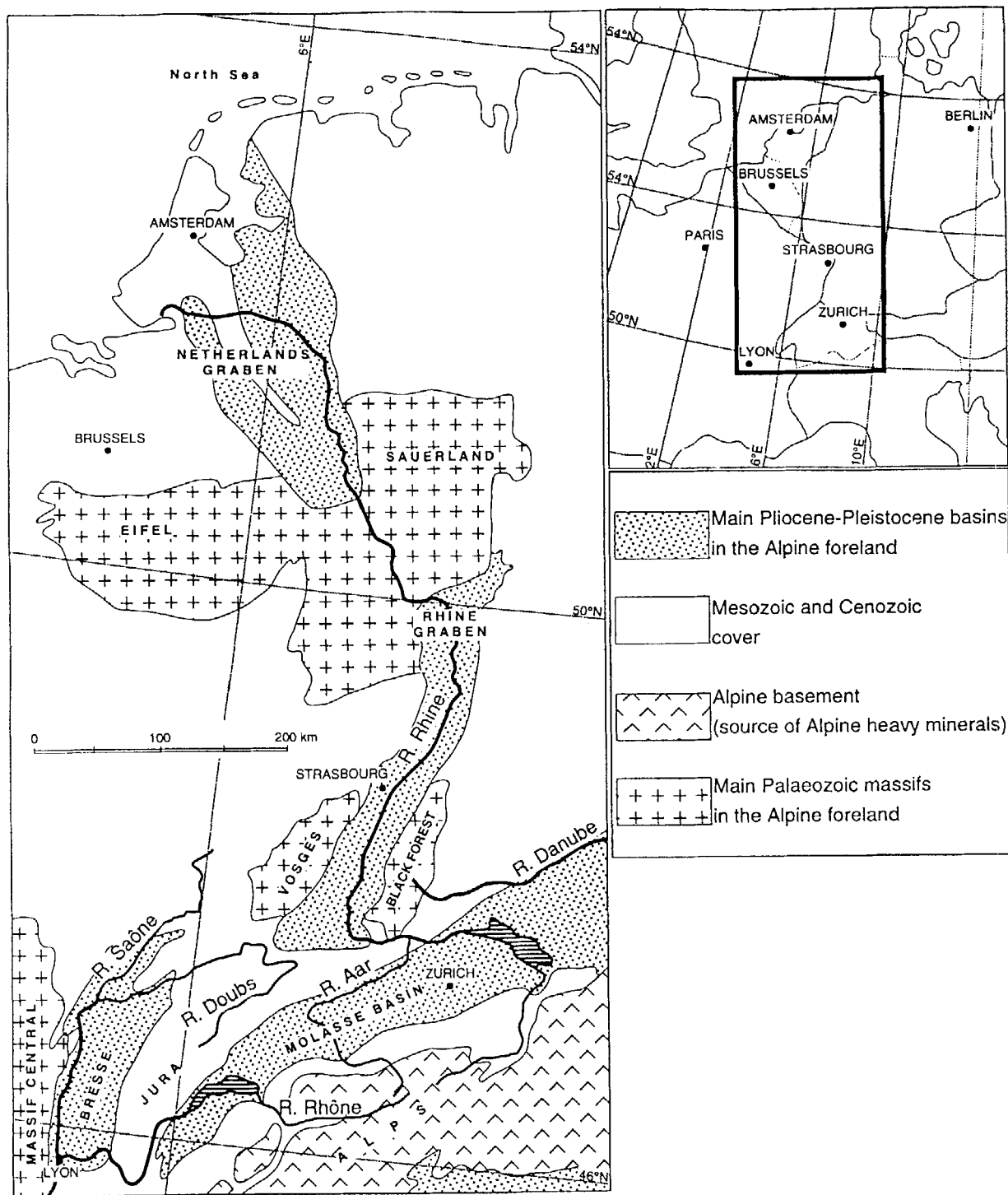


Fig. 1. The Alpine foreland. Location of Pliocene-Pleistocene basins and current pattern of main rivers northwest of the Alps.

The geological map of Bresse and the borderlands (Fig. 2) shows the outcrop of formations. In the Bresse basin proper, the Pliocene-Early Pleistocene deposits are overlain in the west by Later Pleistocene

fluvial terraces of the Saône and its main tributaries and in the south by the Dombes glacial region deposited by meltwater derived from the Rhône glacier during the penultimate glaciation (Bourdier 1962;

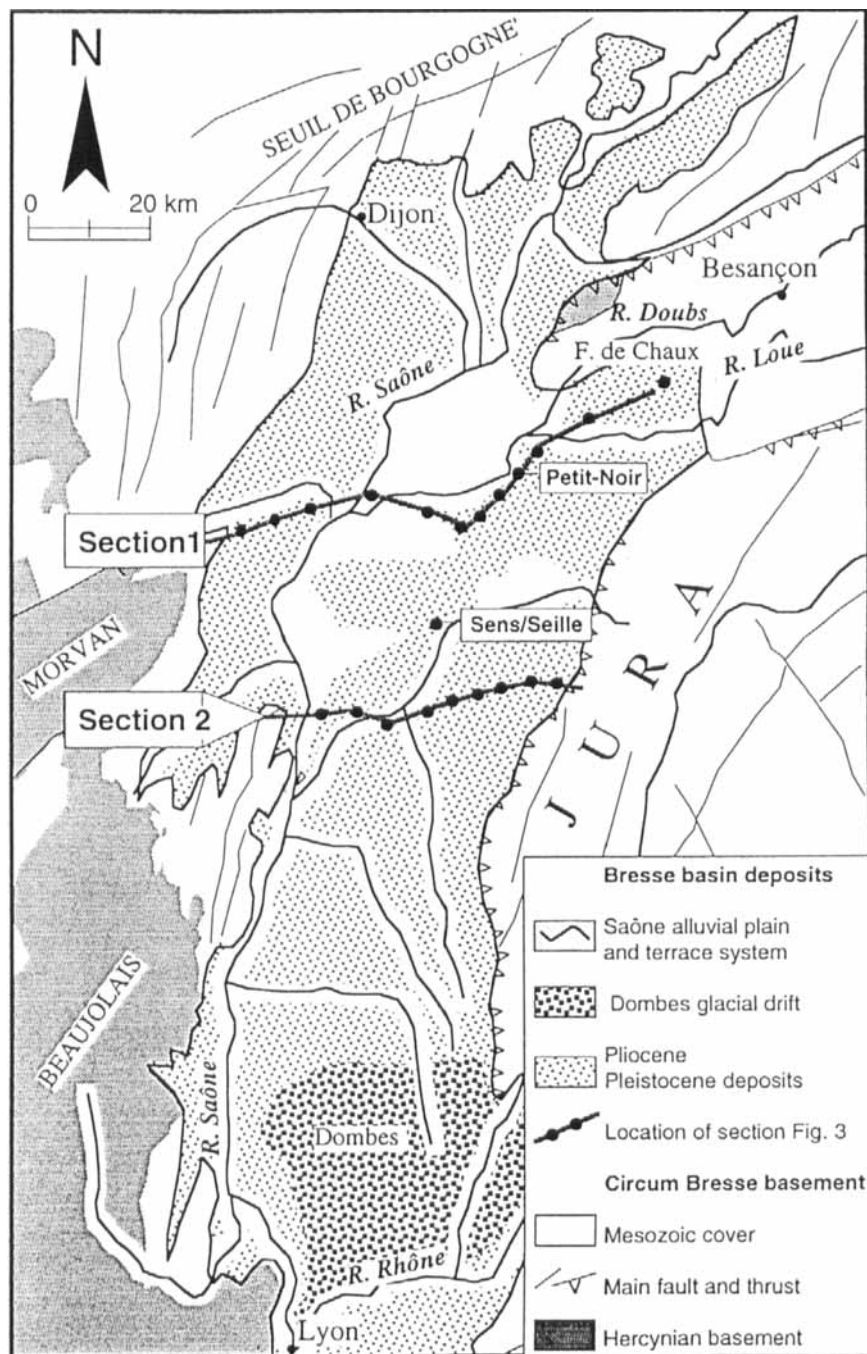


Fig. 2. Geological framework of the Bresse Basin and location of the sections in Fig. 3.

Fleury & Monjuvent 1984; Campy 1992). The Bresse deposits are brought into contact with the various surrounding rock types by faulting: (1) to the north and northwest lie the limestone plateaux of the Seuil de Bourgogne which contributed few heavy minerals to the Bresse area, in comparison to the Hercynian and Alpine deposits; (2) to the west is the Hercynian basement (Beaujolais and Morvan Hills) which provided many central upland-type heavy minerals (zir-

con, distene, staurolite, rutile) (Duplaix *et al.* 1965; Bonvalot 1974) (3) to the east, the Mesozoic cover of the outer Jura is over-folded at Bresse by 5 km along a front of more than 150 km.

Composition and geometry

The Pliocene–Pleistocene Bresse infill has been mapped from over 500 borings drilled during the last

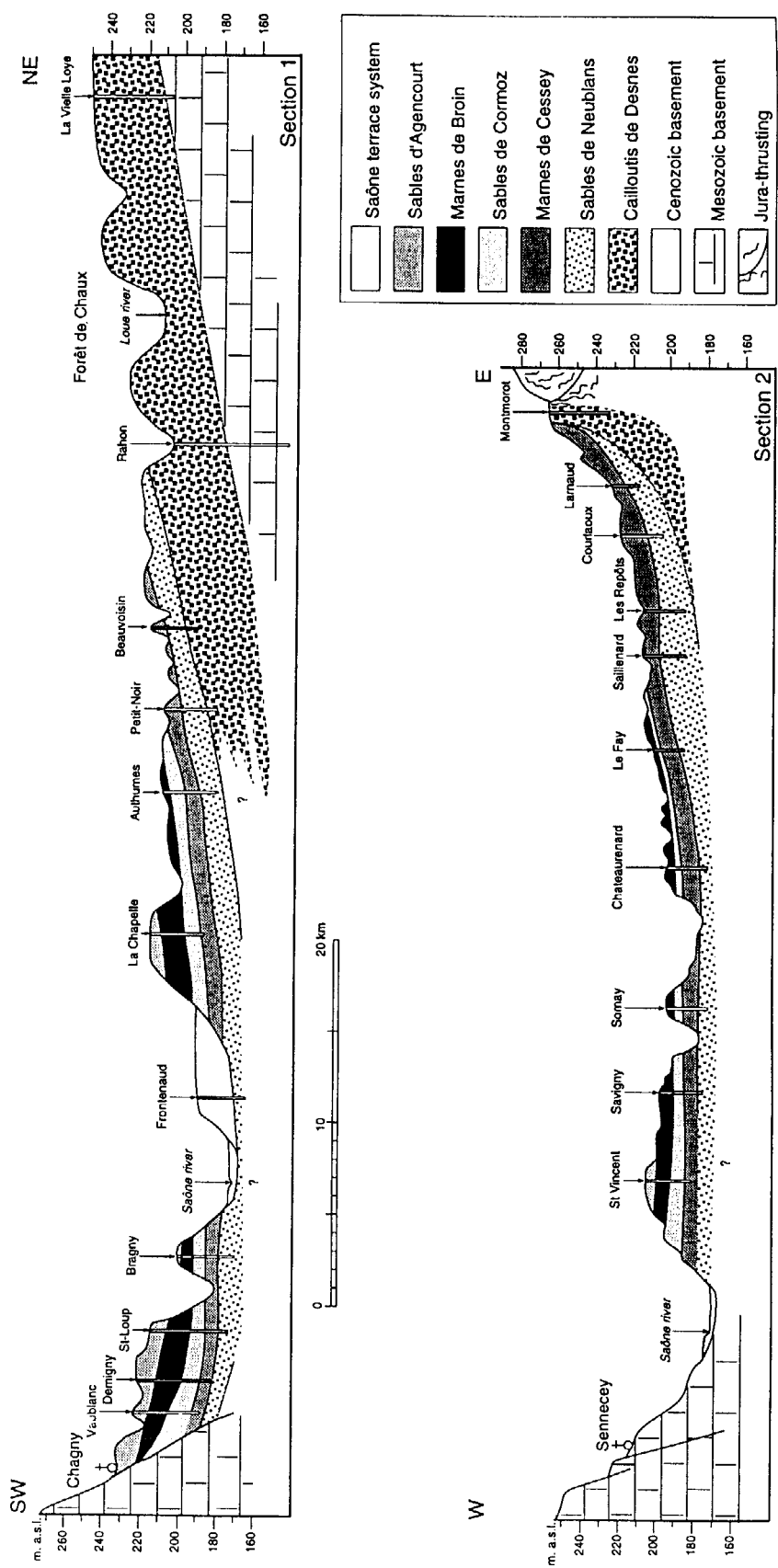


Fig. 3. Sections of Bresse showing the relations of the recognized lithostratigraphic units (location of sections shown in Fig. 2).

Lithological units	Molluscan chronozones	Rodent chronozones	Stratigraphical units	Ages 0 M.A.
Saône terrace system		<i>Microtus</i>	WEICHSELIAN	1.0
			SAALIAN	
			ELSTERIAN	
		CROMERIAN		
		<i>M. savini</i>	BAVELIAN	
MENAPIAN				
Sables d'Agencourt s.l.	BINGES INF.	<i>M. ostromosensis</i>	WAALIAN	1.0
	BINGES SUP. AGENCOURT		EBURONIAN	
Marnes de Broin	BROIN	<i>M. pliocaenicus</i>	TIGLIAN	2.0
Sables de Cormoz	CORMOZ	<i>M. polonicus</i>	PRAETIGLIAN	3.0
Marnes de Cessey	CESSEY	<i>M. hajnackensis</i>	REUVERIAN	
Sables de Neublans	NEUBLANS			
Cailloutis de Desnes	DESNES	<i>M. occitanus</i>	BRUNSSUMIAN	4.0
		<i>M. davakosi</i>		
Marnes de Beaune	ST-SEINE	<i>Promimomys</i>		

Fig. 4. Chronology of lithological units of the European Pliocene–Pleistocene of Bresse.

20 years. Figure. 3 shows their composition and the geometry of deposits in two sections across the centre of the basin. Eight lithological units have been identified that can be summarized in stratigraphical order as follows (Petit 1993):

Marnes de Beaune (M.Be.) are found only in the west of Bresse and are over 100 mm thick in some boreholes. They display a lacustrine marl–limestone facies exhibiting numerous emersion levels (stromatolite crust, micro-karst, nodulization, desiccation, etc.) that are particularly marked in the upper 15 m of the unit. *Cailloutis de Desnes* (C.D.) or *Cailloutis Inférieurs de la Forêt de Chaux* is a cobble-rich formation (70%) with a clay-silt matrix (Bonvalot 1974). It varies in thickness and some boreholes have proven thicknesses of 70 m in the outcrop area where the Doubs stes Bresse. The upper surface dips steeply in the west.

Sables de Neublans (S.N.) are fine to very fine, fairly well-sorted, fluvial sands (Bonvalot 1974; Teste 1977; Petitjean 1991; Petit 1993). They stretch from east to west and vary from 10 to 20 m in thickness. They are not found on the edge of the Jura (section

B). The upper surface declines some 50 m over 50 km. *Marnes de Cessey* (M.C.) are silt to sand-rich clays which contain numerous lignite beds and in particular a continuous bed in the upper part. Faunal and floral remains in the lignites are typical of an aquatic domain that was frequently exposed to form a swamp environment with occasional accumulations of tree trunks (Teste 1977; Puisségur 1984). The sediments have been traced across the basin but are slightly thicker in the west (12–18 m) than the east (5–8 m). Their spiral surface falls in level irregularly towards the west.

Sables de Cormoz (S.C) are poorly sorted, fine to medium sands with a high gravel content on the eastern margin of a fluvial environment (Bonvalot 1974; Petitjean 1991). In the cross-sections (Fig. 3), they are not in contact with the Jura in eastern Bresse. They vary in thickness from 5 to 10 m. The base of the unit varies from 230 m a.s.l. in the east to 190 m a.s.l. in the west.

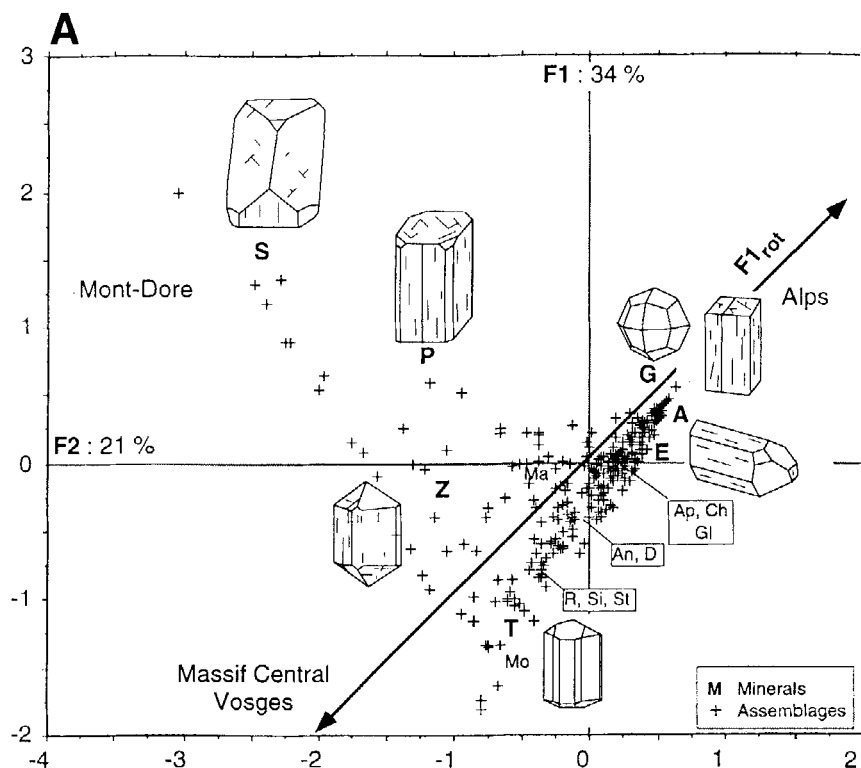
Marnes de Broin (M.Br) is a clay to silt formation laid down in still water lacustrine or palustrine environments (Test 1977). It is only found in the west of Bresse some 15 km from the Jura front. It ranges from less than 5 m thick east of La Seille to 20 m thick in the west. The lower surface of the unit slopes slightly from east (200 m a.s.l.) to west (190 m a.s.l.).

Sables d'Agencourt (S.A) is a sand-gravel unit that forms the final deposit of the Bresse infill, strictly speaking. It varies from 5 to 15 m in thickness and is found only in the western half of Bresse. The base of the unit slopes slightly towards the Saône valley depression.

The river-terrace system. Several river terraces are superimposed on older units on the side of the Saône valley in the west of Bresse. The geometry of the various units indicates an uprising of the oldest units (C.D., S.N., M.C. and S.C.) in eastern Bresse, while the more recent units (M.Br. and S.A.) are confined to the more western part. This arrangement indicates a westward shift of the areas of sedimentation over time and a relative uplift of the eastern border of Bresse with the Jura during the Pliocene–Pleistocene (Petit 1993).

Chronology

Studies of the palaeontological record and especially of rodent (Chaline 1984) and mollusc assemblages (Puisségur 1984) provide a time-scale for the Bresse deposits (Fig. 4). Investigation of pollen assemblages (Jan du Chêne 1974; Farjanel 1985; Bachiri Taoufiq 1988) allows determination of the climatic characteristics of each unit. Synthesis of various biological and climatic evidence allows correlation of each lithological unit with the European Pliocene–Pleistocene chronology (Suc & Zagwijn 1983; Méon *et al.* 1989;



B

Mineral origin	Minerals	Hierarchical classification
Massif central or Mesozoic	R : Titanium minerals	
	Z : Zircon	
	Ma : Secondary minerals	
	D : Disthène	
	An : Andalusite	
	St : Staurolite	
Si : Sillimanite		
Alps	E : Epidote	
	Ch : Chloritoid	
	Gl : Glaucophane	
	G : Garnet	
	A : Amphibole	
Vosges	Ap : Apatite	
	T : Tourmaline	
Mont-Dore	Mo : Monazite	
	S : Sphère	
	P : Pyroxène (augite)	

Fig. 5. Analysis of heavy mineral assemblages of the Pliocene-Pleistocene of Bresse
 □ A. Correspondence factor analysis. □ B. Hierarchical cluster.

Chaline & Farjanel 1990; Rousseau *et al.* 1992; Petit 1993). On this basis, the M.Be. unit is of Brunssumian age (before 3.2 Ma), the C.D. unit containing *Mimomys davakosi* and *Mimomys occitanus* is of Lower Reuverian age and the S.N. unit containing *Mimomys hajnakensis* is associated with a Middle Reuverian pollen assemblage. Likewise, the M.C. unit containing *Mimomys polonicus* and an arboreal pollen assemblage is of late Reuverian age and the S.C. containing

Mimomys polonicus and a steppe pollen assemblage is of Praetiglian age. Similarly, the M.Br. unit containing *Mimomys pliocaenicus* is of Tiglian age, while the S.A. unit with *Mimomys ostromosensis* is of Eburonian age. The earliest river terraces (Fv) including *Mimomys savini* are of Waalian to Bavelian age and the more recent accumulations (Fw, Fx and Fy) containing *Microtus* sp. are of Cromerian to Weichselian age.

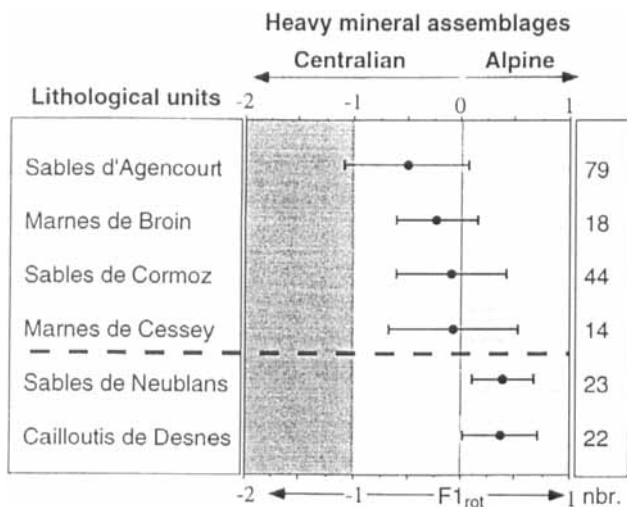


Fig. 6. Mineralogical characterization of the Pliocene–Pleistocene lithological units of Bresse by mean and standard deviation of MF*2 coordinates of the correspondence factor analysis.

Heavy mineral assemblages of the Pliocene–Pleistocene of Bresse and the chronology of Alpine deposits

The Alpine origin of part of the Pliocene–Pleistocene deposits of Bresse has been known since Rollier (1907) from finds of cobbles containing radiolarites that were originally known only in the Central Alps. The identification of sediment sources has been considered more recently by analysing the heavy minerals of the sand facies that are abundant in Bresse. Mineral assemblages have been identified in 200 representative samples collected from the deposits as a whole (Bonvalot 1974; Teste 1977; Zanon 1978; Senac 1981). The results have been investigated using multivariate analysis (correspondence factor analysis) and hierarchical cluster (Petit 1993) (Figs. 5A and B). Seventeen mineral types were identified and the composition of the 200 samples has been expressed as a relative percentage (excluding opaque minerals). The factor

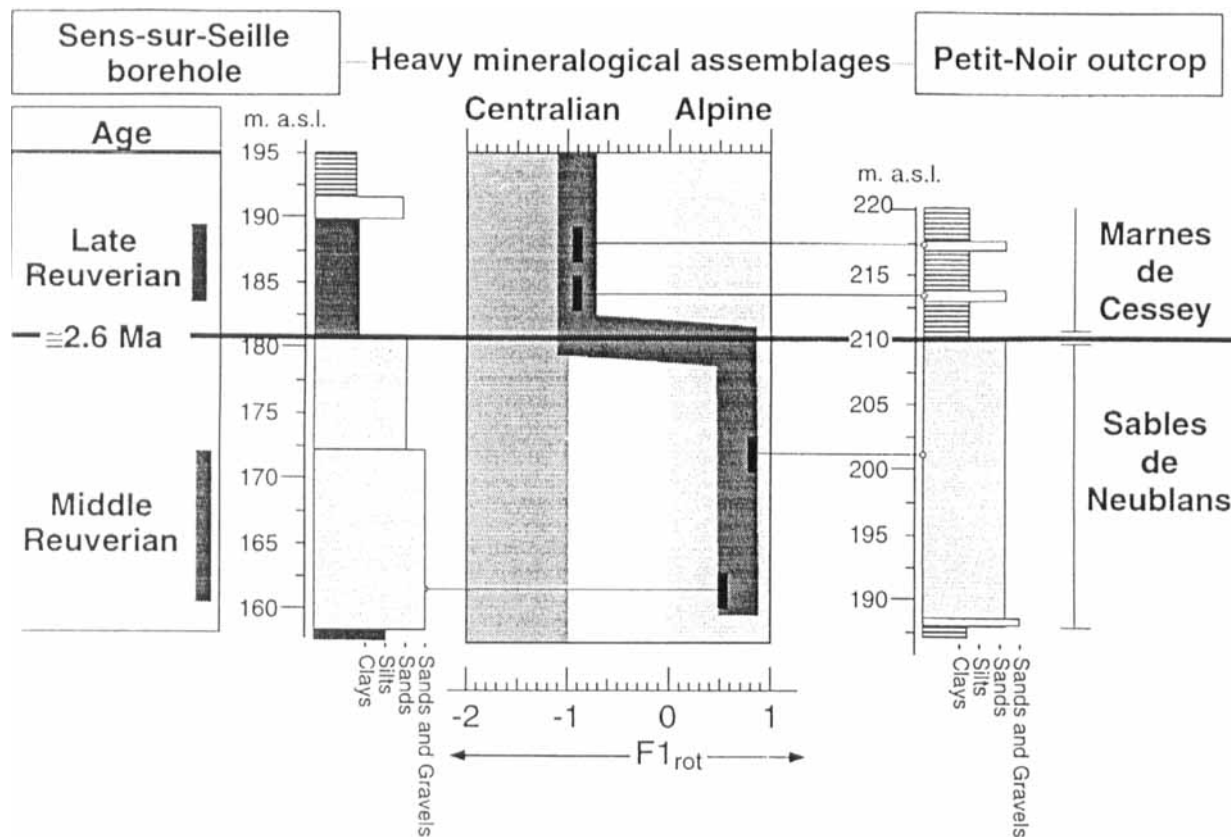


Fig. 7. Chronological position of termination of transport of heavy minerals of Alpine origin in two representative boreholes (Sens-sur-Seille and Petit-Noir).

plane F1-F2 of the CFA analysis represents 55% of the total variability of the samples and the mineral species distributed between axis F1 (34%) and axis F2 (21%). The values obtained are distributed along two perpendicular axes $F1_{rot}$ and $F2_{rot}$, which are diagonal compared with the F1-F2 reference lines. The $F1_{rot}$ axis reveals a slope between a group of fragile or easily weathered minerals – garnet (Gr), amphibole (A) epidote (E) – and a group of stable minerals – tourmaline (T) and monazite (Mo). The $F2_{rot}$ axis shows a gradient between a group of minerals from the general metamorphism of the central uplands – sillimanite (Si), staurolite (St), disthene (D), andalusite (An) and zircon (Z) – and a group of volcanic minerals – sphene (S) and pyroxene (P), which is mainly augite.

These analyses together with the increasing rank ordering (Fig. 5B) indicate four mineral assemblages:

An assemblage of Alpine origin comprising minerals from the Alpine basement – garnet (Gr), amphibole (A) and apatite (Ap) – and from the metamorphic areas of the central Alps – garnet (Gr), glaucophane (Gl), chloritoid (Ch), epidote (E) (Tchmichkian *et al.* 1958; Bonvalot 1974). The occurrence of fragile minerals (G, Ap, A) reflects rapid deposition that allows them to be conserved. The mere presence of more stable minerals (Gl, Ch, E) reflects slower deposition and perhaps some reworking. The samples characterized by these two mineral associations are projected on the positive values of the $F1_{rot}$ axis.

An assemblage of Central origin comprising minerals resulting from general metamorphism (D, An, St, Si) and titanium minerals – (zircon: Z) from rocks occurring on the eastern edge of the Massif Central (Beaujolaïs and Morvan hills) (Duplaix *et al.* 1965; Bonvalot 1974).

An assemblage of Vosgian origin (tourmaline: T and monazite: Mo) that is characteristic of the Hercynian basement of the Vosges mountains (Tchmichkian *et al.* 1958).

An assemblage of volcanic origin (aeolian deposits) which is characterized by sphene (S) and pyroxenes (P) of augite type (Pastre 1987). The occurrence of volcanic minerals is ascribed to nuée ardente type eruptions (Cantagrel & Baudron 1982) and trachytic Plinian fallout (Pastre 1987) from the Mont-Dore stato-volcano in the Massif Central, 250 km southwest of Bresse (Bonvalot & Seddoh 1976; Bonvalot *et al.* 1984; Petit 1993). This mineral assemblage has been identified in numerous Pliocene–Pleistocene sediments of western Europe (Windheuser & Brunnacker 1978; Pastre 1987; Debard & Pastre 1988).

The gradient highlighted on the $F1_{rot}$ axis of Fig. 5A defines the Alpine deposits usually composed of fragile minerals as opposed to the more local deposits from the Vosges and central uplands which are made up of stable minerals. The mineral content of each

rock unit defined in Bresse can be characterized by the mean and standard variation of the co-ordinates of the $F1_{rot}$ axis for the samples analysed. It can be seen (Fig. 6) that the heavy mineral assemblages of Alpine origin are only found in the partly Reuverian age Cailloutis de Desnes and Sables de Neublans formations.

The termination of deposition of Alpine deposits in the Bresse infill is marked very precisely at the boundary between the Sables de Neublans and the Marnes de Cessey facies. The Sens-sur-Seille and Petit-Noir boreholes clearly exhibit this boundary (Fig. 7). These two boreholes are some 20 km apart and show the same lithological succession. At the base, the sandy facies with Middle Reuverian palynological (Farjanel 1985) and malacological (Puisségur 1984) assemblages contain an abundant assemblage of Alpine minerals (garnet: 22%; amphibole: 29%). At the top, the marl facies with intercalated sands contain Upper Reuverian palynological and malacological assemblages containing predominantly minerals characteristic of local sediments from the Vosges (titanium minerals: 9%; zircon: 23%; tourmaline: 17%). Minerals from the Alps are highly weathered and found only in small amounts (garnet: 5.6%; amphibole: 5.8%).

These data allow the dating of the phase of Alpine deposits in the Bresse infill. The phase begins with the accumulation of the Cailloutis de Desnes Formation and ends after deposition of the Sables de Neublans deposits. These Alpine deposits in Bresse begin at the start of the Reuverian (around 3.3 ± 0.2 Ma) and stop before the end of the Reuverian (around 2.6 ± 0.2 Ma). Subsequently, the northern Bresse infill is supplied chiefly by local sediments. The occurrence of small amounts of weathered Alpine minerals in more recent sediments indicates reworking of earlier deposits.

Palaeohydrographic changes in the Alpine foreland

This issue has been covered in part by various workers in a narrower spatial framework (Bourdier 1973; Brunnacker *et al.* 1977) or based on morphological data (Gibbard 1988). The mineralogical and chronological characterization of Alpine deposits in Bresse can be used as a yardstick for other basins of the Alpine foreland (Swiss molassic basin, Alsacian Graben and the German and Dutch Grabens). Five main palaeohydrographic changes can be detected (Fig. 8).

The Rhine (Aar)–Danube phase, before 5 Ma

Alpine deposits have been identified in the Upper Miocene formations east of the Swiss molassic plain

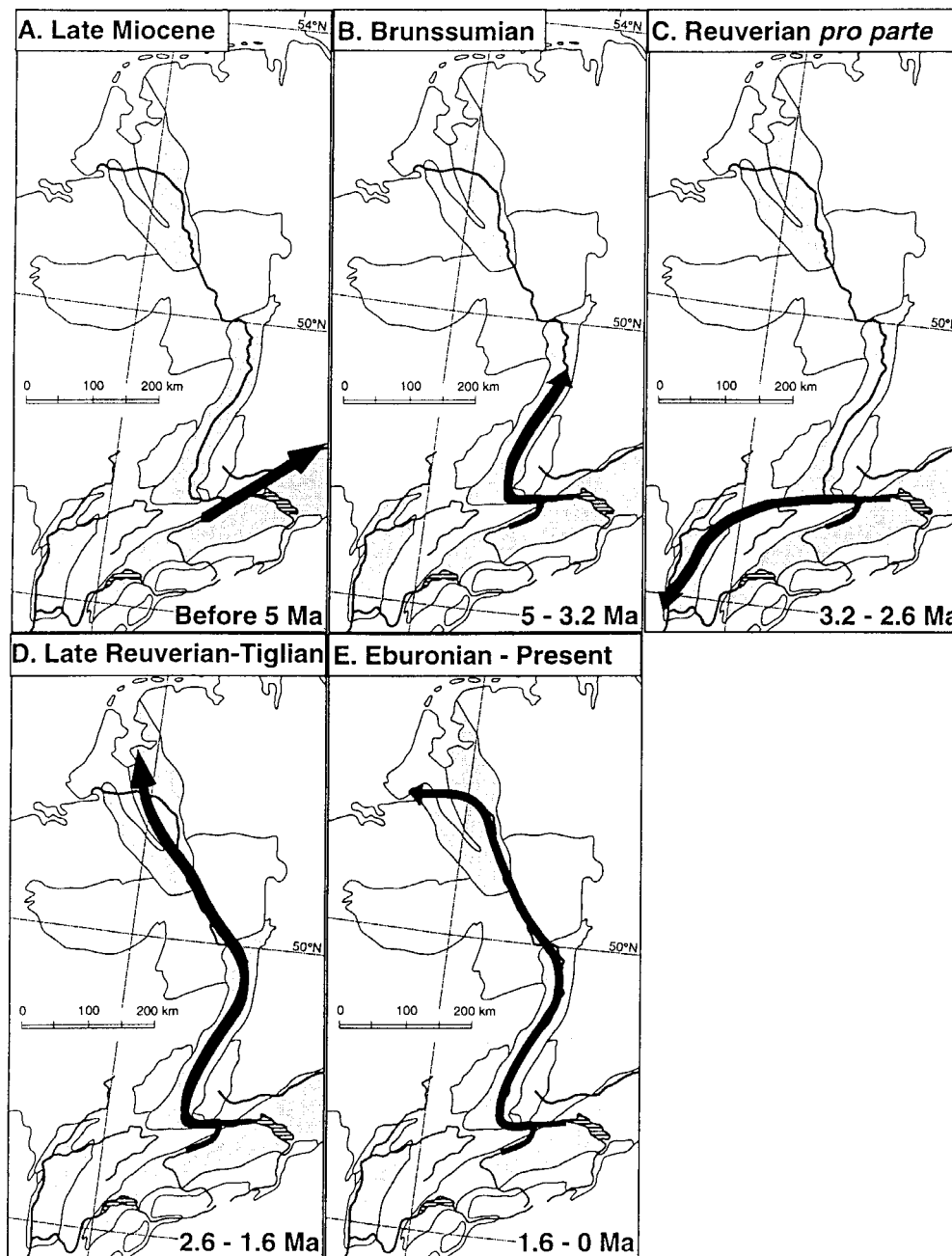


Fig. 8. Major changes in the palaeohydrographic pattern of rivers of the northwestern Alps since the Miocene.

(Brunnacker *et al.* 1977). However, further west, in the south of the Rhine Graben and the Jura, Upper Miocene conglomerates and sands containing *Dinotherium* (Pontian facies) exhibit a local mineral assemblage of Vosgian origin (Sittler 1972). Thus until the end of the Upper Miocene (around 5 Ma), Alpine material was carried east across the Swiss molassic plain by a river course that can be named the Rhine/Aar–Danube (Fig. 8A).

The Rhine/Aar Alsacian phase from 5 to 3.2 Ma (Brunssumian)

Protogyne (Mont-Blanc massif granite) cobbles and Alpine minerals have been identified in the Alsacian Graben (Lauterbourg section) within a formation dated to the Brunssumian (Hagueneau facies) (Geissert *et al.* 1976; Boenigk 1987). However, in all the other basins of the Alpine foreland, Brunssumian age deposits are devoid of Alpine minerals:

- In the North European Grabens (sections of the Ville area: Fortuna & Frechen) and in the Central Graben of The Netherlands where the sandy Kieseloölite Formation is dated to the Upper Miocene to Reuverian (Boenigk *et al.* 1974; Boenigk 1978, 1982; Zagwijn 1974, 1989; Zagwijn & Doppert 1978).
- In Bresse, the Marnes de Beaune of Brunssumian age are devoid of Alpine minerals.

Thus, in the Brunssumian, Alpine deposits from the Rhine/Aar reached the Alsacian Graben but were unknown in the Lower Rhine Grabens. The Rhine and the Aar ceased to be tributaries of the Danube in the early Pliocene and their course seems to have shifted to the northwest within the Swiss molassic plain to join the Alsacian Graben (Fig. 8B).

The Rhine/Aar–Doubs phase from 3.2 to 2.6 Ma (Reuverian p.p.)

Alpine minerals have been identified in the Reuverian formations of Bresse (Cailloutis de Desnes and Sables de Neublans). In the southern part of the Rhine Graben, the lower part of the Cailloutis du Sundgau Formation contains minerals of Alpine origin (Sittler 1972). On the basis of a sedimentological study (mineral assemblages, grain size, depth of formation, extent of weathering), Bonvalot (1974) demonstrated that the Cailloutis du Sundgau formed the upstream part of the same system that deposited the Cailloutis de Desnes (or Cailloutis inférieurs de la Forêt de Chaux). In contrast, Reuverian age deposits in all the other basins of the Alpine foreland contain no Alpine minerals:

- In the grabens of northern Europe, the overlying river-delta sand formation (the sand member of the Schinveld Gravel) and the Reuver Clay (before the uppermost part of the Reuverian B) have assemblages which contain no Alpine minerals (zircon, rutile and tourmaline) (Boenigk *et al.* 1974). The change from stable minerals to instable (molasse provenance) minerals occurs within the upper part of the Reuver Clay, or palynologically within the Reuverian B, around 2.6 Ma.
- In the Rhine Graben (Sessenheim section) where the non-decalcified sands and gravels and the indurated marls and clays ascribed to the Reuverian are supplied with local rivers from the Vosges (white sands with zircon and biotite) (Geissert *et al.* 1976).

The absence of Alpine minerals in the grabens of northern Europe and Alsace, while they are present on the north and northwest slopes of the Jura (Lower Sundgau and Forêt de Chaux), suggests that Alpine material was being transported by the Aar–Doubs. In the Reuverian (between 3.2 and 2.6 Ma), the Aar flowed out to the south of Alsace (Sundgau area) and

drained towards Bresse along the course of the present-day Doubs (Fig. 8C).

The Aar–Rhine phase from 2.6 Ma to the present (late Reuverian to present)

Alpine mineral assemblages have been identified in post-Reuverian formations of a number of Alpine foreland basins:

- In the north of the Rhine Graben near the Ville (Köln area, Fortuna & Frechen sections), heavy minerals of Alpine assemblages appear in the Reuverian B (Figs. 8D & E) (Boenigk *et al.* 1974). All the more recent deposits of the sections contain Alpine minerals (Brunnacker *et al.* 1977; Schnütgen *et al.* 1975).
- In the Netherlands, in the Reuver Clay member, Alpine minerals are found above the peat interbedded between the A1 and A2 clay horizons, a change dated to the Reuverian B around 2.6 Ma (Zagwijn 1989).

However, in Bresse, the transport of Alpine material from the Aar–Doubs ceased in the late Reuverian (around 2.6 Ma). At this time, the Rhine captured the Aar–Doubs south of the Alsacian Graben (Sundgau area). This new palaeographic arrangement (Jura Doubs in Bresse, Aar–Rhine in the North European basins) accounts for the very different sedimentary records between the two areas from the Praetiglian to the present-day.

Praetiglian. – The cold Praetiglian stage is recorded across the Alpine foreland by coarse detrital sedimentation. In northern Europe (Schotter b of the Frechen section; Boenigk *et al.* 1974), as the outlet of the Rhône in southern Bresse (Cailloutis de St Jean sur Reysseuse) (Petit 1993), this detrital pattern is apparent from the occurrence of coarse conglomerates. However, in northern Bresse, this pattern is shown by the deposition of sands (Sables de Cormoz). This apparently arises from the smaller catchment area of the Aar–Doubs which was confined to the Jura Doubs after the Rhine captured the Aar.

Tiglian. – Sandy material with Alpine assemblages was transported into the Rhine Graben. They have been identified and dated at Fort-Louis, in the Haguenau basin, north of Strasbourg (Geisser *et al.* 1976). In The Netherlands, the lower course of the Rhine ran south through the Central Graben during the Tiglian and later shifted slightly northeast into the Venlo Graben (Fig. 8D) (Zagwijn 1974).

Waalian. – In Northern Europe, the Rhine moved westward (Fig. 8E), running beside the Rhine Schist Massif and the Sauerland northeast of Köln as it does today. From that time, the Venlo Graben was occu-

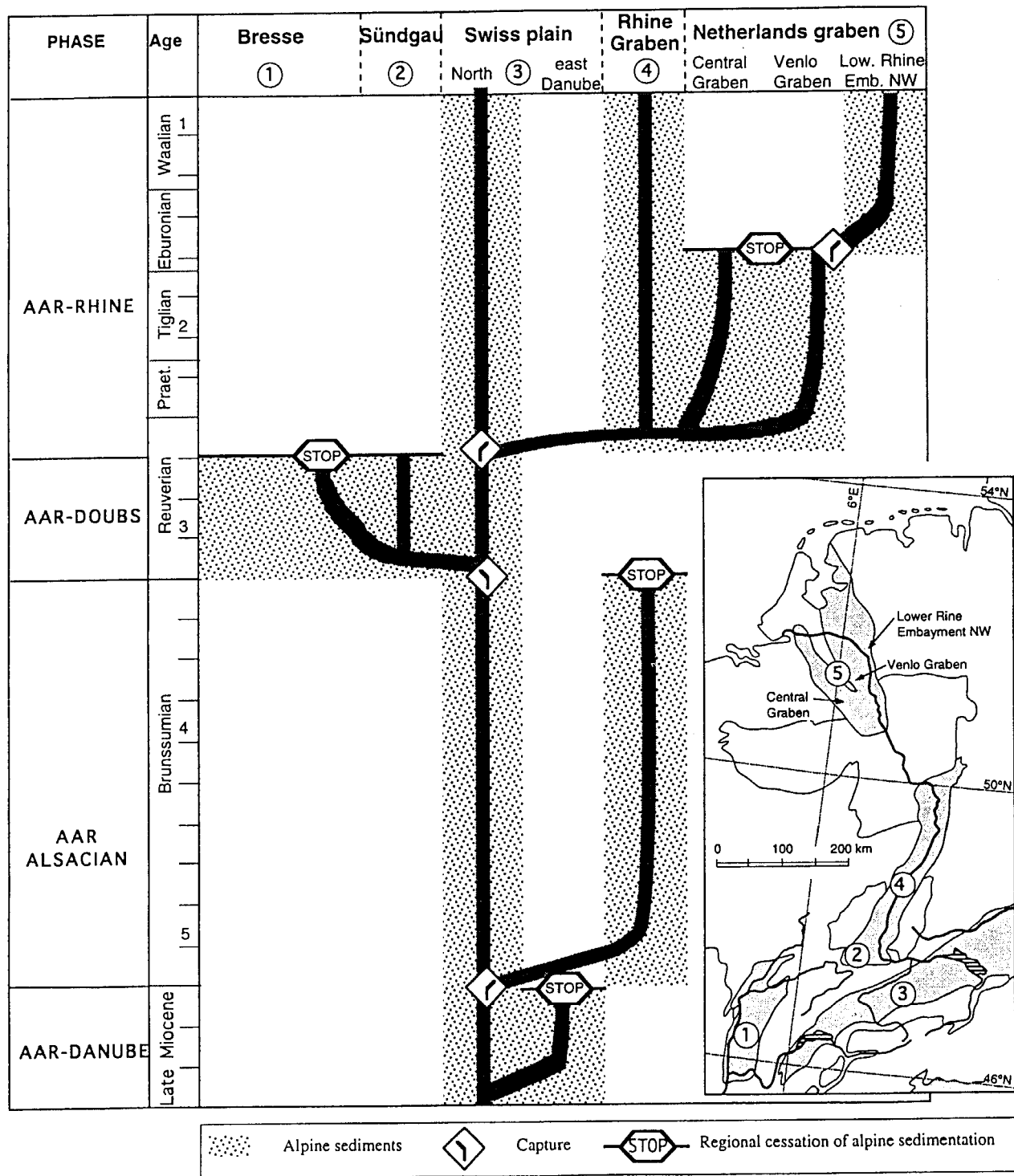


Fig. 9. Distribution of Alpine materials in the Alpine foreland basins from the late Miocene.

ped by the fluvial sediments of the Meuse alone (Zagwijn 1989).

Thus, from the late Reuverian (2.6 Ma) to the present, Alpine material has been carried towards

northern Europe. This has been accompanied by a northwestward shift of the Rhine in The Netherlands. Such palaeogeography explains why sand and gravel sedimentation occurred in northern Europe, whereas

mainly sand and clay sedimentation developed in northern Bresse.

Conclusion

The various captures and hydrographic changes of the upper reaches of the Rhine and the Aar can only be explained by localized relative vertical movement (Fig. 9).

In the Upper Miocene, the upper courses of the Rhine and the Aar drained northeastward across the Swiss molassic plain. It seems that this zone was still subject to subsidence at this time compared with the other areas of the Alpine foreland.

From Brunssumian times, the headwaters of the Rhine and Aar abandoned the Danube direction and were captured by streams flowing in the Rhine Graben. The graben was probably subsiding at the time, whereas the inter-river area between the upper stretches of the Danube and the Rhine was being uplifted. The most remarkable event of this palaeogeographic evolution is the capture of the upper course of the Rhine and the Aar by the Doubs, towards Bresse, in the early Reuverian. A large alluvial corridor developed between the south of the Rhine Graben (Sundgau area) and Bresse along the northwest margin of the Jura mountains. This stream transported most of the Alpine material carried by the Rhine and the Aar. This alluvial corridor ran along a syncline in front of the overlapping folds of the outer Jura during the Reuverian (Glangeaud 1949). From the end of the Reuverian, the Aar/Doubs corridor ceased to operate, as the external zone of the Jura was gradually being uplifted. This uplift brought the Alpine conglomerates to altitudes of 400 m and caused the Doubs to cut down through the Jura folds (Campy 1984). The cessation of sediment transport by Aar–Doubs to Bresse can be explained by the continued tectonic thrusting during the Pliocene–Pleistocene. The Aar in the Sundgau area, at the foot of the Alsacian Jura, was then deflected northwards and thus flowed towards the Alsacian Graben and northern Europe. The Rhine then permanently occupied its present valley and Alpine material was carried down to the North Sea. In the Eburonian, tectonic tilting caused the river to abandon the Dutch Central Graben for the Venlo Graben and then the Lower Rhine Embayment.

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