Depositional sequences in the Triassic series of the Paris Basin: Geodynamic implications

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ABSTRACT

Depositional sequences geometries of the Triassic series of the Paris Basin have been elucidated by high resolution correlations between outcrop and subsurface data using stacking pattern of genetic units. The Triassic may be subdivided into three transgressive-regressive cycles: Scythian, Scythian-Carnian and Carnian-Lias.

The sediments of the Scythian cycle are exclusively fluvial and only record the transgressive trend («Grès vosgien»). The Scythian-Carnian cycle commences with a braided fluvial facies («Conglomérat principal») and is terminated at the base of the «Grès à roseaux». The maximum flooding surface occurs within the marine storm-dominated deposits of Ladinian age (top of the «Calcaires à Cératites»). This cycle may be subdivided into three third order sequences during the transgressive trend –Scythian («Conglomérat principal»-«Couches intermédiaires»), Anisian («Grès à Voltzia»-«Complexe de Vollmunster»), and Anisian-Ladinian («Couches rouges»-«Calcaires à Cératites»)– and two during the regressive trend –Ladinian-Carnian («Lettenkohle») and Carnian («Marnes irisées inférieures»). During the Triassic, only the transgressive trend of the Carnian-Lias cycle, commencing with fluvial deposits of the Grès à roseaux, is preserved. It may be subdivided into three third order sequences: «Grès à roseaux»-«Dolomie de Beaumont», lower «Marnes irisées supérieures» and «Marnes irisées supérieures»-Rhaetian sequences.

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The maximum rate of subsidence for the Scythian-Carnian cycle occured in the east of the basin, and there was a progressive westward migration of depocenters. It was only during the deposition of the Carnian-Lias cycle that subsidence was uniform across what is now the Paris Basin. Two phases of tectonic movements controlled the distribution of depocenters. One phase is recorded in the «Marnes irisées inférieures» and controlled the area of subsidence defined by the salt deposits. The second phase occured during deposition of the «Marnes irisées supérieures» and involved a general westward tilt of the basin together with a westward migration of depocenters.

RESUMEN

La geometria de las secuencias de depósito de las series triásicas de la Cuenca de Paris fueron obtenidas por correlaciones de alta resolución a partir de observaciones de afloramientos e informaciones de subsuelo *utilizando el metodo de «stacking pattern» de las unidades genéticas.* El Triásico puede ser dividido en tres ciclos transgresivos-regresivos: Scitiense, Scitiense-Carniense y Carniense-Liásico.

Durante el ciclo Scitiense se registra unicamente la tendencia transgresiva en los sedimentos fluviales («Grès vosgien»). El ciclo Scitiense-Carniense empieza por una facies fluvial anastomosada («Conglomérat principal») y termina en la base del «Grès à roseaux». La mayor superficie de máxima inundación se ubica dentro de depósitos de edad Ladiniense caracterizados por ambientes marinos de tormenta dominante (techo de las «Calcaires à Cératites»). Este ciclo puede dividirse en tres subciclos durante la tendencia transgresiva: Scitiense («Conglomérat principal»-«Couches intermédiaires»), Anisiense («Grès à Voltzia»-«Complexe de Vollmunster») y Anisiense-Ladiniense («Couches rouges»-«Calcaires à Cératites»), y dos durante la tendencia regresiva: Ladiniense-Carniense («Lettenkohle») y Carniense («Marnes irisées inférieures»). Durante el Triásico, solamente es registrada la tendencia transgresiva del ciclo Carniense-Liásico, que comienza por depsitos fluviales del «Grès à roseaux». Este ciclo puede dividirse en tres menores: «Grès à roseaux»-«Dolomites de Beaumont», base del «Marnes irisées supérieures» y «Marnes irisées supérieures»-Rhaetian sequences.

La máxima tasa de subsidencia del ciclo Scitiense-Carniense se alcanza en la parte oriental de la cuenca, con una migración progresiva de los depocentros hacia el Oeste. La subsidencia dentro de la actual

Cuenca de Paris es homogénea solamente durante el ciclo Carniense-Liásico. Dos fases de reactivación de fallas hercínicas controlaron la distribución de los depocentros. Una fase, que controló el área de subsidencia, está caracterizada por depósitos salinos y representada por las «Marnes irisées inférieures». La segunda fase, corresponde a un basculamiento general de la cuenca hacia el Oeste, con una migración de sus depocentros hacia esa dirección durante la deposición de las «Marnes irisées supérieures».

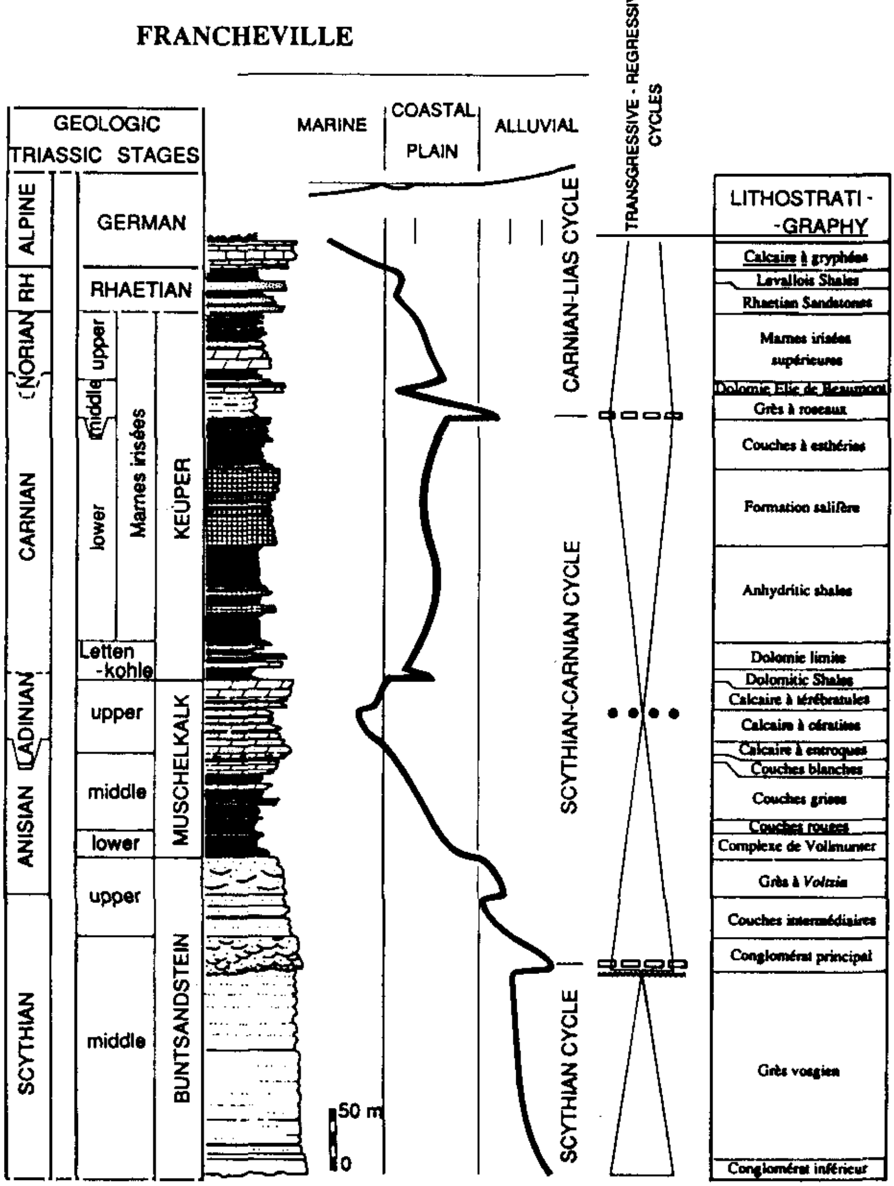
Key words: Triassic, Paris Basin, High resolution sequence stratigraphy, Well-logs.

Palabras clave: Triásico, Cuenca de Paris, Estratigrafía de alta resolución, información de subsuelo.

GEOLOGICAL SETTING

The Triassic deposits of the Paris Basin were laid down in an epicratonic peritethyan basin. The origin of the Paris Basin is classically related to an extensional phase during Permo-Triassic times (Brunet & Le Pichon, 1982, Curnelle & Dubois, 1986, Perrodon & Zabek, 1990). The three main lithological subdivisions of the German Triassic are recognized in the Paris Basin (Fig. 1): (1) the predominantly continental Buntsandstein (Lower Triassic), (2) the marine Muschelkalk (Middle Triassic) and (3) the predominantly continental Keuper (Upper Triassic).

The Lower Triassic deposits are found only in the eastern part of the Paris Basin and consist chiefly of fluvial sediments. The Middle Triassic is composed mainly of carbonate sediments in the eastern part of the basin, with evaporites in the extreme east and consists of fluvial sediments in the west. The Upper Triassic sediments were deposited largely in a continental, and predominantly coastal plain environment. Halitic, anhydritic and dolomitic coastal plain sediments may be recognized. Others sediments belong to an alluvial plain environment with a variety of fluvial systems. The most common of these are anastomosing channel systems («Grès à roseaux» and Donnemarie Sandstones *p.p.*) which grade into braided and alluvial fan deposits (the Chaunoy Sandstones). Paleosols are rare except for dolomitic types within the Chaunoy Formation. Classically, two areas of sedimentation have been distinguished in the Keuper of the Paris Basin (Fig. 2): an eastern area consisting essentially of halitic or anhydritic coastal plain deposits and a western area dominated by flu-


FRANCHEVILLE
GEOLOGIC TRIASSIC STAGES
ALPINE
RH
NORIAN
CARNIAN
LADINIAN
ANISIAN
SCYTHIAN
GERMAN
RHAETIAN
upper
middle
lower
Marnes irisées
KEUPER
Letten-kohle
upper
middle
lower
MUSCHELKALK
upper
middle
BUNTSANDSTEIN
50 m
0
MARINE
COASTAL PLAIN
ALLUVIAL
CARNIAN-LIAS CYCLE
SCYTHIAN-CARNIAN CYCLE
SCYTHIAN CYCLE
TRANSGRESSIVE - REGRESSIVE CYCLES
LITHOSTRATIGRAPHY
Calcaire à gryphées
Levallois Shales
Rhaetian Sandstones
Marnes irisées supérieures
Dolomie Elie de Beaumont
Grès à roseaux
Couches à esthéries
Formation salifère
Anhydritic shales
Dolomie limite
Dolomitic Shales
Calcaire à térébratules
Calcaire à cératites
Calcaire à entroques
Couches blanches
Couches grises
Couches rouges
Complexe de Vollmunster
Grès à Voltzia
Couches intermédiaires
Conglomérat principal
Grès vosgien
Conglomérat inférieur

vial deposits (Dubois & Umbach, 1974, Courel *et al.*, 1980, Matray et al., 1989). The Saint-Martin de Bossenay fault divides these two areas (Fig. 2).

The Triassic of the Paris Basin can be subdivided into three second order transgressive-regressive cycles, the Scythian, Scythian-Carnian and Carnian-Lias cycles (Guillocheau, 1991, Guillocheau *et al.,* 1992). During the Scythian cycle, sediments are exclusively fluvial and record the transgressive trend only («Grès vosgien»). The Scythian-Carnian cycle begins with a braided fluvial facies («Conglomérat principal») and is terminated at the base of the «Grès á roseaux». A major maximum flooding surface occurs in the second cycle within the Ladinian-age marine storm-dominated deposits (top of the «Calcaires à Cératites»). The third cycle (Carnian-Lias, Bourquin & Guillocheau, 1993) commences with fluvial deposits of the «Grès à roseaux» anawas a maximum flooding surface in the Lower to Middle Toarcian marine deposits («Schistes cartons»).

The geometries of the depositional sequences in marine and non-marine environments using outcrop and subsurface information are documented in this paper; and secondly an estimation is made of the importance and nature of tectonic controls during the deposition of the Triassic sediments. The study is based on the correlation of around 240 wells from outcrop and subsurface (core and well-log) data using high resolution sequence stratigraphy.

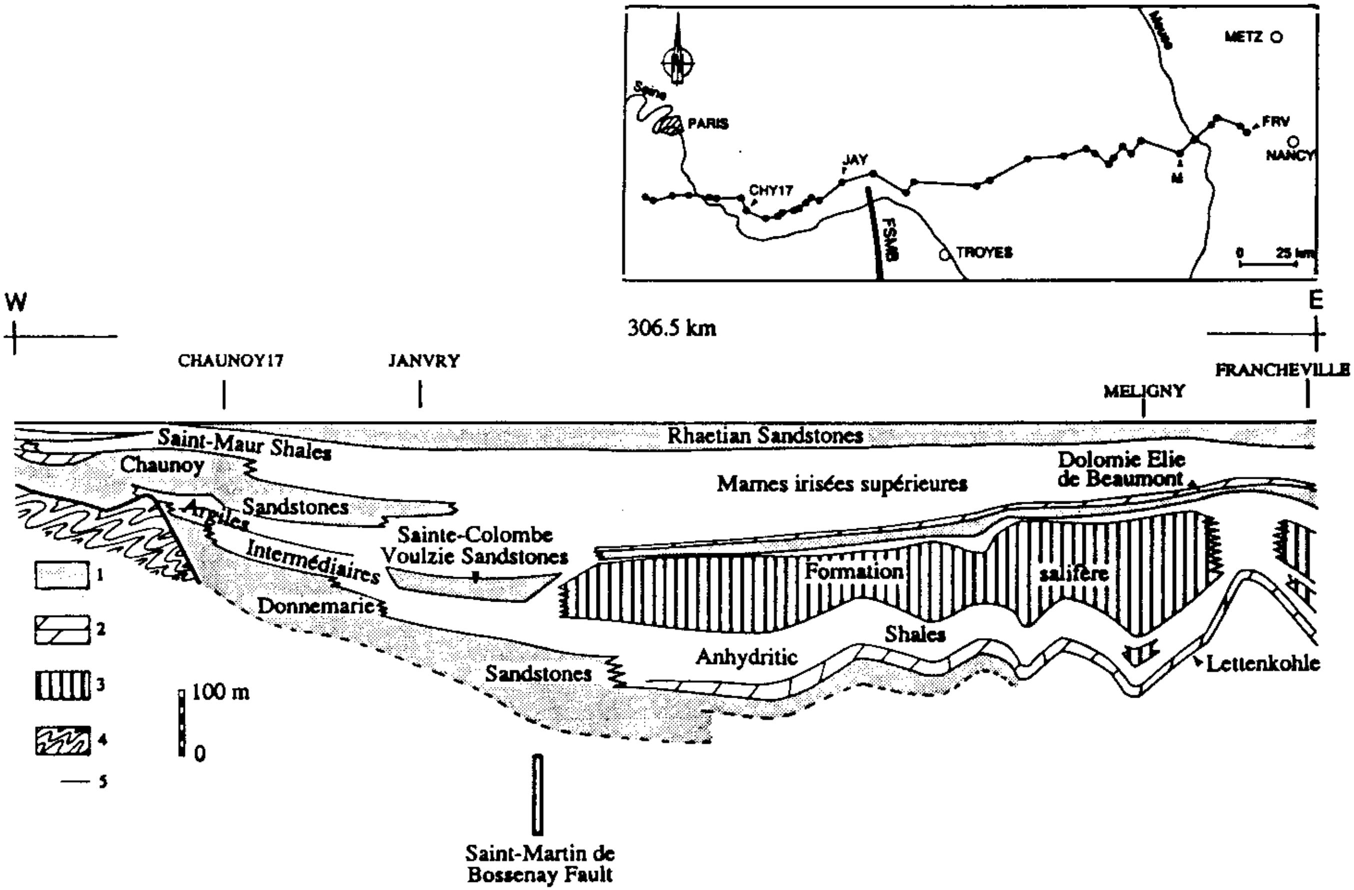
METHODOLOGY: SEQUENCE STRATIGRAPHY

The different orders of superimposed depositional sequences are identified from the stacking pattern of either genetic units or parasequences (Cross, 1988, Van Wagoner *et al.*, 1988, 1990, Mitchum & Van Wagoner, 1991, Homewood *et al.*, 1992). These are the result of either a full cycle of progradation / retrogradation in marine environments or a complete cycle of base-level change in continental environments (Ross, 1989). Genetic units are similar to parasequences in terms of sequence hierarchy, but genetic units are bounded by two maximum flooding surfaces.

The method used requires knowledge of primary depositional fea-

Figure 1.–Stratigraphic framework of the Triassic succession in the east of the Paris Basin based on the Francheville well. The chronostratigraphy is after Courel *et al.* (1980) and Aigner & Bachmann (1992). See figure 2 for the location.

Figura 1.–Esquema estratigráfico de la sucesión triásica al este de la Cuenca de París basado en el sondeo de Francheville. La cronostratigrafía se basa en Courel *et al.* (1980) y Aigner & Bachman (1992). Localización en la figura 2.


METZ
PARIS
FRV
NANCY
JAY
CHY17
M
FSMB
TROYES
0 25 km
W
E
306.5 km
CHAUNOY17
JANVRY
FRANCHEVILLE
MELIGNY
Rhaetian Sandstones
Saint-Maur Shales
Chaunoy
Sandstones
Argiles
Intermédiaires
Sainte-Colombe
Voulzie Sandstones
Marnes irisées supérieures
Dolomie Elie
de Beaumont
Formation
salifère
Donnemarie
Sandstones
Anhydritic
Shales
Lettenkohle
1
2
3
4
5
100 m
0
Saint-Martin de
Bossenay Fault

tures and comprises two phases. The first phase, based on one dimensional (vertical) information, consists in (1) observing sedimentary facies in cores and at outcrops, (2) deducing depositional processes, (3) identifying facies associations and interpreting sedimentary environments, (4) constructing a sedimentological model, (5) distinguishing individual genetic units, (6) obtaining well-log signatures of the genetic units, and (7) establishing the stacking pattern of genetic units. The second phase, of establishing correlations between the various vertical sections produced in phase one, includes: (8) selecting a regional datum, (9) correlating individual genetic units and sequences, and is completed by (10) mapping sequences (Homewood *et al.*, 1992).

In subsurface studies, it is essential to use complete sets of log data to identify and correlate genetic units, especially in continental environments (Bourquin *et al.*, 1990, 1993). For example, sandstones that consist large amounts of radioactive minerals (potash feldspar, heavy minerals, etc.) may produce high gamma-ray values similar to values obtained from clays. Consequently, the use of gamma-ray and the sonic logs alone may lead to mis-interpretation. Similarly, a density log coupled with a photoelectric factor log is required to distinguish between dolomitic and anhydritic shales. Neutron-porosity, density and photo-electric factor logs, used with high resolution logs (dipmeter or Formation Microscanner) are necessary (1) to determine sedimentary facies, (2) to calibrate cores and outcrops with well-logs and (3) to obtain significant correlations.

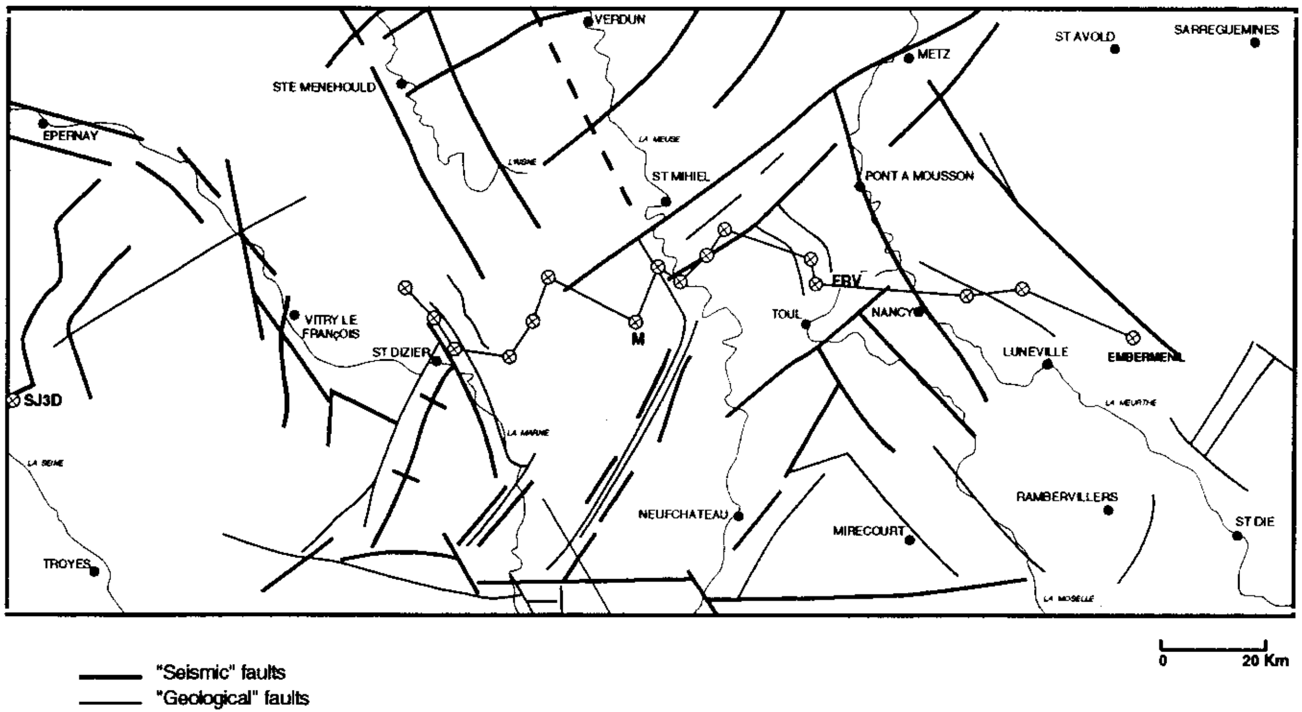
The results are summarized on an east-west section between Emberménil (east of Nancy) and south-west Paris.

SCYTHIAN CYCLE

Only the transgressive part of this cycle is recorded in continental sediments («Grès vosgien»). This hemi-cycle corresponds to a vertical

Figure 2.–Lithostratigraphic units along an E-W sections. a: location of the 37 wells correlated in this sections, b: geometry of the lithostratigraphic units. The limits between the lithostratigraphic units are not time-lines. See figure 1 for the stratigraphy. 1: sandstones; 2: dolomite; 3: halite; 4: basement; 5: lithostratigraphic limits. CH 17: Chaunoy 17; JAY: Janvry; M: Méligny; FRV: Francheville.

Figura 2.–Unidades litostratigráficas en un corte E-W. a: localización de los 37 sondeos correlacionados en el corte, b: geometría de las unidades litostratigráficas. Los límites de las unidades no son líneas-tiempo. Estratigrafía en la figura 1. 1. areniscas; 2. dolomías; 3. halita; 4. basamento; 5 límites litostratigráficos. CH 17: Chaunoy 17; JAY: Janvry; M: Meligny; FRV: Francheville.


VERDUN
STE MENEHOULD
EPERNAY
LA MEUSE
L'AISNE
ST MIHIEL
METZ
ST AVOLD
SARREGUEMINES
PONT A MOUSSON
ERV
TOUL
NANCY
LUNEVILLE
EMBERMENIL
VITRY LE FRANÇOIS
ST DIZIER
M
SJ3D
LA MARNE
LA SEINE
LA MEURTHE
NEUFCHATEAU
MIRECOURT
RAMBERVILLERS
ST DIE
TROYES
LA MOSELLE
0
20 Km
"Seismic" faults
"Geological" faults

stacking of channels. These channels belong to straight to braided systems. The top of the sequence is characterized by the «Conglomérat principal» basal erosional surface. This sequence is dominated by a tendency of base-level fall. This cycle doesnt exis't on the western part of the basin because all the sediments pinch out laterally, displaying onlap truncation over the «Haute-Marne» fault (Figs. 2, 3).

SCYTHIAN-CARNIAN CYCLE

TRANSGRESSIVE PART OF SCYTHIAN-CARNIAN CYCLE

The transgressive part of this second order cycle may be subdivided into higher order sequences. However, the exact order of these sequences, third or fourth order, is very difficult to establish because of poor biostratigraphic information. Whereas Buntsandstein may be subdivided into two sequences (Friedenberg, 1994), only one sequence is recorded by the Muschelkalk.

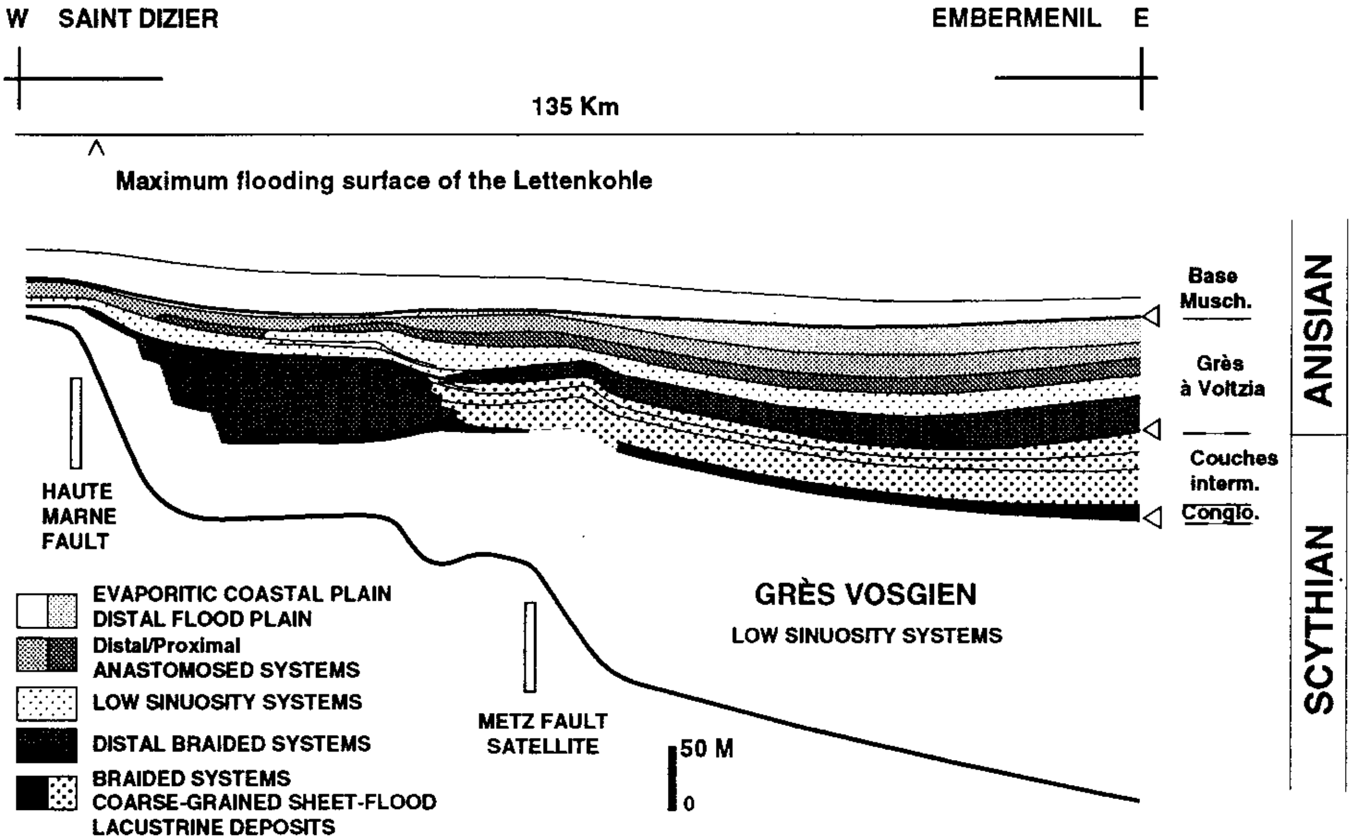
The «Conglomérat principal»-«Couches intermédiaires» sequence

This sequence is highly asymmetric anawas dominated by a rising base-level. The basal unconformity is very well marked: it is a major erosional surface, cut across locally tilted underlying sediment of the «Grès vosgien».

Both the «Conglomérat principal» and «Couches intermédiaires» exhibit lateral facies changes when traced away from the outcrops in the east (Figs. 3, 4). The «Conglomérat principal» was deposited by proximal braided channels (Durand, 1978, Courel *et al.,* 1980) and grades westward into muddier deposits. In contrast the «Couches intermédiaires», which in the east consists of lacustrine coarse-grained sheet-flood deposits grades westwards into a distal braided channel. These facies

Figure 3.–Location of the wells and faults (after Perrodon & Zabek, 1990) for the E-W sections of the Buntsandstein and the Muschelkalk. M: Méligny; FRV: Francheville; SJD: Saint-Just-Sauvage Figure 3: Localizacin de sondeos y fallas (segn Perrondon & Zabek, 1990) en el corte E-W del Buntsandstein y el Muschelkalk. M: Méligny; FRV: Francheville; SJD: Saint-Just-Sauvage.

Figura 3.–Localización de sondeos y fallas (según Perrodon & Zabek, 1991) en el corte E-W del Buntsandstein y el Muschelkalk. M: Meligny; FRV: Francheville, S J D: Saint-Just-Sauvage.



W SAINT DIZIER
EMBERMENIL E
135 Km
Maximum flooding surface of the Lettenkohle
Base Musch.
Grès à Voltzia
Couches interm.
Conglo.
ANISIAN
SCYTHIAN
HAUTE MARNE FAULT
METZ FAULT SATELLITE
GRÈS VOSGIEN
LOW SINUOSITY SYSTEMS
50 M
0
EVAPORITIC COASTAL PLAIN
DISTAL FLOOD PLAIN
Distal/Proximal
ANASTOMOSED SYSTEMS
LOW SINUOSITY SYSTEMS
DISTAL BRAIDED SYSTEMS
BRAIDED SYSTEMS
COARSE-GRAINED SHEET-FLOOD
LACUSTRINE DEPOSITS

changes are located over major basement faults such as the Meuse and Metz faults and suggest a reversal of the tendency (Friedenberg, 1994).

The boundary between these two formations has been termed the «Couches violettes» and corresponds to paleosols of several meters thickness.

The «Grès à Voltzia»-«Couches de Vollmunter» sequence

The lower boundary of this sequence corresponds to a by-pass zone overlain in the east by more proximal facies (braided deposits) than the underlying ones. This sequence is again highly asymmetric and dominated by a trend of base-level rise.

The sequence boundary records a major change in facies zonation; the depositional profile dips westward, *i.e.* the most proximal facies are located to the east (Figs. 3, 4). In the eastern part, the «Grès à Voltzia» was produced by a fluvial system (Durand, 1978) which evolved (Fig. 5) from braided, to straight, and then mainly anastomosing channels and finally a distal alluvial plain (Friedenberg, 1994). This paleogeographic trend has led to misunderstanding of the stratigraphic record in the west where the distal anastomosing channel facies are mixed with overlying Muschelkalk sediments.

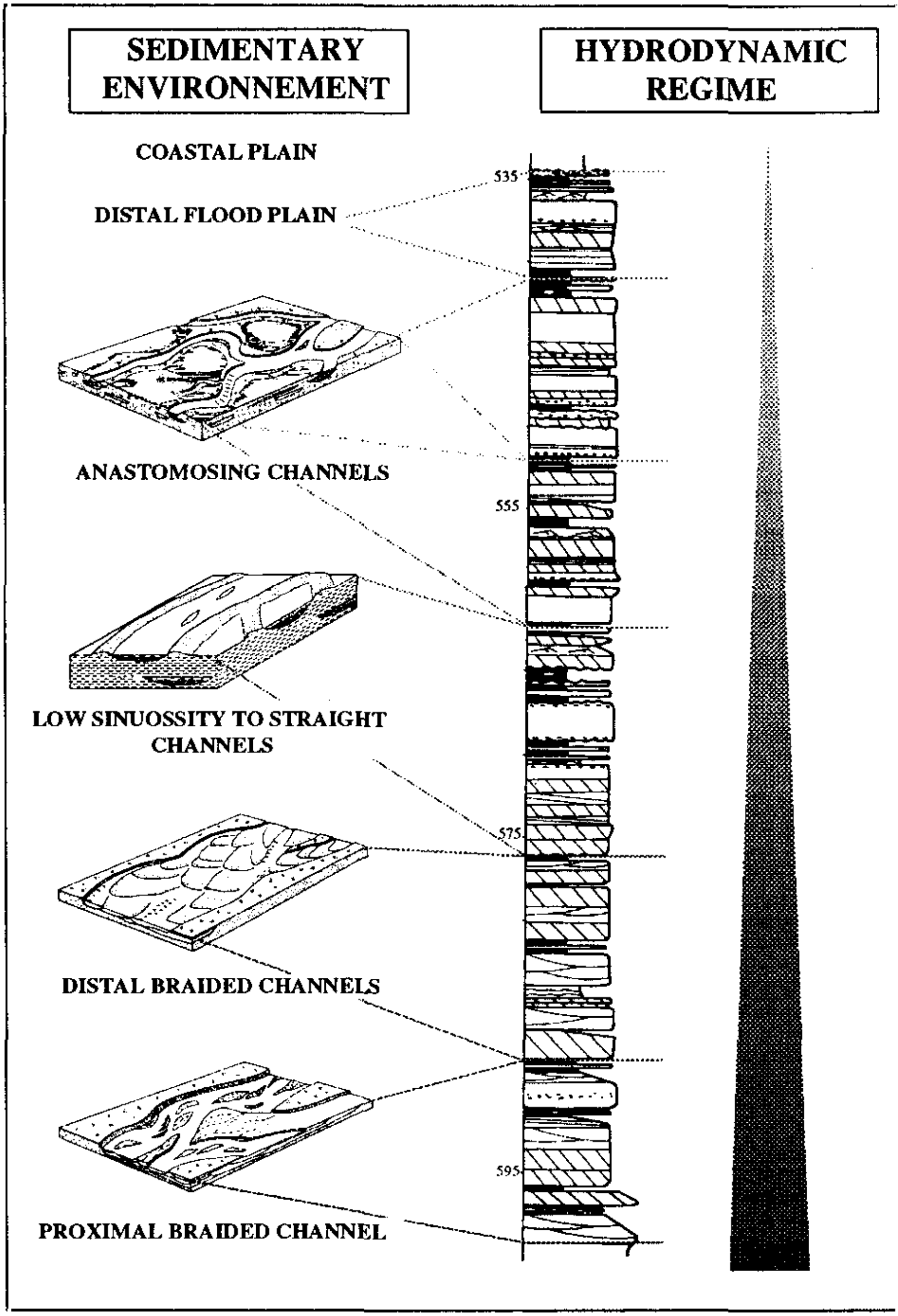
The end of this base-level rise is marked by the evaporitic coastal plain deposits of the Lower Muschelkalk («Complexe de Vollmunster») which pinch out laterally and display an onlap truncation on the «Grès à Voltzia» over the Haute-Marne fault.

The «Couches rouges», «Couches grises», «Couches blanches», «Calcaires à Cératites», «Calcaires à térébratules» sequence

This third sequence shows a general evolution to more marine environments (Middle to Upper Muschelkalk). The maximum flooding is reach at the top of the «Calcaires à Cératites» deposits (Figs. 3, 6, 7).

Figure 4.–E-W section of the Buntsandstein between Embermćnil and Saint Dizier: depositional sequence geometries-relationship between time-lines and facies (after Friedenberg, 1994). See figure 3 fot the location.

Figura 4.–Corte E-W del Buntsandestein entre Embermenil y Saint Dizier: Geometría de las secuencias deposicionales y relación entre líneas-tiempo y facies (según Friedemberg, 1994). Localización en la figura 3.


SEDIMENTARY ENVIRONNEMENT
HYDRODYNAMIC REGIME
COASTAL PLAIN
DISTAL FLOOD PLAIN
ANASTOMOSING CHANNELS
LOW SINUOSSITY TO STRAIGHT CHANNELS
DISTAL BRAIDED CHANNELS
PROXIMAL BRAIDED CHANNEL
535
555
575
595

REGRESSIVE PART OF SCYTHIAN-CARNIAN CYCLE

The Lettenkohle sequence

The lower boundary of this sequence corresponds to a flooding surface. It consists of mixed terrigenous-evaporitic sediments which thicken to the west from the Aire Fault (Fig. 8). Its base is an unconformity and its top is a base-level fall surface which is the lateral equivalent of a flooding surface.

In the east, this sequence consists of Lettenkohle sediments deposited in a restricted marine environment (Courel *et al.*, 1980, Duringer, 1982). The upper part of the Lettenkohle stage is characterized by a recurrence of lagoonal-marine facies (Ainardi, 1988). This sequence is the result of a landward stepping in a restricted marine environment, followed by marine dolomitic clays which mark a maximum flooding surface. This grades into an abrupt seaward stepping, made-up of coastal plain sulfate-rich shales («Marnes irisées inférieures»).

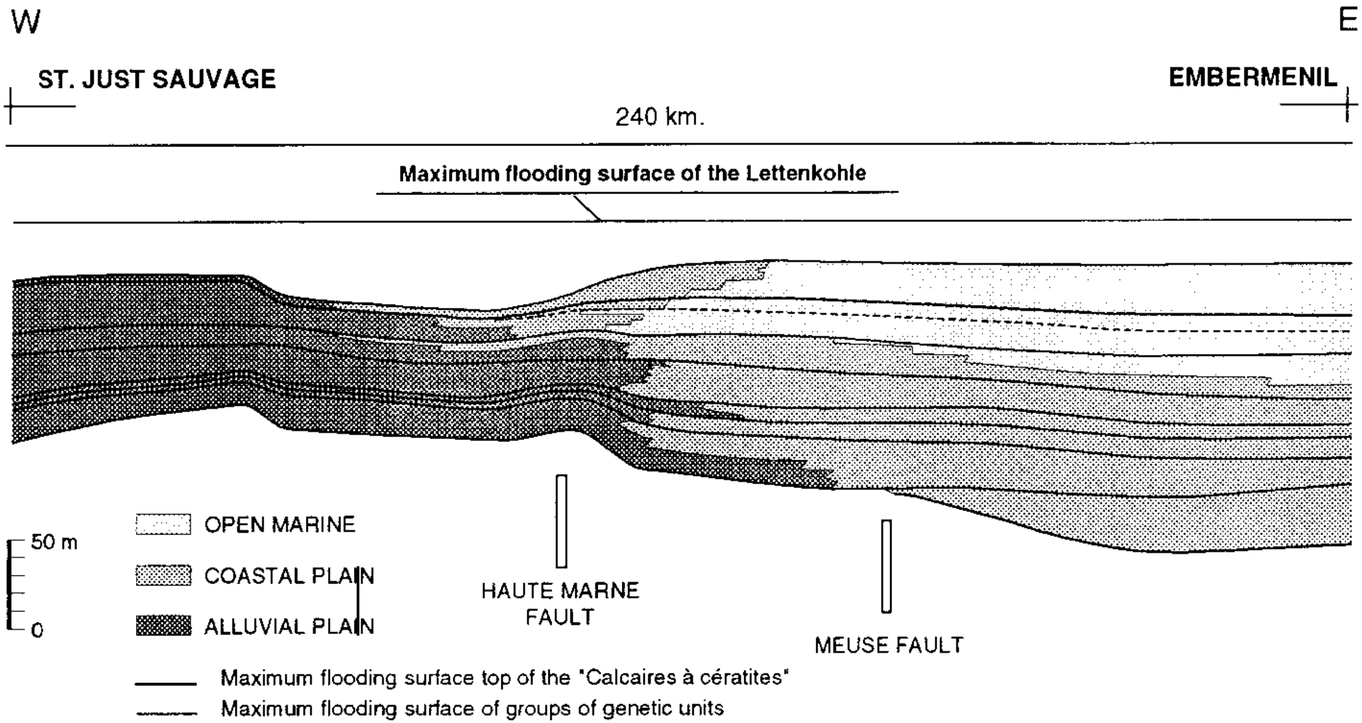
Fluvial sediments of the Donnemarie Sandstones are present west of the Saint-Martin-de-Bossenay Fault (Fig. 8). Within these sediments, bioturbated clays, with occasional dolomitic or anhydritic nodules, characterize a more distal environment (coastal plain). These are the most seaward facies of this area and should be correlated with the maximum flooding deposits of the Lettenkohle (Figs. 8, 10).

The «Marnes irisées inférieures» sequence

The lower boundary of this sequence corresponds to a flooding surface with the absence of a basal unconformity.

In the east of the basin, this sequence is made up of evaporitic coastal plain deposits: the Anhydritic Shales, «Formation salifère» and «Couches à esthéries» (Courel *et al.*, 1980, Marchal, 1983, Geisler-Cussey, 1986). These grade laterally westwards into alluvial plain deposits consisting of the fluvial deposits of the Donnemarie Sandstones and are overlain by shale-anhydritic coastal plain deposits («Argiles intermédaires», Bourquin, 1991).

Figure 5.–Variation of sedimentary environments of the «Grès à volzia» deduced from cores and well-log analysis (after Friedenberg, 1994).
Figura 5.–Variación de medios de sedimentación del «Grés à Voltzia» según testigos y análisis de registros de pozos.


W
E
ST. JUST SAUVAGE
EMBERMENIL
240 km.
Maximum flooding surface of the Lettenkohle
50 m
0
OPEN MARINE
COASTAL PLAIN
ALLUVIAL PLAIN
HAUTE MARNE FAULT
MEUSE FAULT
Maximum flooding surface top of the "Calcaires à cératites"
Maximum flooding surface of groups of genetic units

Geometrically, the salt deposits migrate to the west with the fluvial sediments of Donnemarie Sandstones migrating landward in transgressive pattern (Figs. 8, 9). Vertical aggradation predominated during deposition towards the top of the salt formation, with lateral transitions into shale-anhydritic coastal plain facies.

The sites of maximum halite accumulation within the Formation salifére are in the areas of greatest subsidence. These salt accumulations grade laterally into anhydritic coastal plain environments in the less subsidence-prone areas (at the east of the transect, Fig. 8).

CARNIAN-LIAS CYCLE

During the Triassic only the transgressive trend of this cycle is recorded.

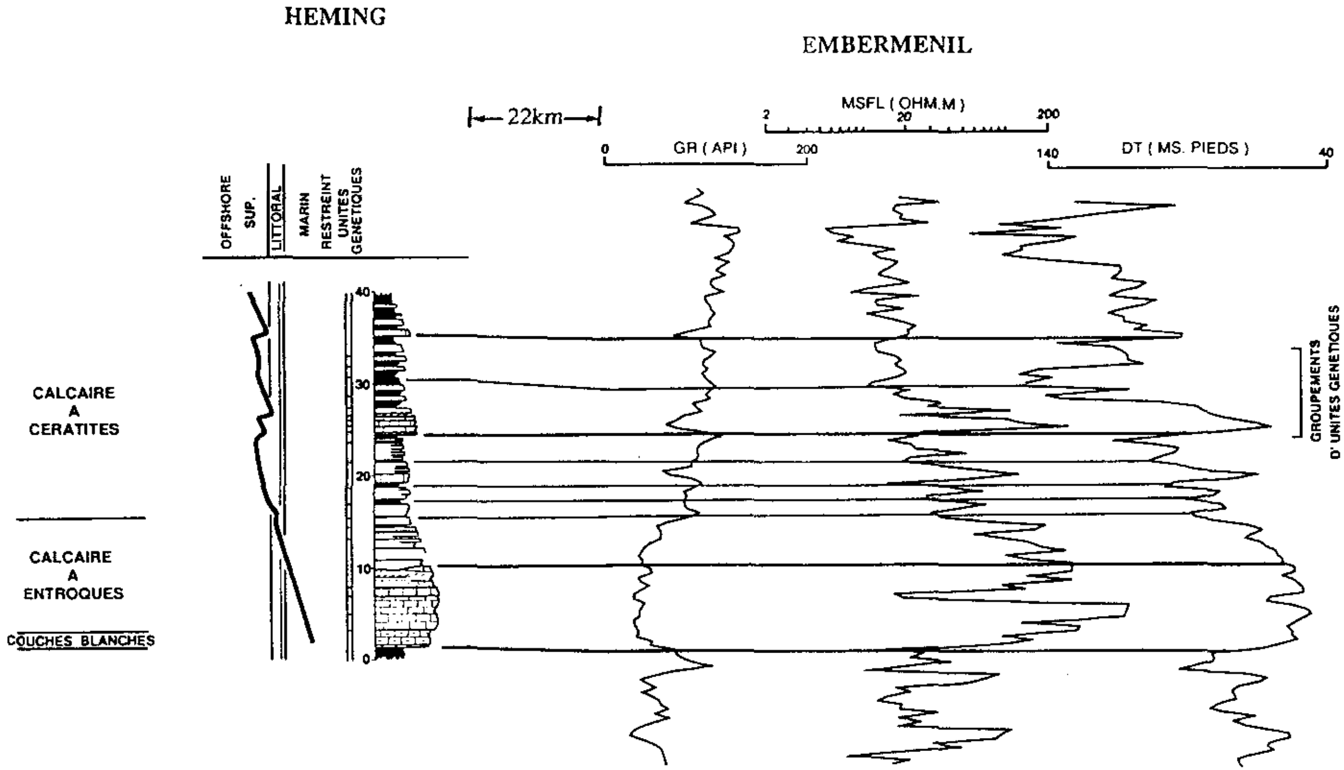
TRANSGRESSIVE PART OF SCYTHIAN-CARNIAN CYCLE

The «Grès à roseaux»-Beaumont dolomite-«Marnes irisées supérieures» sequence

This lower boundary of this sequence corresponds to the base of the fluvial «Grès à roseaux» and is marked by a major change in facies from marine-influenced evaporitic coastal plain to non-marine fluvial deposits. This surface is not erosional and there is no evidence of any incised valley. A non erosional valley-shaped depression has been formed due to local flexure where the Saint-Martin de Bossenay, Seine and Bouchy Faults converge (Figs. 8, 9). This depression is filled with lenticular fluvial sediments (Sainte-Colombe-Voulzie Sandstones) indicating a basal onlap overlain by the «Grès à roseaux».

The sequence starts with the deposition of alluvial plain sediments of anastomosing and meandering channels («Grès à roseaux», Palain, 1966, Courel *et al.*, 1980) during a period of base-level rise. These sediments grade vertically into the marine deposits of the «Dolomie de Beaumont» over an interval of a few metres. The landward lateral equivalent of the maximum flooding surface observed in the marine deposits of the «Dolomie de Beaumont» occurs within clayey coastal plain deposits (within

Figure 6.–E-W Muschelkalk section between Emberménil and Saint-Just-Sauvage: depositional sequence geometries-relationship between time-lines and facies. See figure 3 for the location.
Figura 6.–Corte E-W del Muschelkalk entre Emberménil y Saint Just Sauvage: geometría de las secuencias deposicionales y relación entre líneas-tiempo y facies. Localización en la Figura 3.


HEMING
EMBERMENIL
22km
MSFL (OHM.M)
2
20
200
0
GR (API)
200
140
DT (MS. PIEDS)
40
OFFSHORE
SUP.
LITTORAL
MARIN
RESTREINT
UNITES
GENETIQUES
40
30
20
10
0
CALCAIRE
A
CERATITES
CALCAIRE
A
ENTROQUES
COUCHES BLANCHES
GROUPEMENTS
D'UNITES GENETIQUES

the upper part of the «Argiles intermédiaires», Figs. 8, 9). The regressive phase is made up of a dolomitic coastal plain sediments which grade vertically into an anhydritic coastal plain sediments. To the west, this trend ends with the basal part of the fluvial Chaunoy Sandstones which is a major by-pass surface *i.e.* where multiple erosions have taken place with development of some paleosols.

The «Marnes irisées supérieures»-Rhaetian

The «Marnes irisées supérieures» (Figs. 8, 9) show a retrogradation from anhydritic coastal plain to dolomitic coastal plain deposits grading upward into the restricted marine deposits of the Rhaetian Sandstones (Courel *et al.*, 1980). To the west, this transgressive trend is recorded in the alluvial Chaunoy Sandstones by a retogradation from alluvial fan deposits to those of a braided fluvial system, which was covered by a dolomitic coastal plain deposits (Figs. 8, 10).

During this period two third order sequence are observed:

The lower «Marnes irisées supérieures» sequence

The lower boundary of this sequence corresponds to a flooding surface with no basal unconformity.

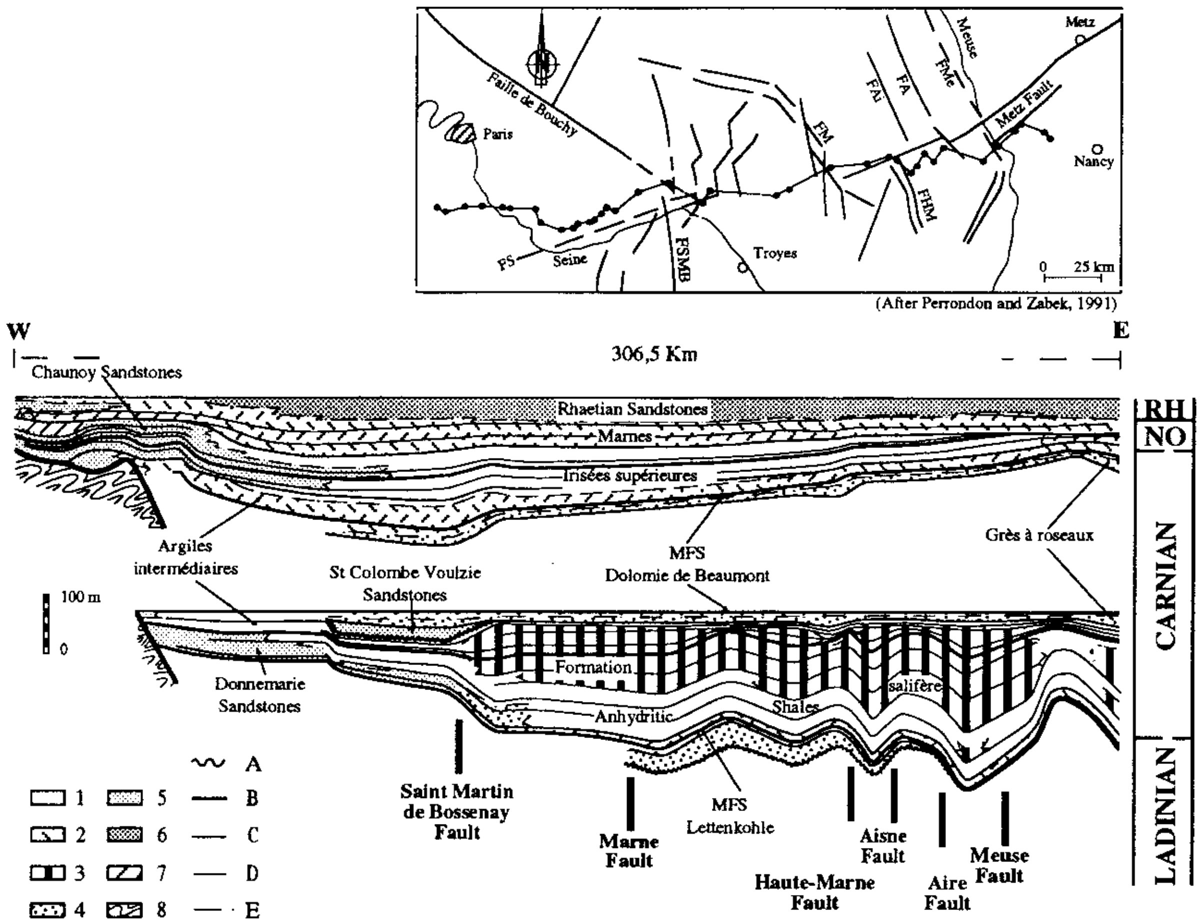
Sedimentological studies of the distal eastern part of the Chaunoy Sandstones revealed extensive flooding of the alluvial fan by lacustrine sediments. This base-level rise surface is overlain by braided channel deposits. To the east, this retrogradational trend is recorded within the anhydritic coastal plain sediments (Figs. 8, 9, 10). The progradational trend, characterized in the central part of the basin by numerous well developped anhydritic strata, ends with an erosional unconformity.

The upper «Marnes irisées supérieures»-Rhatian sequence

This lower boundary of this sequence corresponds to a major unconformity. It is an erosional feature in the eastern part of the basin overlain

Figure 7.–Correlations between the quarry of Heming (Lorraine) and the well-log of Embermenil.

Figura 7.–Correlación entre la cantera de Heming (Lorena) y el registro del sondeo de Embermenil.


Metz
Meuse
FMe
FA
FAi
Metz Fault
Nancy
Faille de Bouchy
Paris
FM
FHM
FSMB
Troyes
FS
Seine
0 25 km
(After Perrondon and Zabek, 1991)
W
E
306,5 Km
Chaunoy Sandstones
Rhaetian Sandstones
Marnes
Irisées supérieures
Argiles intermédiaires
MFS Dolomie de Beaumont
Grès à roseaux
St Colombe Voulzie Sandstones
100 m
0
Formation
salifère
Shales
Anhydritic
Donnemarie Sandstones
MFS Lettenkohle
Saint Martin de Bossenay Fault
Marne Fault
Haute-Marne Fault
Aisne Fault
Aire Fault
Meuse Fault
RH
NO
CARNIAN
LADINIAN
A
B
C
D
E
1
2
3
4
5
6
7
8

by sediments lying parallel to the surface (Figs. 8, 9). This discontinuity is recorded within the «Marnes irisées supérieures», *i.e.* in evaporitic coastal plain deposits where it separates the deposits of anhydritic and dolomitic coastal plain sediments. Westward, it is a conformable surface overlain by onlapping dolomitic coastal plain deposits which ended the depositions of braided channels or of the dolomitic paleosols in the extreme west of the Chaunoy Formation (Figs. 8, 10).

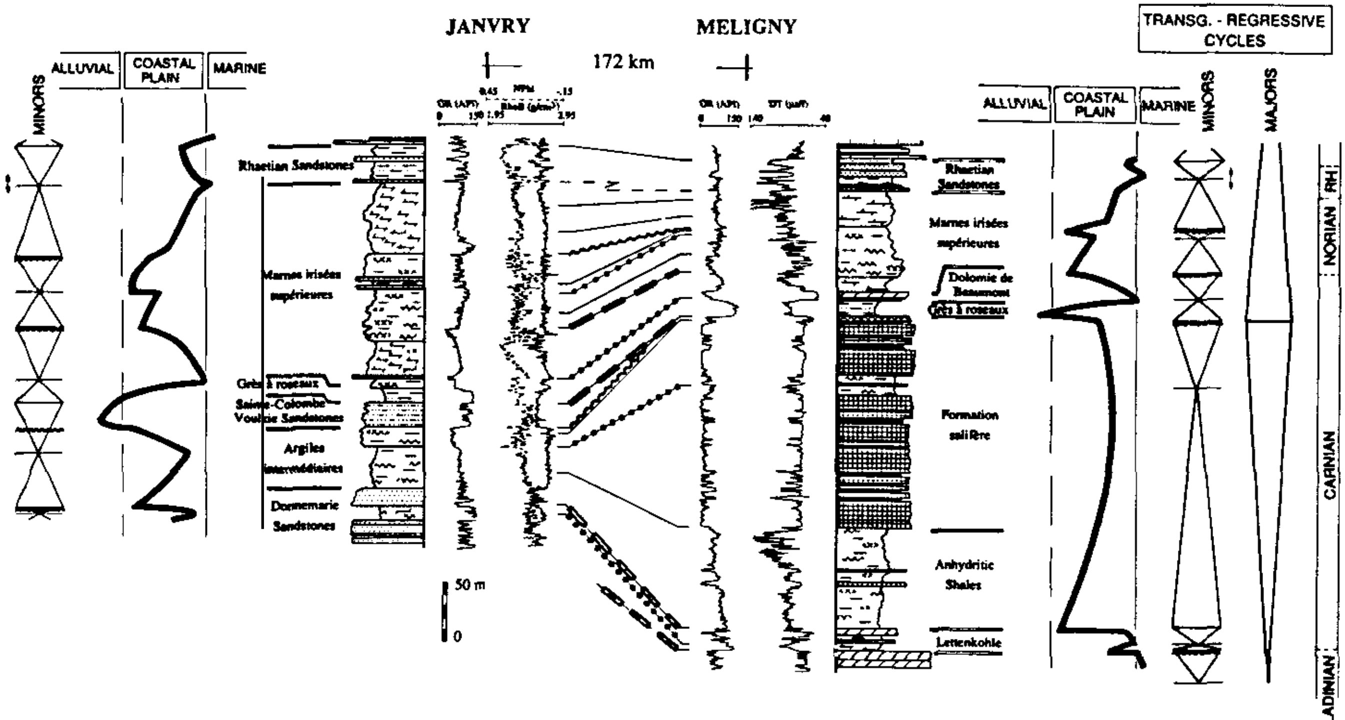
The upper part of the «Marnes irisées supérieures» is made up of dolomitic coastal plain facies alone grading upwards into the restricted marine deposits of the Rhaetian Sandstones which display some limited open marine influences (Figs. 8, 9). Correlations show that the Rhaetian boundary is a diachronous facies boundary between a coastal plain and a restricted marine environment within a transgressive trend (Figs. 8, 9, 10). The regressive trend is recorded in the upper part of the Rhaetian, characterized by the continental deposits of the «Argiles de Levallois» (Al Khatib, 1976).

COMPARISON OF THIRD ORDER TRIASSIC SEQUENCES IN THE PARIS AND GERMAN BASINS

The third order Triasic sequence described above may be compared with the sequences descibed by Aigner & Bachmann (1992).

Figure 8.—E-W section of the Keuper between Nancy and south-west of Paris: depositional sequence geometries-relationship between time-lines and facies (after Bourquin & Guillocheau, 1993, modified). A: unconformity; B: flooding surface of the third order sequences; C: maximum flooding surface (MFS) of third order sequences; D: maximum flooding surface of groups of genetic units; E: facies boundary; 1: anhydritic coastal plain; 2: dolomitic coastal plain; 3: halitic coastal plain; 4: alluvial plain and coastal plain with anastomosing and meander channels; 5: alluvial plain and fluvial system; 6: restricted marine environment of Rhaetian Sandstones; 7: dolomitic paleosols; 8: basement; NO: Norian; R: Rhaetian. FMe: Meuse fault; FA: Aire fault; FAi: Aisne fault; FHM: Haute-Marne fault; FM: Marne fault; FSMB: Saint-Martin de Bossenay fault; FS: Seine fault.

Figura 8.—Corte E-W del Keuper entre Nancy y el suroeste de París: geometría de las secuencias deposicionales y ralación entre líneas-tiempo y facies (Modificada de Bourquin & Guillocheau, 1993). A: dicontinuidad; B: superficie de inundación de las secuencias de tercer orden; C: superficie de inundación máxima de las secuencias de tercer orden (MFS); D: superficie de inundación máxima de grupos de unidades genéticas; E: límites de facies; 1: llanura costera anhidrítica; 2: llanura costera dolomítica; 3: llanura costera halítica; 4: llanura costera y llanura aluvial con canales anastomosados y meandriformes; S: llanura aluvial y sistema fluvial; 6: medio marino restringido de las areniscas Retienses; 7: paleosuelos dolomíticos; 8: basamento; NO: Noriense; R: Rhetiense; FMe: Falla del Meuse; FA: Falla de Aire; FAi: Falla de Aisne; FHM: Falla del Alto Marne; FM: Falla del Marne; FSMB: Falla de Saint-Martín de Bossenay; FS: Falla del Sena.


JANVRY
MELIGNY
172 km
ALLUVIAL
COASTAL PLAIN
MARINE
MINORS
MAJORS
TRANSG. - REGRESSIVE CYCLES
GR (API)
NPM
RhoB (g/cm³)
DT (µs/f)
Rhaetian Sandstones
Marnes irisées supérieures
Grès à roseaux
Sainte-Colombe
Voulzie Sandstones
Argiles intermédiaires
Donnemarie Sandstones
Dolomie de Beaumont
Formation salifère
Anhydritic Shales
Lettenkohle
50 m
0
RH
NORIAN
CARNIAN
LADINIAN

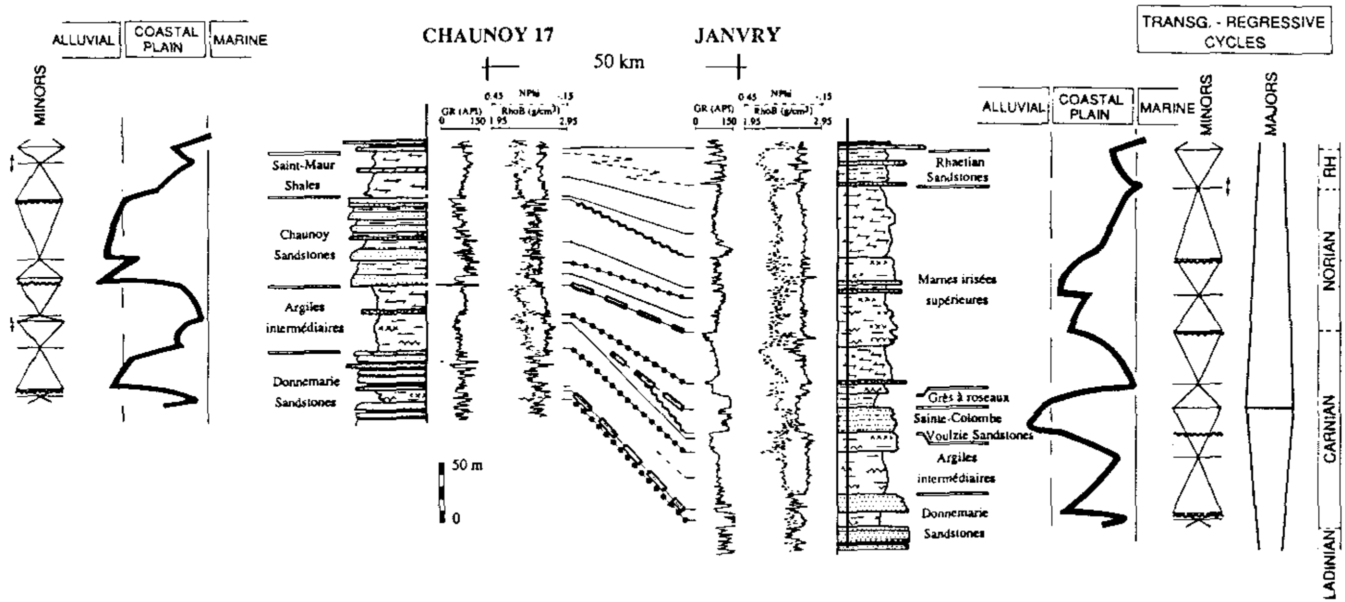
During the Buntsandstein, the first sequence of these authors (Lower Buntsandstein) corresponds to «Grès d'Annweiler» and the basal part of the «Grès vosgien» (Courel *et al.*, 1980, Friedenberg, 1994), and thus it appears that the unconformity between the «Grès d'Annweiler» and the «Grès vosgien» does not occur in the German Basin (Friedenberg, 1994). The second sequence («Volpriehausen» Formation), within the «Grès vosgien», is not found in the Paris Basin (Friedenberg, 1994). The third sequence («Detfurth» and «Hardegsen» Formations) is thought to correspond to the «Conglomérat principal» (Courel *et al.*, 1980) and is not recorded in the Paris Basin. The fourth sequence («Solling» Formation) is considered to be an equivalent of the «Couches intermédiaires» (Courel *et al.*, 1980, Friedenberg, 1994) and features a most spectacular unconformity, often characterized by a paleosol. This unconformity is not recorded in the eastern part of the Paris basin. Paleosols («Couches violettes») are found below the «Couches intermédiaires» and their base corresponds to an acceleration of the base level rise (Friedenberg, 1994). Consequently these third and fourth sequences are equivalents of the «Conglomérat principal»-«Couches intermédiaires» sequence. The basal part of the fifth sequence («Röt» Formation) is an equivalent of the «Grès á voltzia» (Friedenberg, 1994). In the Paris Basin, this sequence continues into the Muschelkalk, and there is no unconformity between the Buntsandstein and the Muschelkalk. The «Grès à voltzia»-«Complexe de Vollmunster» sequence may be an equivalent of the fifth sequence of the Buntsandstein and the first sequence of the Muschelkalk (Lower Muschelkalk).

The maximum flooding surface of the second sequence of the Muschelkalk (Middle and Upper Muschelkalk) in the German Basin is an interval termed the «cycloïdes-Bank» which is an equivalent of the maximum flooding surface of the top of the «Calcaires à Cératites» in the Paris Basin.

During the Keuper sedimentation, the regional pattern of coastal onlap exhibits many similarities between the Paris and German Basins. But the Triassic succession is more complete in the German Basin where more cycles have been observed within the Ladinian and the Norian. The

Figure 9.–Lithostratigraphy, variations of sedimentary environments and ordering of depositional sequences in two wells characteristic of the east and central parts of the Paris Basin. See figures 2 and 8 for location. RH: Rhaetian.

Figura 9.–Litostratigrafía, variaciones de medios de sedimentación y ordenación de las secuencias deposicionales en dos sondeos característicos de las zonas oriental y central de la Cuenca de París. Ver figuras 2 y 8 para la localización. RH: Rhetiense.


CHAUNOY 17
JANVRY
50 km
ALLUVIAL
COASTAL PLAIN
MARINE
MINORS
MAJORS
TRANSG. - REGRESSIVE CYCLES
GR (API)
NPhi
RhoB (g/cm³)
Saint-Maur Shales
Chaunoy Sandstones
Argiles intermédiaires
Donnemarie Sandstones
Rhaetian Sandstones
Marnes irisées supérieures
Grès à roseaux
Sainte-Colombe
Voulzie Sandstones
Argiles intermédiaires
Donnemarie Sandstones
50 m
0
RH
NORIAN
CARNIAN
LADINIAN

Lettenkohle sediments record only one sequence in the Paris Basin, whereas the equivalent Lettenkeuper (Courel *et al.,* 1980) is a record of two sequences in the German Basin (first and second sequence of the Keuper). The «Grès à roseaux»-«Dolomie de Beaumont» sequence is the equivalent of the third sequence («Schilsandstein» and «Untere Bunte Mergel»). The maximum flooding surface of the «Dolomie de Beaumont» is an equivalent of the «Hauptsteinmergel» (Aigner & Bachmann, 1992). During the Norian, a truncation in the Paris Basin disturbs the sequence record, and consequently it is very difficult to establish a comparison between the two sequences found in the Paris Basin and the three sequences described in the German Basin. The major difference between these two basins during the Keuper is that the «Marnes irisées inférieures» sequence does not occur in the German Basin and that the entire «Gipskeuper» is part of a regressive trend.

NATURE OF STRATIGRAPHIC CONTROL

Second order transgressive-regressive cycles record variations in the rate of subsidence both in time and in space. The maximum rate of subsidence for the Scythian cycle and the transgressive trend of the Scythian-Carnian cycle is limited by the Haute-Marne fault in the east of the Paris Basin (Figs. 4, 6). During, the regressive trend of the Scythian-Carnian cycle, the area with the highest rate of subsidence is bounded to the east by the Saint Martin de Bossenay Fault (Fig. 8). The maximum rate of subsidence for this latter cycle occurs during the deposition of the «Marnes irisées inférieures». During the Carnian-Lias cycle, subsidence was uniform across what is now the Paris Basin (Fig. 8). Geographically, the area of the highest rate of subsidence moved westwards during this cycle. This is a transitional period in which the maximum of subsidence shifts westward to form an independent Paris Basin and no longer simply the western margin of the German Basin. Stratigraphically, this is the beginning of the subsidence in the west which increased progressively to reach a maximum during the Upper Pliensbachian.

Figure 10.–Lithostratigraphy, variations of sedimentary environments and ordering of depositional sequences in two wells characteristic of the central and west parts of the Paris Basin. See figures 2 and 8 for location. RH: Rhaetian.

Figura 10.–Litostratigrafía, variaciones de medios sedimentarios y ordenación de secuencias deposicionales en dos sondeos característicos de las zonas central y oriental de la Cuenca de París ver figuras 2 y 8 para la localización. RH: Rhetiense.

During the transgressive trend of the Buntsandstein, the geometric relations (unconformities) or changes in sedimentary polarities, show a structural controle of third order sequences. The «conglomérat principal»-«Couches intermédiaires» sequence is unconformable on the «Grès vosgien» and shows a proximal-distal polarity westward. This sequence records a change in rate of accomodation which would initiate on satellite Metz fault (Fig. 4). The «Grès à Voltzia»-«Complexe de Vollmunster» sequence shows an inversion of the distal-proximal polarity (from westwards to eastwards) with respect to the «Conglomérat principal-Couches intermédiaires» sequence. The deformation resulting are medium and long wavelenghts, not in relation with the faults at the scale of the transect.

During the Keuper, two phases of tectonic movements control the distribution of the depocenters (Fig. 8). The first one is recorded in the «Marnes irisées inférieure» deposits: the activation of Hercynian faults controlled evaporite sedimentation and sequence arrangements by creating areas of subsidence where halite could accumulate. The second, within the «Marnes irisées supérieures», induced a general westward tilt of the basin with migration of depocenters to the west inducing intra-«Marnes irisées supérieures» truncation.

This study shows the lack of major extensional movements during this first phase of formation of the Paris Basin because no tilting exists during the deposition of salt and only a slight truncation occurs within the «Marnes irisées supérieures» Formation.

CONCLUSIONS

High resolution correlation (genetic stratigraphy) is a fundamental tool for a geodynamic study of sedimentary basins. The Triassic series is divided into nine third order sequences separated by unconformities or more frequently by their correlative conformities. These appears to have been a lack of major extensional movements during the first phase of formation of the Paris Basin. The similarity of local tectonic events in the Paris Basin and in other Triassic peritethyan basins (Aigner & Bachmann, 1992, Dromart *et al.,* 1992) may have been induced by tectonic events on the scale of the west European Craton.

Furthermore, these results demonstrate the complex evolution of the Paris Basin which appears to have been multiphased, with numerous fluctuations in the ráte of subsidence (Guillocheau, 1991) and with no real extensional phase during the Triassic.

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