Bull. Soc. géol. Fr., 2003, t. 174, nº 1, pp. 93-100

Quantification of the control of sequences by tectonics and eustacy in the Dniepr-Donets Basin and on the Russian Platform during Carboniferous and Permian

ALAIN IZART[1], YVES LE NINDRE[2], RANDELL STEPHENSON[3], DENIS VASLET[2] and SERGEI STOVBA[4]

Key words. – Tectonic subsidence, Carboniferous, Permian, Moscow Basin, Dniepr-Donets Basin, East European Platform.

Abstract. – A comparative quantitative analysis of late Paleozoic subsidence in the Moscow and Dniepr-Donets basins provides additional insight into the relative importance of tectonics and eustacy as sedimentation driving forces. Late Devonian rifting clearly displayed in the Dniepr-Donets Basin and underlying Precambrian East European Craton probably also affected the Moscow Basin. After this episode, however, the history of both basins diverged ; rifting processes ceased in the Moscow Basin but continued in the Dniepr-Donets Basin. The Moscow Basin is an intracratonic basin that can be modelled with a lithospheric heating phase from Devonian to Bashkirian times and a subsequent cooling phase generating thermal subsidence from Moscovian to Asselian times. The Dniepr-Donets Basin is a rift basin displaying an initial rifting phase during the late Devonian, an initial phase of post-rift evolution from the Tournaisian to the base of late Viséan, and a second rifting phase, seen mainly in the Donets and Donbas segments only, from late Viséan to Asselian times. Subsequent subsidences ended with uplift during the Sakmarian and were overprinted by compressional tectonics during Mesozoic and Cenozoic times. A comparison of local and global second-order stratigraphic sequences, allowing an estimation of the ratio of the importance of eustatic to tectonic processes controlling subsidence in each basin, demonstrates that eustacy controlled sedimentation in the Moscow Basin and tectonics prevailed in the Dniepr-Donets Basin.

Quantification du contrôle des séquences par la tectonique et l'eustatisme dans le bassin du Dniepr-Donets et sur la plate-forme russe pendant le Carbonifère et le Permien

Mots clés. – Subsidence tectonique, Carbonifère, Permien, Bassin de Moscou, Bassin du Dniepr-Donets, Plate-forme Est-européenne.

Résumé. – **Introduction.** – Une analyse quantitative comparative de la subsidence dans les bassins d'âge paléozoïque supérieur de Moscou (MB) et du Dniepr-Donets (DDB) apporte une vision nouvelle sur l'importance relative de la tectonique et de l'eustatisme comme contrôle de la sédimentation et du fonctionnement de ces bassins. Les résultats publiés sur le segment du Dniepr [Stovba *et al.*, 1995 ; van Wees *et al.*, 1996] sont comparés à de nouveaux résultats provenant du MB et de la partie orientale du DDB (segments du Donets et du Donbass) en utilisant le programme AQUASUB du BRGM.

Le bassin de Moscou (MB). – Le MB est situé dans la partie occidentale de la plate-forme russe (fig. 1). Le Carbonifère (fig. 2) y est représenté par environ 650 m de sédiments principalement carbonatés d'origine marine. Une lacune stratigraphique et une érosion importante y sont connues entre le Serpukhovien et le Bashkirien supérieur. La figure 2 présente les séquences du second ordre du MB [Briand *et al.*, 1998] et leur corrélation avec les séquences glaciaires et interglaciaires du Gondwana [Lopez-Gamundi, 1997]. La subsidence totale du Carbonifère (courbe SUTO, fig. 3A) est d'environ 750 m et la subsidence tectonique sous eau (courbe SUTE, fig. 3A) est d'environ la moitié de cette valeur. Deux phases de subsidence sont identifiables : la première du Tournaisien au Bashkirien inférieur avec un faible taux de subsidence tectonique (2 m/Ma) et la seconde du Bashkirien supérieur à l'Assélien avec un taux un peu plus important de subsidence tectonique (22 m/Ma). La méthode proposée par Middleton [1980] pour les bassins intracratoniques américains fut utilisée pour modéliser la subsidence tectonique observée dans le MB (fig. 3B). Le modèle est caractérisé par une phase de subsidence initiale plus faible pendant la période de chauffage de la lithosphère que lors de la seconde phase de subsidence thermique pendant le refroidissement de la lithosphère. Le rapport entre la variation eustatique du niveau marin (DSLE, fig. 3A) et la subsidence tectonique à l'air libre (SUAL) permet de calculer le rapport eustatisme/tectonique (E/T) qui est égal à 4 en faveur de l'eustatisme pendant la première phase et à 0,3 à l'avantage de la tectonique pendant la deuxième phase. La phase de subsidence 1 correspond aux séquences du second ordre D, 0 et I et la phase 2 aux séquences II à VII.

[1]Sciences de la Terre, Université de Nancy I, UMR CNRS 7566, B.P. 239, 54506 Vandœuvre-lès-Nancy, France, E-mail : Alain.Izart@g2r.u-nancy.fr
[2]BRGM, SGN/GEO, B.P. 6009, 45060 Orléans cedex 2, France.
[3]Netherlands Research School of Sedimentary Geology, Vrije Universiteit, Amsterdam, The Netherlands.
[4]Ukrgeofyzika, Zapadinskaya Street, Kiev, Ukraine.
Manuscrit déposé le 31 août 2001 ; accepté après révision le 27 juin 2002.

Le bassin du Dniepr-Donets (DDB). – Le DDB est un rift situé entre deux massifs précambriens et est divisé en différents segments, appelés Pripyat, Dniepr, Donets et Donbass (fig. 1). Le DDB présente environ 14 km de sédiments principalement terrigènes dans le segment du Dniepr et environ 21 km dans le Donets et Donbass, d'âge dévonien moyen à sakmarien [Izart *et al.,* 1996 ; 1998]. La couverture d'âge mésozoïque et cénozoïque a une épaisseur de 2 km excepté dans le Donbass où elle a été érodée. Une subsidence tectonique maximale d'environ 3,4 km fut calculée dans le Dniepr par van Wees *et al*., [1996]. Selon ces auteurs, le segment du Dniepr présente une phase de rifting initiale pendant le Dévonien supérieur et une phase post-rifting du Carbonifère inférieur à la base du Mésozoïque avec quelques rajeunissements, suivie par une inversion tectonique. A la limite entre le segment du Donets et du Donbass nous avons calculé une subsidence totale de 22,8 km et une subsidence tectonique d'environ 6,1 km (fig. 3C). Deux phases tectoniques peuvent être distinguées : la première du Dévonien au Carbonifère inférieur qui présente un taux moyen de subsidence tectonique de 40 m/Ma correspond à la phase du rifting initial et du début de la phase post-rifting du Dniepr et la seconde phase de rifting du Viséen supérieur à l'Assélien qui présente un taux important de subsidence tectonique de 90 m/Ma correspond aux rajeunissements du segment du Dniepr. Un soulèvement a lieu au Sakmarien, puis une compression pendant le Trias supérieur et à la limite Crétacé-Tertiaire [Stovba et Stephenson, 1999]. La subsidence tectonique fut modélisée (fig. 3D) en utilisant la méthode de Royden et Keen [1980]. Les deux phases tectoniques, appelées rifting 1 et 2, furent modélisées successivement. Les facteurs d'extension crustale (δ) sont respectivement pour les deux phases de 1,18 et 3,5 et les facteurs d'extension sous-crustale (β) de 1,1. Le rapport E/T est de 0,24 en faveur de la tectonique pendant la phase 1 et de 0,03 pendant la phase 2. La phase 1 correspond aux séquences du second ordre D et 0 et la phase 2 aux séquences I à VII (fig. 2). Les segments du Dniepr, Donets et Donbass possèdent donc les mêmes caractéristiques tectoniques, avec une intensité plus importante dans le Donets et le Donbass.

Conclusion. – Le rifting d'âge dévonien supérieur a existé dans le DDB et probablement aussi dans le MB. L'histoire de ces deux bassins diverge ensuite avec la poursuite du rifting dans le seul DDB. Le MB est un bassin intracratonique qui peut être modélisé avec une phase de chauffage du Dévonien au Bashkirien et une phase de refroidissement engendrant une subsidence thermique du Moscovien à l'Assélien. Le DDB est un rift montrant une première phase de rifting durant le Dévonien supérieur, une phase post-rift jusqu'au Viséen supérieur et une deuxième phase de rifting jusqu'à l'Assélien uniquement dans les segments du Donets et Donbass. Si l'eustatisme contrôle la sédimentation dans le MB, la tectonique prévaut dans le DDB.

INTRODUCTION

A comparative quantitative analysis of late Paleozoic subsidence in the Moscow (MB) and Dniepr-Donets (DDB) basins (fig. 1) provides additional insight into the relative importance of tectonics and eustacy as a driving force for sedimentation and basin development. The goal of this paper is a comparison between already published results for the Dniepr segment of the DDB [Stovba *et al.*, 1995 ; van Wees *et al.*, 1996], and new results presented for the MB and south-easternmost part of the DDB at the boundary between the Donets segment and the proximal part of the adjoining Donbas Foldbelt using the BRGM's AQUASUB program.

Although different computer programs have been utilized, their fundamental principles are similar, being those of the well-known backstripping techniques developed by Sleep [1971] and applied at the North Atlantic margin by Watts and Ryan [1976]. The new results are based on stratigraphic data from boreholes, synthetic lithostratigraphic cross-sections, and depth-converted seismic sections. Absolute ages of backstripped units are known or interpolated according to available biostratigraphic and geochronological data. According to Hess *et al.* [1999] and Menning *et al.* [2001], the weathering of tonsteins prevents to date precisely the sediments of the Donets Basin. Sediment decompaction was carried out using standard porosity-depth relations for those lithologies encountered in each unit [e.g. Steckler and Watts, 1978]. Paleobathymetry was inferred from original paleo-environmental assessments. Eustatic curves for the late Paleozoic were compiled from various eustatic charts, in particular Ross and Ross [1987, 1988], with some modifications. The particular variant employed had the specific purpose of obtaining a long-range curve displaying a lowstand during the early Viséan and Bashkirian and a highstand in the Tournaisian, late Viséan, and Moscovian. The results are presented as curves for total basement subsidence as well as only the tectonic component of basement subsidence, in each case without corrections for paleobathymetric and eustatic effects.

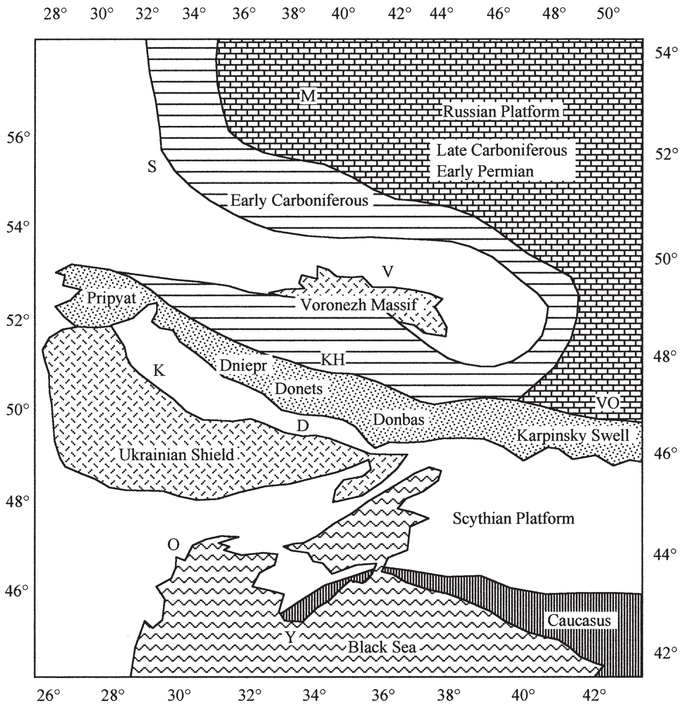

FIG. 1. – Location map showing the Moscow and Pripyat-Dniepr-Donets-Donbas basins. D : Donetsk, K : Kiev, KH : Kharkov, M : Moscow, O : Odessa, S : Smolensk, V : Voronezh, VO : Volgograd, Y : Yalta.
FIG. 1. – *Carte de localisation des bassins de Moscou et du Pripyat-Dniepr-Donets-Donbass*

THE MOSCOW BASIN (MB)

Basin fill

The Moscow Basin (MB) is located in the western part of the Russian Platform (fig. 1). The entire Carboniferous system (fig. 2) is represented by about 650 m of mainly carbonate sediments. The synthetic stratigraphic log was built from quarry and borehole data from the Moscow area [Makhlina *et al.*, 1993 ; Alekseev *et al.*, 1996 ; Briand *et al.*, 1998]. The Tournaisian, Viséan and Serpukhovian successions are marine or lagoonal and consist of alternations of limestones and terrigenous sediments. Limnic coals are known during the early Viséan. There is a significant erosional unconformity at the Serpukhovian-Bashkirian boundary. The late Bashkirian is known from one paleovalley only that is filled with continental deposits. Moscovian, Kasimovian, and Gzhelian sediments consist of interbedded carbonate and terrigenous deposits. The paleo-environment is mainly marine, with depth of deposition less than 50 m. Briand *et al.* [1998] and Izart *et al.* [2002] have published the sequence stratigraphy of the MB using the available sedimentological and biostratigraphic data.

Figure 2 shows a correlation of the second order sequences of the MB with those that are known elsewhere in the world linked with Gondwanan glaciation and deglaciation events [Lopez-Gamundi, 1997]. In the Moscow Basin, the first second order sequence (labelled D) in figure 2 occurs from the Eifelian to the Frasnian with its transgression maximum (MF) in the Frasnian ; the second (labelled 0) is Famennian to Tournaisian with a lowstand during Famennian and MF during the Tournaisian ; the third (labelled I) is Viséan to Serpukhovian with a lowstand during early Viséan and MF during the late Viséan and the Serpukhovian ; the fourth (II), of Bashkirian age is unknown in the Moscow Basin ; the fifth (III) is of late Bashkirian and Moscovian age with MF during the late Moscovian ; the sixth (IV) is Kasimovian ; the seventh (V) is Gzhelian ; and the eighth (VI-VII) is of Asselian and Sakmarian age with MF during the Asselian followed by regression during the Sakmarian.

Tectonic subsidence analysis

No quantitative analysis of the subsidence of the Devonian succession of the MB has been made. However, it is noted that Alekseev *et al.* [1996] described evidence for a rifting

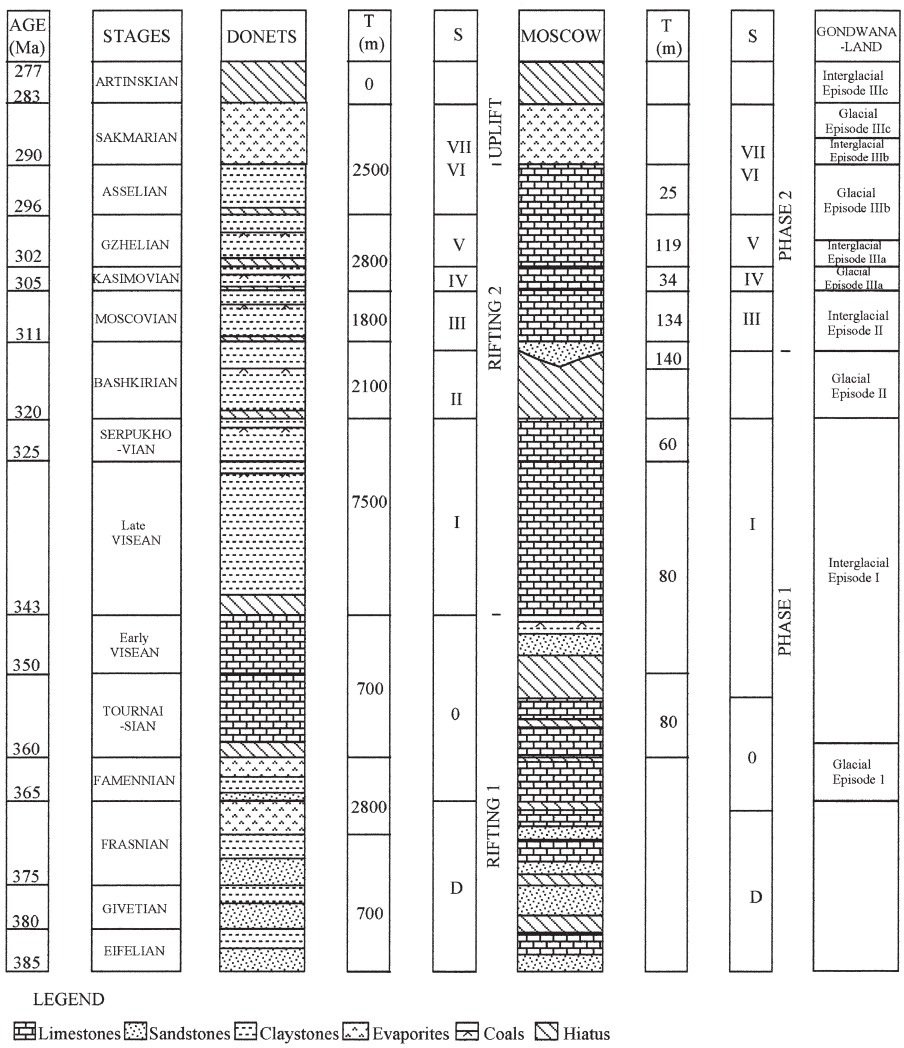

FIG. 2. – Lithostratigraphy, chronostratigraphy, thickness and second order sequences of the Devonian, Carboniferous and Permian in the Donets and Moscow basins. T : thickness, S : second order sequences

FIG. 2. – *Lithostratigraphie, chronostratigraphie, épaisseur et séquences du second ordre du Dévonien, Carbonifère et Permien dans les bassins du Donets et de Moscou.* T : *épaisseur,* S : *séquences du second ordre*

phase near Smolensk during the Eifelian followed by an uplift event from Givetian to Famennian times.

The total Carboniferous subsidence in the MB is about 750 m with the tectonic subsidence being about half of this (curves SUTO and SUTE in fig. 3A, respectively). The tectonic subsidence rate is low during the Tournaisian (3 m/m.y.), decreasing further during the Viséan (1.5 m/m.y.) until the Bashkirian unconformity that is to correspond with uplift in this area. In the late Bashkirian, the apparent tectonic subsidence rate increases to its maximum (56 m/m.y.) and then decreases from the Moscovian (41 m/m.y.) until the early Permian (14 m/Myr during the Kasimovian and Gzhelian, 1.5 m/m.y. during the Asselian). Two subsidence phases are identifiable : the first from the Tournaisian to the early Bashkirian with a low average rate of tectonic subsidence (2 m/m.y.) and the second from the late Bashkirian to the Asselian, exhibiting a higher average rate of tectonic subsidence (22 m/m.y.).

Subsidence model

The method proposed by Middleton [1980] for the Michigan and Illinois intracratonic basins was used to model the tectonic subsidence observed in the Moscow Basin (fig. 3B). The Middleton model differs from the model of McKenzie [1978] in that it includes subsidence caused by deep crustal metamorphism taking place during the latter part of an initial lithospheric heating phase. Accordingly, the model is characterized by an initial phase with a lower rate of subsidence than a subsequent, thermal-contraction driven subsidence phase. In the Moscow Basin model, the initial (heating) phase lasts for 100 m.y. until the early late Carboniferous (up to 312 Ma). This ceased during the late Bashkirian, with the acceleration of subsidence that is the manifestation of thermal subsidence during the cooling period. The thermal anomaly at the base of the lithosphere in the model during the heating phase was estimated to 130°C.

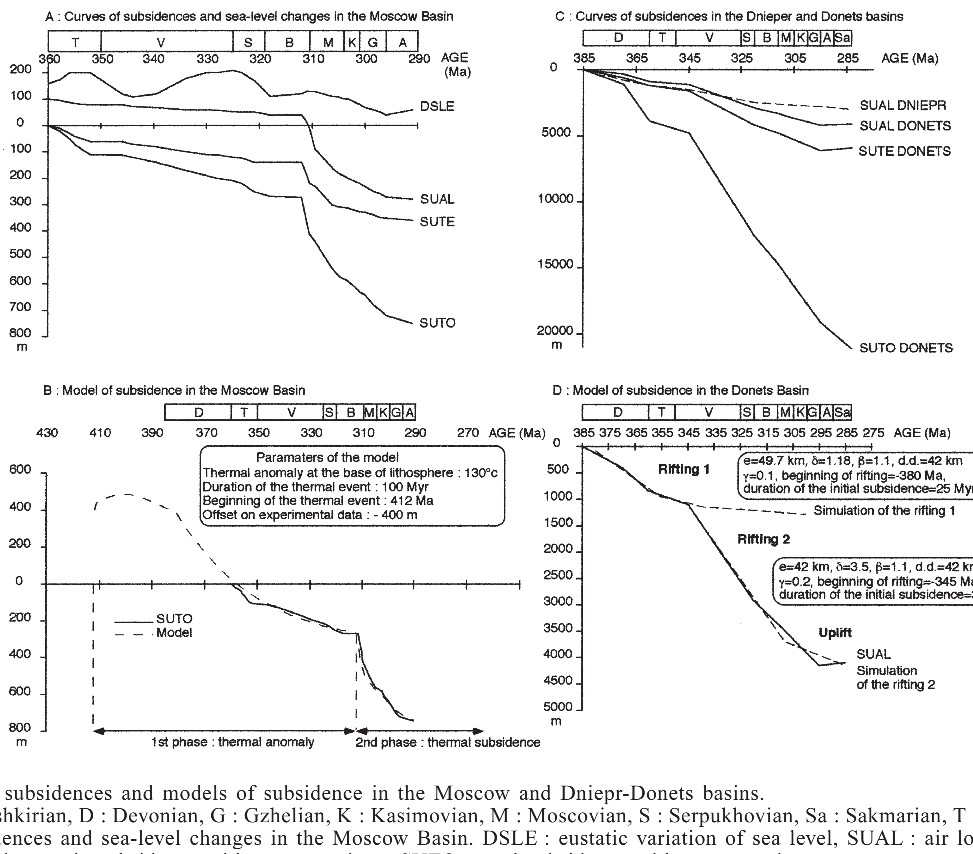

FIG. 3. – Curves of subsidences and models of subsidence in the Moscow and Dniepr-Donets basins.
A : Asselian, B : Bashkirian, D : Devonian, G : Gzhelian, K : Kasimovian, M : Moscovian, S : Serpukhovian, Sa : Sakmarian, T : Tournaisian, V : Viséan.
A : curves of subsidences and sea-level changes in the Moscow Basin. DSLE : eustatic variation of sea level, SUAL : air loaded tectonic subsidence, SUTE : water loaded tectonic subsidence without corrections, SUTO : total subsidence without corrections.
B : model of subsidence in the Moscow Basin. SUTO : total subsidence.
C : curves of subsidences in the Dniepr and Donets basins. SUAL : air loaded tectonic subsidence of Donets Basin, SUAL DNIEPR after van Wees *et al.* [1996], SUTE : water loaded tectonic subsidence of Donets Basin without corrections, SUTO : total subsidence of Donets Basin without corrections.
D : models of subsidence in the Donets Basin. SUAL : air loaded tectonic subsidence in dark line, models in dashed lines. β : factor of subcrustal extension, γ : percentage of dike δ : factor of crustal extension, d.d : depth of decoupling, e : initial thickness of the crust.
FIG. 3. – *Courbes de subsidences et modèles de subsidence dans les bassins de Moscou et du Dniepr-Donets.*
A : *Assélien*, B : *Bashkirien*, D : *Dévonien*, G : *Gzhélien*, K : *Kasimovien*, M : *Moscovien*, S : *Serpoukhovien*, Sa : *Sakmarien*, T : *Tournaisien*, V : *Viséen*.
A : *courbes de subsidences et variations du niveau marin dans le bassin de Moscou*. DSLE : *variation eustatique*, SUAL : *subsidence tectonique à l'air libre,* SUTE : *subsidence tectonique sous eau sans corrections*, SUTO : *subsidence totale sans corrections*.
B : *modélisation de la subsidence dans le bassin de Moscou*. SUTO : *subsidence totale.*
C : *courbes de subsidences dans les bassins du Dniepr et du Donets*. SUAL : *subsidence tectonique à l'air libre du bassin du Donets*, *SUAL DNIEPR d'après van Wees* et al. *[1996],* SUTE : *subsidence tectonique sous eau sans corrections bathymétriques et eustatiques du bassin du Donets*, SUTO : *subsidence totale sans corrections du bassin du Donets.*
D : *modélisation de la subsidence dans le bassin du Donets*. SUAL : *subsidence tectonique à l'air libre en ligne continue et la modélisation en pointillés*.
β : *facteur d'extension sous-crustale*, γ : *pourcentage de dike* δ : *facteur d'extension crustale*, d.d : *profondeur de découplage*, e : *épaisseur initiale de la croûte*.

Eustacy versus tectonics

During the first (Tournaisian to Bashkirian) subsidence phase in the MB the recorded tectonic subsidence rates are low compared with the inferred amplitude of eustatic sea level variation. We preferred to calculate the ratio between the maximum eustatic amplitude (curve DSLE on fig. 3A) during the subsidence phase and the air loaded tectonic subsidence (curve SUAL), named the eustacy/tectonics ratio (E/T), rather than to remove the DSLE to the SUAL [Steckler and Watts, 1978]. This ratio is equal to 4 (SUAL) in favour of eustacy during the first subsidence phase. In contrast, during the second (late Bashkirian to Asselian) phase of MB subsidence, E/T is equal to 0.3 (SUAL) in favour of tectonic subsidence. Subsidence phase 1 corresponds with second order sequences D, 0, and I (fig. 2) ; phase 2 corresponds with sequences III to VII. During the first phase, carbonate sedimentation was greater during Gondwanan interglacial episode I (Tournaisian, Viséan-Serpukhovian) than during glacial episodes I (Famennian) and II (late Serpukhovian-Bashkirian). During subsidence phase 2, carbonate sedimentation was greater during interglacial episodes II (Moscovian) and IIIa-b (Gzhelian, Asselian), corresponding with periods of rapid transgression as indicated by Vai *et al.* [2000a ; the Moscovian Peri-Tethys map] than during the glacial episodes (Kasimovian, Sakmarian). However, sedimentation ceased in the MB with a regression towards the Urals during the Artinskian [Vai *et al.*, 2000b] during the last interglacial episode IIIc (Artinskian and late Permian) of the Gondwanaland that is a period of global high transgressivity.

THE DNIEPR SEGMENT OF THE DNIEPR-DONETS BASIN (DDB)

Basin fill

The Dniepr-Donets Basin (DDB) is a rift basin from Devonian to Asselian times and located between two Precambrian massifs, the Voronezh Massif north-eastwards and the Ukrainian Shield south-westwards, and can be divided into segments, namely the Pripyat, Dniepr, Donets, and Donbas basins (fig.1). The last is contiguous with the Donets and is the uplifted and folded expression of the same.

In the Dniepr segment of the DDB up to about 14 kilometres of mainly terrigenous sediments were accumulated between the middle Devonian and the early Permian [e.g. Aisenverg *et al.*, 1975]. Basin development occurred in an intracratonic rift setting, probably related to "active" rifting processes affecting the underlying Precambrian East European Craton [e.g. Stephenson *et al.,* 2001]. The architecture of the Dniepr Basin is well controlled by numerous boreholes and seismic profiles [e.g. Stovba *et al.,* 1995 ; 1996 ; Stovba and Stephenson, 1999]. The total thickness of the Devonian succession varies from some hundreds of metres to more than 4 km with evaporites (1000 m) and Frasnian and Famennian volcanic rocks (2000 m). The early Carboniferous consists of terrigenous rocks and limestones. The late Carboniferous presents an alternation of sandstones, coals, limestones, and claystones with thicknesses increasing southeastwards towards the Donets Basin. The Early Permian is evaporitic and terrigenous. The Mesozoic succession is up to 2000 m thick and consists of marine and continental sediments. The Cenozoic is terrigenous and reaches a maximum thickness of 400 m.

Tectonic subsidence analysis

In the Dniepr Basin, numerous boreholes were decompacted and the air loaded tectonic subsidence calculated by Stephenson *et al.* [1993] and van Wees *et al.* (1996), all without paleobathymetric and eustatic corrections. The amount of tectonic subsidence is up to 3,400 m (borehole VPOL12, van Wees *et al.,* [1996], their figure 4C). The tectonic subsidence rate is high during the late Devonian (60 m/m.y.), moderate during the Carboniferous (20 m/m.y.), and low from the Permian to the Quaternary (2 m/m.y.). According to Stovba *et al.* [1995], the Dniepr Basin presents pre- and syn-rift phases during the Devonian, a post-rift phase with tectonic reactivations from the early Carboniferous to the base of the Cenozoic and a tectonic inversion at the base of the Cenozoic. These tectonic reactivations, as expressed in seismic data, correlate with extensional structures formed at the base of the late Viséan, uplift and salt tectonics at the base of the Serpukhovian, and the early Permian. Late Devonian rift-related stretching factors are moderate (β =1.1-1.5 ; Stephenson *et al.* [1993] ; van Wees *et al.* [1996]).

THE DONETS AND DONBAS SEGMENTS OF THE DNIEPR-DONETS BASIN (DDB)

Basin fill

The Donets and Donbas segments of the DDB (figs. 1 and 2) exhibit, in their centre, up to about 20,900 m of middle Devonian (Eifelian) to early Permian (Sakmarian) sediments. The Eifelian, Givetian, and early Frasnian (700 m) consist of sandstones, limestones, and shales. The late Frasnian and Famennian (2800 m) comprise evaporites, shales, and sandstones. The late Devonian succession actually can reach up to 4.5 km thickness in the most southeastern part of the uninverted part of the Donets segment. The Tournaisian and early Viséan (700 m) bear limestone ; this contrasts with early Viséan continental deposits in Moscow Basin. The Late Viséan-Serpukhovian (7500 m), Bashkirian (2100 m), Moscovian (1800 m), and Kasimovian- Gzhelian (2800 m) exhibit paralic sedimentation with alternations of shales, sandstones, limestones, and coals. The Asselian and Sakmarian (2500 m) comprise evaporites, shales, and limestones. Mesozoic and Cenozoic sediments are for the most part eroded in the Donbas segment ; 2 km of burial was assumed in the subsidence analysis by comparison with the Dniepr Basin [Stephenson *et al.*, 2001].

The paleobathymetry is thought always to be less than 50 m and is effectively zero at the end of each elementary sequence [Izart *et al.,* 1996 ; 1998]. The second order sequences [Izart *et al.*, 2002] are presented in figure 2 : the first (labelled D) is dated from the Eifelian to the Frasnian ; the second (0) occurs from the Famennian to the early Viséan with an MF during the Tournaisian and early Viséan ; the third (I) is late Viséan to Serpukhovian ; the fourth (II) is of Bashkirian age ; the fifth (III) is of late Bashkirian and Moscovian age, the sixth (IV) is Kasimovian ; the seventh (V) is Gzhelian ; and the eighth (VI-VII) is of Asselian and Sakmarian age and has an MF during the Asselian followed by a regression during the Sakmarian.

Tectonic subsidence analysis

The subsidence analysis was calculated using the lithology of a synthetic log built with geological data from boreholes and sections near Donetsk city in the Donbas segment (figs. 1 and 2, Izart *et al.* [1996 ; 1998]) with thicknesses inferred from a seismic line located in the centre of the basin along the Donets and Donbas segments [Stovba and Stephenson, 1999 ; Fig. 6]. Total basement subsidence is 22,900 m and tectonic subsidence (SUTE) is about 6,100 m (fig. 3C). The tectonic subsidence rate is moderate from the Eifelian to the Famennian (48 m/m.y.), relatively low for the Tournaisian and the early Viséan (26 m/m.y.), and high from the late Viséan to the Gzhelian (90 m/m.y.). A period of uplift begins in the early Permian.

Two main tectonic phases can be distinguished. The first takes place from Devonian to early Viséan times and displays a moderate average rate of tectonic subsidence (40 m/m.y.). This phase is correlable with the syn-rift plus initial part of the post-rift phases identified in the adjacent Dniepr segment of the DDB [e.g. Stephenson *et al.*, 2001]. The second tectonic phase occurs from late Viséan to Asselian times. It exhibits a significantly higher average apparent rate of tectonic subsidence (90 m/Myr) than the first and correlates with the main periods of post-rift extensional rejuvenation seen in the Dniepr segment.

Thereafter, uplift occurred during the Sakmarian and, in the contiguous Donbas Foldbelt, compressional deformation occurred in the late Triassic (Cimmerian phase) and latest Cretaceous-earliest Tertiary (Alpine phase) times [Stovba and Stephenson, 1999].

Subsidence model

The tectonic subsidence in the Donets Basin shown in figure 3D was modelled using the method of Royden and Keen [1980], in which there is non-uniform extension of the crust and the lithospheric mantle [cf. van Wees *et al.,* 1996]. Each tectonic phase – referred to as "Rifting 1" and "Rifting 2" in figure 3D – was modelled successively. The modelling parameters are for the rifting 1 : beginning of the rifting –380 Ma, initial thickness of the crust 49.7 km, final thickness of the crust 42 km, crustal extension factor (δ) 1.18, subcrustal extension factor (β) 1.1, depth of decoupling 42 km, percentage of dike (γ) 0.1, duration of the initial subsidence 25 m.y. The modelling parameters are for the rifting 2 : beginning of the rifting –345 Ma, initial thickness of the crust 42 km, final thickness of the crust 12 km, crustal extension factor (δ) 3.5, subcrustal extension factor (β) 1.1, depth of decoupling 42 km, percentage of dike (γ) 0.2, duration of the initial subsidence 37 m.y. The results are roughly in keeping with results from boreholes in the adjacent Dniepr segment of the DDB by van Wees *et al.* [1996], in which sub-crustal lithospheric extension becomes relatively more important in the post-early Viséan tectonic phase compared to the initial late Devonian rifting phase. Models for the evolution of extension basins predict that most of the thermal anomalies accompanying rifting vanish with a relative short time-span of 50-70 m.y. [Mc Kenzie, 1978 ; Starostenko *et al.*, 1999]. As the rifting 2 begins 35 m.y. after the beginning and only 10 m.y. after the end of the first one, the thermal state of the lithosphere is probably not totally at the equilibrium and the calculated factors of the rifting 2 are certainly biased.

Eustacy versus tectonics

In the Donets and Donbas segments, the amplitude of eustatic oscillations appears to be very gentle in comparison with the tectonic subsidence. The ratio E/T was estimated in the same way as in the Moscow Basin. This ratio is equal to 0.24 (SUAL) in favour of tectonics during the late Devonian and early Carboniferous (rifting phase 1). This ratio is equal to 0.03 (SUAL) in favour of tectonics during the Carboniferous to early Permian (rifting phase 2). The former corresponds with second order sequences D and 0 with detritic and evaporitic syn-rift sedimentation and carbonate sedimentation thereafter ; the latter corresponds with sequences I to VII, displaying a huge thickness of paralic sediments during active extension and evaporitic and continental sedimentation or uplift subsequently.

In the course of the rifting phase 1, sedimentation rate was high during the Frasnian highstand, but also during the Famennian lowstand. Note that sedimentation was medium-thicked and carbonated during the Tournaisian highstand and early Viséan lowstand. In the course of the rifting phase 2, sedimentation rate was high during Gondwanan glacial and interglacial episodes with coal bearing sequences and only some depositional gaps. Sediment accumulation ceased in this basin, just like in the Moscow Basin, at the end of the Sakmarian during the last Gondwanan interglacial episode IIIc. It follows that tectonic processes provided the main controls on sedimentation in the Dniepr-Donets Basin.

Comparison between Dniepr, Donets and Donbas segments of the DDB

The Dniepr and Donets-Donbas segments of the DDB are often referred to in the literature as two independent tectonic entities whose tectonic evolution diverged during the late Carboniferous and Permian, when both basins were thought to be separated by a set of dextral faults known as the Donets-Kharkov lineament [e.g. Popov, 1963]. Stovba and Stephenson [1999] take the opposing view that the Dniepr and Donets-Donbas segments display fundamentally the same tectonic character during this time, although post-Devonian tectonic effects are significantly more intense in the Donets and Donbas than in the Dniepr. The subsidence results are not inconsistent with this interpretation, although a lack of seismic and deep borehole data from the Donetsk region makes it difficult to propose a direct comparison of the timing of events in the Carboniferous and younger succession. New seismic data collected in 2000 should help to resolve some of the enigmatic issues surrounding the Donets Basin and contiguous Donbas Foldbelt [e.g. DOBREflection Working Group, 2001]. The role of a mantle plume during the Devonian may be a manifestation of a back-arc magmatism associated with the subduction of oceanic lithosphere at the eastern (Uralian) and/or southern (Paleo-Tethyan) margins of the East European Platform [Nikishin *et al.*, 1996]. Additional stretching and thermal thinning of the lithosphere during the Carboniferous was invoked to explain observed tectonic subsidence curve of the DDB, but refuted by the absence of arguments on seismic lines (faults) and of magmatism by Stephenson *et al.*

[2001]. The proofs of paleothermicity and magmatism during the Carboniferous and Permian must be now researched. Works in progress on organic maturity and paleothermicity will test : (1) the scenario 1 of one phase of rifting and plume activity during the Devonian and then reactivations during the Carboniferous and Permian, or (2) the scenario 2 of two phases of rifting and plume activity, the first during Devonian and the second during the Carboniferous and Permian. Nevertheless, these scenarios will be certainly difficult to test because in the Donbas segment, Sachsenhofer *et al.* [2002] observed that coalification pattern was overprinted by late Permian or Mesozoic thermal events linked with magmatic intrusions.

CONCLUSION

Late Devonian rifting clearly displayed in the Dniepr-Donets Basin and underlying Precambrian East European Craton probably also affected the Moscow Basin. After this episode, however, the history of the two basins diverged ; rifting processes ceased in the Moscow Basin but continued in the Dniepr-Donets Basin.

The Moscow Basin is an intracratonic basin that can be modelled with a lithospheric heating phase from Devonian to Bashkirian times and a subsequent cooling phase generating thermal subsidence from Moscovian to Asselian times. The Dniepr-Donets Basin is a rift basin displaying an initial rifting phase during the late Devonian, an initial phase of post-rift evolution from the Tournaisian to the earliest late Viséan, and a second rifting phase, seen mainly in the Donets and Donbas segments only, from late Viséan to Asselian times. This phase ended with uplift during the Sakmarian and was overprinted by compressional tectonics during Mesozoic and Cenozoic time.

While eustacy controlled sedimentation in the Moscow Basin, tectonics clearly prevailed in the Dniepr-Donets Basin. The driving force of rifting in the Dniepr-Donets Basin appears to be related at least in part to "active" processes in the late Devonian. This and subsequent extension may also be related to processes involved in back-arc opening behind a north-directed subduction zone in which the Paleo-Tethys ocean was subducted under the Caucasus during the Carboniferous and Permian.

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