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Geology and basin structure of the Trier–Luxembourg Basin – implications for the existence of a buried Rotliegend graben

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Abstract

This paper presents the geology of the Trier–Luxembourg Basin (TLB) in a comprehensive and updated manner. It describes the structural and lithological features of the basin, which comprises sediments of Permian to Mesozoic age. The regional geological assessment profited from recently published information on the geology and regional tectonics, as well as from borehole data from Luxembourg and adjoining areas in France, Belgium and Germany. The paper specifically focuses on the location of major synsedimentary faults and weakness zones, which gave rise to a new conceptual model of basin structure and evolution. The total depth of the basin as well as the thickness estimates of the fault-controlled subunits are supported by the interpretation of a Bouguer gravity map. In addition, the stratigraphy of the Cessange borehole and the depositional conditions of the Luxembourg Sandstone have been reinterpreted in accordance with the new concept. Supported by numerous geological cross sections it is suggested that the TLB has developed along a SW–NE trending weakness zone above a Permian Graben in direct prolongation of the Wittlicher Senke.

Zusammenfassung

Dieser Beitrag befasst sich mit einer umfassenden und aktualisierten Überarbeitung der Geologie des Trier–Luxemburger Beckens (TLB). Die strukturellen und lithologischen Merkmale des Beckens, welches Sedimente permischen bis mesozoischen Alters enthält, werden beschrieben. Die regionale geologische Neubewertung stützt sich auf kürzlich veröffentlichte Daten über die Geologie und die regionale Tektonik sowie auf Bohrdaten aus Luxemburg und den angrenzenden Gebieten in Frankreich, Belgien und Deutschland. Der Beitrag konzentriert sich besonders auf die Lage der wichtigsten synsedimentären Störungen und Schwächezonen, woraus ein neues konzeptionelles Modell der Beckenstruktur und -entwicklung abgeleitet wurde. Die Gesamttiefe des Beckens und die geschätzten Mächtigkeiten der von Störungen beeinflussten Untereinheiten werden durch die Interpretation einer Schwerekarte gestützt. Außerdem wurde die Stratigraphie der Bohrung Cessingen und die Ablagerungsbedingungen des Luxemburger Sandsteins im Einklang mit dem neuen Konzept neu gedeutet. Gestützt durch zahlreiche geologische Profilschnitte wird vorgeschlagen, dass sich das TLB entlang einer SW–NE streichenden Schwächezone über einem permischen Graben in direkter Verlängerung der Wittlicher Senke gebildet hat.

1 Introduction

In this paper, the geology of the Trier–Luxembourg Basin (TLB) is reviewed by inclusion of new data available in Luxembourg and adjoining areas. The work is performed as a necessary first step to explore Luxembourg's geothermal potential and for the assessment of the thermal field to come.

The TLB is expressed as the northeastern extension of the Paris Basin (Fig. 1), designated by the descriptive terms Gulf of Luxembourg (Golfe du Luxembourg respectively Trier–Luxemburger Bucht) or Luxembourg Syncline (Synclinal du Luxembourg). As a sub-basin of the German Triassic Basin in the early Triassic and a sub-basin of the Paris Basin since the late Triassic, the TLB progressively increased its spatial extension covering most of the older Variscan basement except the highest regions of the Ardennes in the northwest and the Rhenish Massif in the east (e.g., Lucius, 1937; Murawski et al., 1983; Dittrich, 1989). After Tertiary and Quaternary uplift and erosion, the resulting Gulf of Luxembourg is again framed by exhumed parts of the basement, namely the Palaeozoic Ardennes Massif in the north and the Eifel and Hunsrück massifs in the east (Fig. 1). The western border of the TLB is set at the Meuse valley near Verdun (Fig. 1), where its signature fades (Le Roux, 1980, 1999, 2000). The southern border of the TLB is classically associated with the Ridge of Mettlach–Sierck ("Siercker Schwelle") consisting of particularly resistant Taunus Quartzite (Fig. 2; Müller, 1973; Muller, 1987). Lithostratigraphic studies in Lorraine (e.g., Courel et al., 1980; Mouterde et al., 1980), however, reveal that the southern border of the TLB is actually located at the Metz Fault, which also correlates with a major boundary between basement structures, namely the Rhenohercynian Zone in the north and the Saxothuringian Zone in the south (e.g., Prijac et al., 2000). The presented update of geology focuses on a more restricted area including the Luxembourgish part of the basin and its adjoining areas (Fig. 1). The study area encompasses the Guttland in Luxembourg, northern Lorraine in France, the Gaume (or Lorraine belge) in southeastern Belgium as well as the Südeifel (Rhineland-Palatinate) and Saargau (Rhineland-Palatinate and Saarland) in Germany.

The geology of Luxembourg has last been addressed as a whole and integrated in a regional context by Lucius (1937, 1948). Since then, several local studies were performed mainly focusing on new geological mapping and sedimentology (e.g., Dittrich, 1989; Wagner, 1989; Konrad and Wachsmut, 1973; Berners, 1985; Muller, 1987) as well as a sedimentology-based reassessment of tectonic structures (e.g., Dittrich, 1989, 2008, 2009, 2011b, 2012). In the older literature (i.e. prior to Dittrich 1989), the TLB is classically described to have a central syncline, the so named “Mulde von Weilerbach”, forming the southwestern prolongation of the Eifel Depression (Fig. 2; e.g., Lucius, 1948; Bintz et al., 1985; Murawski et al., 1983; Muller, 1987). Detailed observations, mostly in the widely exposed series of the Keuper, by Dittrich (1989, 2011a) and Dittrich et al. (1997) describe a more complex setting leading to the rejection of the Weilerbach Mulde concept.

However, the link of this old concept with the present-day appearance of the Lower Liassic Luxembourg Sandstone and the initial interpretation of the geological section encountered by the Cessange borehole and vice-versa still remained. This paper questions these former interpretations by providing new geological insight into the basin geology based on the possibility of a southwestern prolongation of the Wittlicher Senke underneath the TLB. The new concept is based on information from a Bouguer gravity map and a reinterpretation of the Cessange borehole stratigraphy (Rost, 1839; Lucius, 1948). Additional information provided by borehole data (Table 1) from Luxembourg, France, Belgium and Germany are incorporated in a new comprehensive basin model visualized in several isopach maps and regional cross sections.

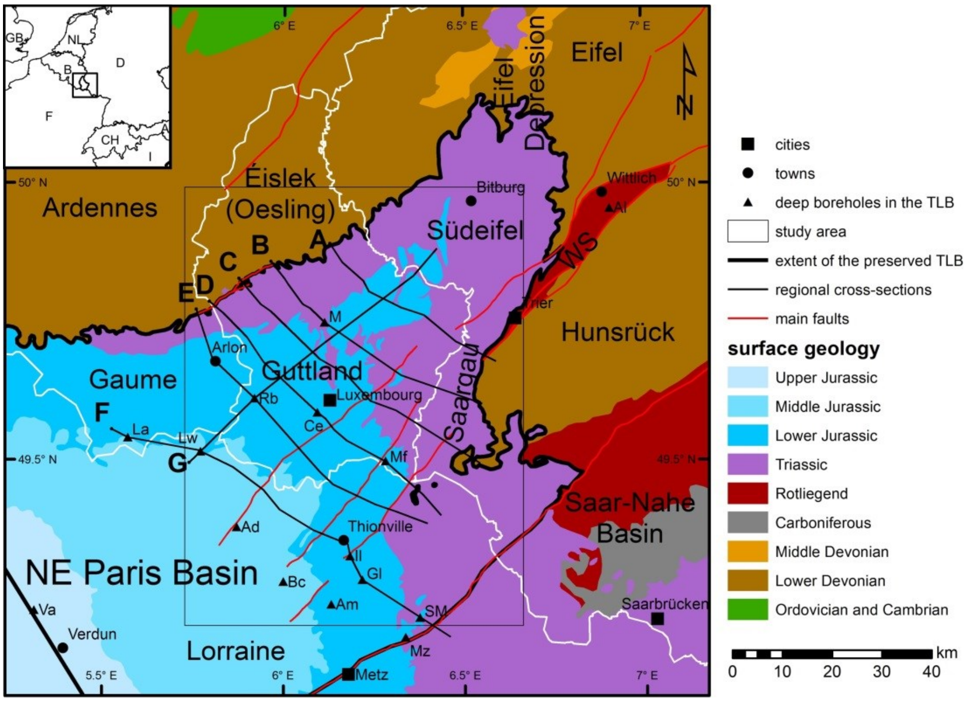


Fig. 1: Regional geological map of the study area and its surroundings with indication of the geographical units. The location of the map area within Western Europe is shown in the top left corner. National borders are shown as white lines. Black lines and bold letters correspond to the regional cross sections presented in Section 3.3. Locations of deep boreholes (Table 1) are shown with IDs.

Table 1: Deep boreholes in the TLB. The coordinates of the Cessange and Altrich boreholes are only indicative. TD = total depth, Stratigraphy refers to stratigraphy at total depth.

Borehole	ID	Year	TD	Stratigraphy	Latitude N	Longitude E	Target
Cessange	Ce	1839	534 m	Muschelkalk	49° 35.373' ?	6° 05.646' ?	rock salt
Mondorf KIND	Mf	1846	730 m	Devonian	49° 30.070'	6° 16.946'	rock salt
Altrich	Al	1890?	537 m	Permian	49° 57.423' ?	6° 54.538' ?	geology
Longwy	Lw	1908	922 m	Devonian	49° 31.117'	5° 46.217'	coal
Bois châté	Bc	1909	1100 m	Permian	49° 17.033'	6° 00.083'	coal
Mondorf ADELAIDE	Mf	1913	589 m	Buntsandstein	49° 30.109'	6° 16.985'	hydrothermal water
Vacherauville	Va	1953	2250 m	Devonian	49° 13.817'	5° 18.783'	iron, gas, oil
Audun-le-Roman	Ad	1957	1251 m	Permian	49° 22.933'	5° 52.333'	geology, oil
Metz	Mz	1961	1078 m	Devonian	49° 10.983'	6° 20.266'	geology
Mersch	M	1968	328 m	Devonian	49° 45.132'	6° 06.826'	geology, hydrogeology
Rebierg	Rb	1972	705 m	Devonian	49° 36.891'	5° 55.159'	geology, hydrogeology
Mondorf LUCIUS	Mf	1979	750 m	Devonian	49° 30.191'	6° 16.969'	hydrothermal water
Amnéville F1	Am	1979	900 m	Permian	49° 14.550'	6° 08.117'	hydrothermal water
Illange	Il	1982	538 m	Buntsandstein	49° 19.817'	6° 11.067'	oil
Guélange	Gl	1984	499 m	Buntsandstein	49° 17.250'	6° 13.133'	oil
St. Michel	SM	1985	857 m	Devonian	49° 13.133'	6° 22.667'	oil
Latour	La	1986	494 m	Devonian	49° 32.505'	5° 34.113'	geology
Amnéville F2	Am	1989	880 m	Permian	49° 14.633'	6° 07.767'	hydrothermal water

2 Background on geology

2.1 Pre-Mesozoic basement structures

The evolution of the TLB is closely associated with inherited basement structures generated in different geodynamic contexts (e.g., Lucius, 1948; Le Roux, 1980; Berners, 1985; Dittrich, 1989). The basement of the TLB, being part of the Rhenohercynian Zone of the Variscan orogen, exibits a generally northwest-vergent fold-and-thrust belt consisting mostly of Devonian series. The Ardennes and Eifel massifs in the north are separated by a north–south-oriented depression or cross-fold, the so-called Eifel Depression ("Eifeler Nord-Süd-Zone", Fig. 1). The Eifel Depression is classically seen to continue in the TLB and thus to control its evolution (Murawski et al., 1983). The rather fold-dominated Eifel and thrust-dominated Hunsrück are separated by a Permian graben, the so-called Wittlicher Senke (WS) bound by normal faults (Fig. 2). The main known thrust faults from south (-west) to north (-east) are: the Metz Fault (MF) continued northeastwards by the Hunsrück Boundary Fault (HBF), the Boppard–Dausenau–Longuich Thrust (BDLT), the Siegen Main Thrust (SMT) and the Plein Thrust (PT; Fig. 2; Kölschbach, 1986; LGB, 2005). In the Ardennes–Eifel block, the most important structures are: the Olkenbach Syncline (OSc), which is truncated by the Plein Thrust, the Givonne–Oesling–Manderscheid Anticlinorium (GAc–OAc–MAc) and the Neufchâteau–Wiltz–Eifel Synclinorium (NSc–WSc–ESc).

The late- to post-Variscan evolution of the area resulted in the formation of intramontane half-grabens such as the Permo-Carboniferous Saar–Nahe Basin (Korsch and Schäfer, 1996) and the Permian Wittlicher Senke (WS; Fig. 1; Fig. 2; Stets, 2004a). In the NW, the WS is bound by the Wittlich Main Fault (WMF; "Wittlicher Hauptverwerfung"; Kopp, 1955) which is a strike-slip fault with a throw of more than 1000 m. In the southeast, the WS is bound by the "Südrandstörung" or "südliche Randverwerfung" (also: "Störung Konz–Longuich" in [LGB and LUWG 2010]) for which a throw of 400 m is inferred (Stets, 2004b). Initially being part of a larger Permian sedimentation area (Lucius, 1948; Schäfer, 1986; Stets, 1990; LGB, 2005), the sediments of the WS are mainly preserved between the two border faults in a well-defined up to 7-km-wide and 40-km-long structure (Stets, 1990). In the Trier region (Fig. 1), the Buntsandstein and younger Mesozoic sediments overlying the Permian sediments mask the southwestern prolongation of the WS (Stets, 1990, 2004b; LGB and LUWG, 2010).

Although the main tectonic activity of the WS terminated by the end of the Rotliegend, post-Permian subsidence along the WMF also affected the Mesozoic cover in the TLB (Kopp, 1955; LGB, 2005; LGB and LUWG, 2010). According to Stets (2004b) and Dittrich (2011b), the WS was at least marginally incorporated during the formation of the TLB. However, as already mentioned, the structure and evolution of the TLB is classically assigned to the Weilerbach Mulde as a southwestern prolongation of the Eifel Depression (e.g., Lucius, 1948; Bintz et al., 1985; Murawski et al., 1983; Muller, 1987). The present-day appearance of the TLB as Gulf of Luxembourg is enhanced by the preferential preservation of the relatively resistant Luxembourg Sandstone framed by Triassic deposits in the northwest and east. The Ridge of Mettlach–Sierck, which is exposed in the Mosel valley at the southeastern tip of Luxembourg, is thereby considered to be the southern limit of the Eifel Depression (Muller, 1980). The post-Variscan tectonics is characterized primarily by fracture tectonics affecting the consolidated crust, which is well observable in the Mesozoic cover of the Südeifel (Stets, 2004b; LGB and LUWG, 2010), the Guttland (e.g., Lucius, 1948; Dittrich, 1989) and the northeastern Paris Basin (e.g., Le Roux, 2000). Whereas Variscan (N60–70°E) and Rhenish (N–S) fault systems are long known (Lucius, 1937), Dittrich (1989, 2008) reports also a SW–NE (N45°E) striking fault system. In particular the SW–NE striking faults play an important role in the TLB (Dittrich, 1989), which is also reported from the NE Paris Basin (Fig. 2; Le Roux, 1971, 1980, 2000).

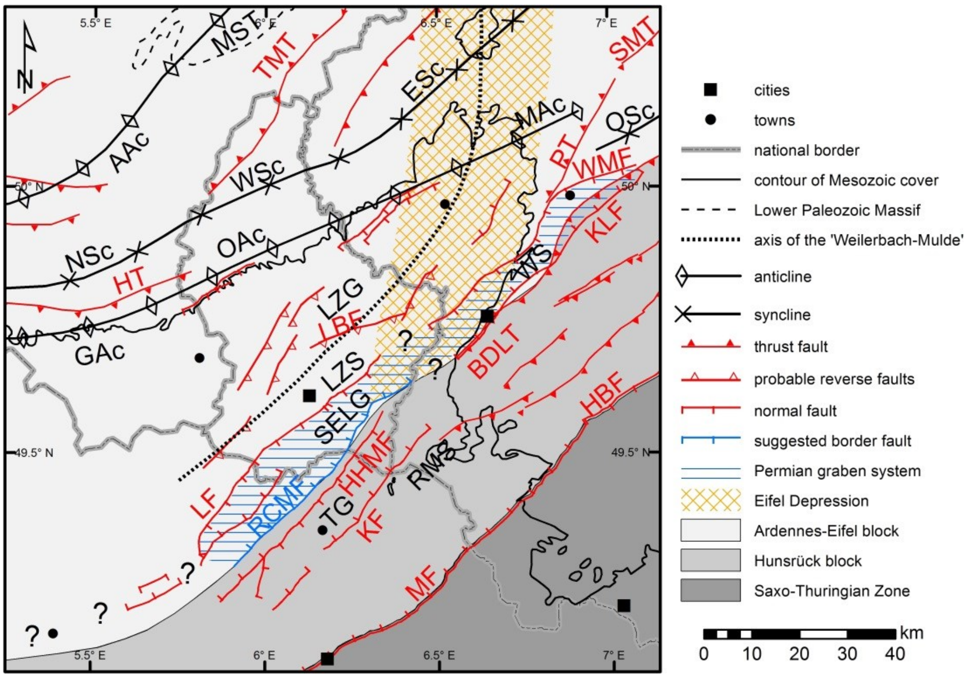


Fig. 2: Regional tectonic map with localities as in Fig. 1.

Tectonic structures: MST = Stavelot Massif, AAc = Ardenne Anticlinorium, NSc = Neufchâteau Synclinorium, WSc = Wiltz Synclinorium, ESc = Eifel Synclinorium, GAc = Givonne Anticlinorium, OAc = Oesling Anticlinorium, MAc = Manderscheid Anticlinorium, OSc = Olkenbach Syncline. TMT = Troisvierges–Malsbenden Thrust, HT = Herbeumont Thrust, SMT = Siegen Main Thrust, PT = Plein Thrust, WMF = Wittlich Main Fault, BDLT = Boppard–Dausenau–Longuich Thrust, KLF = Konz–Longuich Fault, LBF = Lorentzweiler–Bech Fault, LF = Luxembourg Fault, RCMF = Roussy-le-Village–Canach–Machtum Fault, HHMF = Hayange–Hettange–Mondorf Fault, KF = Koenigsmacker Fault, MF = Metz Fault, HBF = Hunsrück Boundary Fault, LZG = Luxemburger Zentralgraben, LZS = Luxemburger Zentralschwelle, SELG = SE-Luxembourg Graben, WS = Wittlicher Senke, TG = Thionville Graben, RMS = Ridge of Mettlach-Sierck.

2.2 Mesozoic evolution of the TLB and lithostratigraphic units

According to the present-day state of knowledge, the development of the TLB begins in the more or less N–S trending Eifel Depression where the oldest known post-Variscan deposits in Luxembourg are of Middle Buntsandstein age (e.g., Lucius, 1937; Muller, 1987). In the German Südeifel area, also deposits of Lower Buntsandstein age are known. However, limited Rotliegend is suggested underneath the TLB as reported from the Mondorf Kind borehole (Lucius, 1948). During the Triassic, progressive transgression resulted in the enlargement of the sedimentation area by roughly 50 km at the expense of the Ardennes (Lucius, 1948; Courel et al., 1980), and in the development of the so-called Germanic facies province with its tripartite subdivision into Buntsandstein, Muschelkalk and Keuper. In southern Luxembourg, the total thickness of the Triassic series amounts to more than 600 m (655 m in the Mondorf Kind borehole). During the Buntsandstein and Muschelkalk, the TLB is characterized by a marginal position in the German Triassic Basin. In this context, a distinct margin facies formed in NW-Guttland, and has also been recorded in the Rebierg and Longwy boreholes. A correlation of these typically more sandy and conglomeratic units with their counterparts in the basin facies is difficult (e.g., Lucius, 1948; Dittrich, 1989; Wagner, 1989).

The Buntsandstein, which consists typically of red-colored, fluviatile sandstone (e.g., Muller, 1987; Guillocheau et al., 2002), unconformably overlies the Devonian basement (Lucius, 1948; Dittrich, 2011a). It is largely concealed below younger units, and exposures of Upper Buntsandstein are restricted to the southern margin of the Ardennes in N-Guttland, to an anticline near Born in E-Guttland and to a small occurrence at the Ridge of Mettlach–Sierck in the Mosel valley to the south of Schengen. In the adjoining Südeifel region, the Buntsandstein shows a much more complete development and exposure. The Muschelkalk transgression results in marine conditions giving rise to the formation of the Lower Muschelkalk carbonates (mu; Table 2; Ziegler, 1982), which comprise various sandy-marly-dolomitic rock types (Dittrich, 2011a). The latter grade into Middle Muschelkalk evaporitic and dolomitic marls, typical of a lagoonal environment, and culminate in a dolomitic succession during the Late Muschelkalk. The Muschelkalk carbonate sedimentation is terminated by a regional regression (Ziegler, 1982), which triggers the return to a clastic-evaporitic environment typical for the Keuper.

In contrast to the Lower Triassic, the Keuper is characterized by a different make-up reflecting the birth of the Paris Basin (Guillocheau et al., 1999; Bourquin and Guillocheau, 1993). The intercalated sandstone channels of the Schilfsandstein (Stuttgart Fm.), which are mainly developed in E-Guttland, are an important marker for the subdivision of the overall more or less monotonous, marl-dominated series of the Middle Keuper. The heterochronous Upper Keuper (Rhaetian) marks the transition from a clastic-evaporitic environment typical for the Keuper to a marine environment typical for the Liassic.

Table 2: Stratigraphy (in part simplified) of the Mesozoic in Luxembourg and adjacent areas. Grey areas mark eroded or non-existent units.

C. = Couches, M. = Membre, Fm. = Formation.

				FRANCE (N-Lorraine)		BELGIUM (E-Gaume)			LUXEMBOURG (Guttland)				GERMANY (Südeifel + Saargau)	
				Le Roux (2007) + geological maps 1:50,000		Boulvain et al. (2001) + Belanger et al. (2002)			geological maps 1:25,000		Dittrich (1989), simplified		LGB (2005), simplified	
JURASSIC	Middle	Dogger	Bajocian	Oolithe de Jaumont	j1c1									
				Marnes de Longwy										
				Calcaires siliceux de l'Orne	j1b-a	Fm. de Longwy		LGW	Marnes sableuses d'Audun-le-Tiche	dom4				
				Calcaire à polypiers					Calcaires d'Audun-le-Tiche					
				Calcaire à entroques (ou de Haut-Pont)					Calcaire de Haut-Pont	dom3				
				Calcaire sableux (ou d'Ottange)					Calcaire d'Ottange	dom2				
				Marnes micacées (ou de Charennes)					Marnes micacées	dom1				
			Aalenian	Formation ferrifère (ou Minette)	l6	Fm. de Mont St. Martin		MSN	Minette (C. à *Graphoceras concavum*)	dou				
	Lower	Liassic	Toarcian						Minette	lo7				
									Minette	lo6				
				Grès supraliasique	l5	Fm. de Grandcourt		GRT	C. à *Pseudogrammoceras fallaciosum*	lo5				
									C. à *Grammoceras striatulum*	lo4				
				Marnes à septarias (à *Voltzi* , à *Crassum* , à *Bifrons*)					Marnes à *Astarte voltzi*	lo3				
									C. à *Hildoceras bifrons*	lo2				
				Schistes cartons (ou bitumineux)					C. à *Harpoceras falciferum*	lo1				
			Pliensbachian (Domerian)	Grès médioliasique	l4c	Fm. d'Aubange		AUB	Macigno (C. à *Pleuroceras spinatum*)	lm3b				
					l4b	Fm. de Messancy		MES	Faciès sablo-marneux	lm3a				
				Argiles à Amalthées	l4a	Fm. d'Ethe		ETH	C. à *Amaltheus margaritatus*	lm2				
			Carixian	Calcaire à *Protodactylioceras davoei*		M. de Hondelange	HON	ARL	Calcaire ocreux	lm1				
				Marnes à *Zeilleria numismalis*										
			Sinemurian	Calcaire ocreux	l3c									
				Argiles à *Promicroceras*	l3b	M. de la Posterie	POS		Marne pauvre en fossiles	li4				
				Marne de Strassen	l3a-2	M. de Strassen	STR		Marnes et calcaires de Strassen	li3			Mergel und Kalke von Strassen	li3
			Hettangian	Grès d'Hettange, du Luxembourg Calcaire à gryphées	l2G	Fm. de Florenville		FLO	Grès de Luxembourg	li2			Luxemburger Sandstein	li2
				Marnes de Jamoigne	l1b	Fm. de Jamoigne		JAM	Marnes d'Elvange	li1			Mergel von Elvange	li1
TRIASSIC	Upper	Keuper	Upper	Argiles de Levallois	li1b	Fm. de Mortinsart		MOR	Argiles de Levallois	ko2	Oberes Rhät	ko2	Rhätkeuper	koR
				Grès rhétiens	li1a				Grès de Mortinsart	ko1	Unteres Rhät	ko1		
			Middle	Argiles bariolées dolomitiques	t7e	Fm. d'Attert		ATT	Steinmergelkeuper	km3	Steinmergelkeuper	km3St	Steinmergelkeuper	kSt
				Argiles de Chanville							Rote Gipsmergel	km3R	Rote Gipsmergel	km3R
				Dolomie de Beaumont	t7d				Rote Gipsmergel	km2	Elie-de-Beaumont-Dolomit	km2E	Hauptsteinmergelschichten	km3H
				Argiles bariolées intermédiaires	t7c						Dunkle Mergel	km2D		
				Grès à roseaux	t7b				Schilfsandstein	km2S	Oberer Schilfsandstein	km2S2	Oberer Schilfsandstein	km2S2
											Unterer Schilfsandstein	km2S1	Unterer Schilfsandstein	km2S1
				Marnes irisées inférieures	t7a	Fm. d'Habay		HAB	Pseudomorphosenkeuper	km1	Pseudomorphosenkeuper	km1P	Pseudomorphosenkeuper	km1P
			Lower	Dolomie limite/ supérieure	t6c				Grenzdolomit	ku2	Grenzdolomit	ku2G	Grenzdolomit	ku2G
				Argile de la Lettenkohle	t6b				Bunte Mergel	ku1	Bunte Mergel	ku2B	Bunte Mergel	ku2B
				Dolomie inférieure	t6a				Basisschichten	ku1α	Basisschichten	ku1	Basisschichten	ku1B
	Lower	Muschelkalk	Upper						Gilsdorfer Sandstein	mos	Gilsdorfer Sandstein	mo2C	Ceratitenschichten	mo2C
				Calcaire à cératites et calcaire à térébratules	t5b				Ceratitenschichten	mo2	Ceratitenschichten			
				Calcaire à entroques	t5a				Trochitenschichten	mo1			Trochitenschichten	mo2T
			Middle	Couches blanches	t4b				Linguladolomit	mm2			Linguladolomit	mm2
				Couches grises	t4a				Gipsmergel	mm1			Gipsmergel	mm1
				Couches rouges										
			Lower	Dolomie à *Myophoria orbicularis*	t3b				Orbicularisschichten	mu2			Dolomitbankschichten	mu2
				Grès coquiller	t3a				Muschelsandstein	mu1			Muschelsandstein	mu1
		Buntsandst.	Upper	Grès à Voltzia	t2b				Voltziensandstein	so2			Voltziensandstein	soV
				Couches intermédiaires	t2a				Zwischenschichten	so1			Zwischenschichten	soZ
			Middle	Grès vosgien	t1				Vogesensandstein	sm			Höherer Hauptbuntsandstein	sHBh
			Lower										Tieferer Hauptbuntsandstein	sHBt

During the Jurassic, the sedimentation area is designated as the Luxembourg Basin (LB), instead of TLB because Jurassic deposits are at present almost completely eroded in the Trier area (Fig. 1). In the Paris Basin, the Liassic is characterized by a marine transgression from SW-Germany onto the old massifs which were already largely eroded. The sediments are generally very fine-grained, i.e. comprising clays and silts, especially in the most subsided part of the basin, and locally calcareous clays or even bioclastic limestones (Mouterde et al., 1980). The detritic material is provided from the north through the Eifel Depression (Berners, 1985). In the vicinity of the Ardennes mainland, some units are characterized by a more sandy facies, notably the Luxembourg Sandstone (li2) and the Grès médioliasique (lm3; Table 2). The Toarcian regression culminates in the uppermost Toarcian (lo6 and lo7) and Aalenian (dou) formation of oolithic ironstone known as Minette Formation in northern Lorraine and SW-Luxembourg (Bubenicek, 1961; Teyssen, 1989; Guillocheau et al., 1999). The thickness of the whole Liassic succession in the LB amounts to more than 500 m (Mégnien, 1980: map L7). In contrast to the clay- and silt-dominated Lower Jurassic, the Middle Jurassic (Dogger) sedimentation is characterized by bioclastic and reef limestones (Thierry et al., 1980).

The Mesozoic lithostratigraphic units of Luxembourg (Table 2) are addressed by the symbols widely used in the Luxembourgish geological maps (new series, scale 1:25,000). These symbols are used in this work instead of the new, more complex and detailed Upper Triassic (Keuper) stratigraphy of Dittrich (1989, 2011a) and LGB (2005), which is not yet established in Luxembourg.

3 Methodology

3.1 Interpretation of the Bouguer anomaly map

A Bouguer anomaly map of Luxembourg (Fig. 3; M. Everaerts, 2012, pers. comm.), which is based on 509 gravity measurements performed in 1996 for the Administration du Cadastre et de la Topographie (Everaerts, 1997), was used to shed light on the Mesozoic basin structure and the topography/structure of the basement. The coverage of one data point per 5 km^2 is comparable to the adjoining areas (Everaerts, 1997, 2002). The gravity points are tied to the reference point of Uccle, Belgium. The Bouguer anomalies are calculated with a standard density of 2.67×10^3 kg m^{-3} (Everaerts and De Vos, 2012: 42).

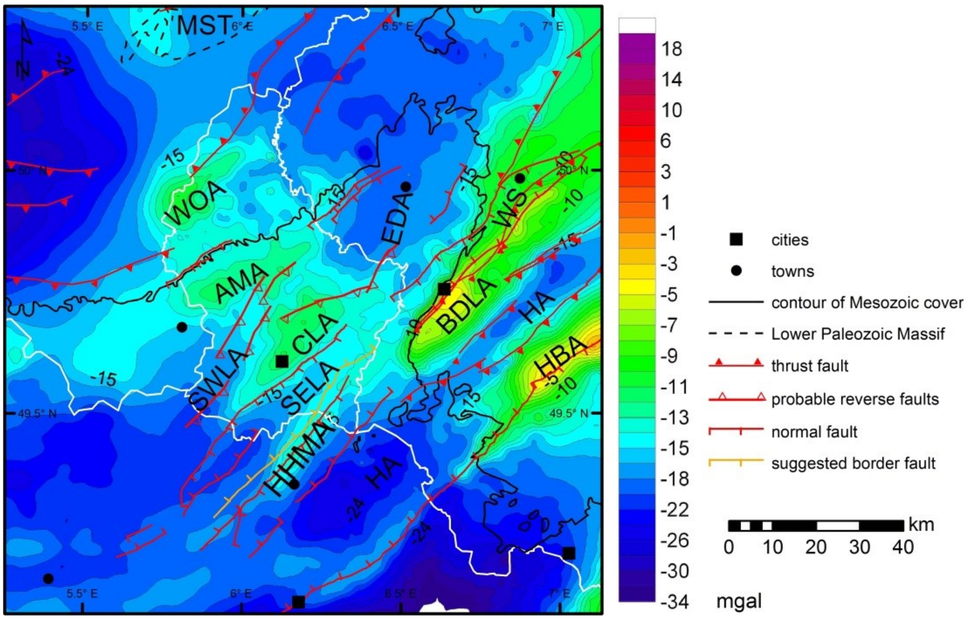


Fig. 3: Bouguer anomaly map with localities and areal extent of the TLB as in Fig. 1.
MST = Stavelot Massif, WS = Wittlicher Senke, WOA = Western Oesling Anomaly, AMA = Ardennes Margin Anomaly, CLA = Central Luxembourg Anomaly, SWLA = SW-Luxembourg Anomaly, SELA = SE-Luxembourg Anomaly, EDA = Eifel Depression Anomaly, HHMA = Hayange–Hettange–Mondorf Anomaly, BDLA = Boppard–Dausenau–Longuich Anomaly, HA = Hunsrück Anomaly, HBA = Hunsrück Boundary Anomaly.

In general, the most important Variscan structures, involving rock of different density, are well outlined by anomalies. Positive anomalies usually indicate thrusts or anticlines and negative anomalies synclines or depressions, respectively. The Bouguer map reveals the continuation of the main WSW–ENE to SW–NE striking Variscan structures below the TLB. Within the Rhenohercynian Zone, the structures belonging respectively to the Ardennes–Eifel block and Hunsrück block (Fig. 2) can thus be distinguished. The anomalies or the boundary between anomalies are often correlated with major faults observable at the surface. In addition, the Variscan structures are crossed by a more or less NW–SE arrangement of positive anomalies probably corresponding to exposed and buried Caledonian massifs, from the Stavelot Massif (Figs. 2 and 3) in the north to the CLA (Fig. 3) in the south. In contrast, the Eifel Depression is characterized by the relatively large negative anomaly EDA (Fig. 3). However, the Bouguer map also shows a fundamental problem with the “Variscan” (N60–70°E) and “diagonal” (SW–NE) structural directions in the Variscan basement first differentiated by Dittrich (1989) and defined as to have no particular genetic meaning. The anomalies and the associated main faults indicate that the Variscan direction, which is dominant in the Oesling (i.e. the Luxembourgish Ardennes) turns gradually into a dominantly

SW–NE orientation towards the south. Only to the west of Luxembourg, e.g. in the Belgian Ardennes, the structures in the Variscan orogenic belt turn into the W–E orientation (Fig. 2). This may be due to more southward contouring of more resistant, buried Caledonian massifs during the Variscan Orogeny (Autran et al., 1980; Keppie, 1994). Therefore, we put forward that both directions are actually inherently Variscan. Consequently, if not specified, by "Variscan" we mean a Variscan origin, not a Variscan direction or strike.

The Bouguer map does not only show the existence of major structures with higher density at depth, responsible for higher background gravity, but also provides hints about the depth of the basin itself when combined with available borehole data. A sufficiently thick Mesozoic succession with an average density lower than that of the basement generally produces a negative anomaly. This effect is best observed along the eastern margin of the TLB where the contrast between Mesozoic and Devonian rock also corresponds to a sharp gravimetric boundary.

Based on these findings, the Weilerbach Mulde (Fig. 2), which, in the older literature, is classically seen as the central syncline of the TLB and as the southwestern prolongation of the Eifel Depression, should have a gravimetric signature. The Bouguer map, however, shows a remarkable positive anomaly in the region classically expected to be the deepest area of the TLB (Lucius; 1948: Tafel III; Berners, 1985; Muller, 1987). This anomaly will hereafter be named Central Luxembourg Anomaly (CLA; Fig. 3). The regional context reveals that the CLA, as well as the other positive anomalies in the Variscan basement, are very likely buried Caledonian massifs similar to the exposed massifs in the Ardennes. At the surface, the CLA is well defined to the north and northwest by several fault segments and to the southeast by the so-called Luxembourg Fault (LF; Guillocheau et al., 1999) (Figs. 2 and 3), which is locally also known as Audun-le-Tiche Fault or Hesperange Fault. The LF separates the CLA from the gravity low named SE-Luxembourg Anomaly (SELA; Fig. 3), being a depositional trough, hereafter named SE-Luxembourg Graben (SELG; Fig. 2), that deepens towards the Paris Basin. Thus the Bouguer map does not indicate an independent depocentre in the Luxembourg City area with an axis traced from Weilerbach at the German border (Fig. 2), along the outcrops of thick Luxembourg Sandstone to the northwest of Luxembourg City and further to the vicinity of Longwy in the southwest. To the southeast, the narrow, but distinct, positive gravity anomaly, named Hayange–Hettange–Mondorf Anomaly (HHMA; Fig. 3), is likely linked to the Hayange–Hettange–Mondorf Fault (HHMF; Fig. 2). The northeastern prolongation of the latter structure in the Trier area likely is the so-called Boppard–Dausenau–Longuich Anomaly (BDLA; Fig. 3) which clearly is associated with the nearby thrust fault (BDLT; Fig. 2). The Wittlicher Senke does not produce a particular negative anomaly, despite an up to 1000-m-thick infill of Rotliegend (Stets, 2004a), which is probably due to the superimposed effect of a denser basement related to the BDLA.

Most importantly, the Bouguer map allows for a parallelization of buried and exposed structures. In addition to their Variscan affinity, the LF–SE-Luxembourg Graben–HHMF structure shows a remarkable similarity to the WMF–Wittlicher Senke–BDLT structure and is located in the southwestern continuation of the latter. However, in a zone of intense Tertiary and Quaternary block faulting in the German-Luxembourgish border region some Variscan basement structures are probably partially overprinted. The negative SWLA anomaly (Fig. 3) in SE-Belgium and SW-Luxembourg may be caused by lower-density rock in the basement. Alternatively, an increased sediment accumulation during the Keuper and the Lower Liassic may be responsible as documented notably in the Rebierg borehole (Dittrich, 1989). The positive AMA anomaly to the south of the border of the Ardennes (Fig. 3) may correspond to the actual axis of the Givonne–Oesling–Manderscheid Anticlinorium (Fig. 2), which would then be concealed below the Mesozoic cover, instead of being located in the southern Oesling (e.g., Dittrich and Norbisrath, 2006). A relatively small but strong positive anomaly at the Belgian-Luxembourgish border, the Western Oesling Anomaly (WOA; Fig. 3), also likely corresponds to a body of dense Caledonian rock at depth.

3.2 Reinterpretation of the Cessange borehole section

The 534.85-m-deep Cessange borehole (Kind, 1842; Lucius, 1948), which is located just SW of the city of Luxembourg, was drilled from 1837 to 1839 and is still the only deep borehole in the vicinity of the (geographical) centre of the TLB (Fig. 1). It is among the first deep boreholes that were drilled for the purpose of finding salt deposits in the Keuper. Two lithological descriptions of the borehole section are known, one by Rost (1839), a business associate, and another by the head driller Kind (1842). No core was drilled, and the interpretation of the lithologies was based on the reading of drill cuttings. The lithology as well as the stratigraphic interpretation of Rost (1839) were used by Lucius (1948). His interpretation of the borehole geology has so far not been contested, except for some details (Dittrich, 1989). The existence of Liassic to Rhaetian sediments from the surface to about 171 m depth in the borehole is corroborated by nearby exposures. The Rhaetian rests on the 359-m-thick Middle Keuper, and the borehole section ends in the Lower Keuper (Fig. 4; Rost, 1839; Lucius, 1948; Dittrich, 1989).

However, a thickness of 359 m for the Middle Keuper is greater than what is expected from regional mapping. In the TLB, in particular in Luxembourg and northern Lorraine, the Middle Keuper is known to reach a maximum thickness of about 200 m in numerous boreholes. A Middle Keuper thickness as high as 359 m would require an independent depocentre in the Cessange area or, more generally, in the centre of the TLB. However, this is challenged by the Bouguer map (Fig. 3). Here, the Cessange area coincides with a remarkable positive gravity anomaly, not indicating any particularly deep basin. This calls for revisiting the borehole descriptions.

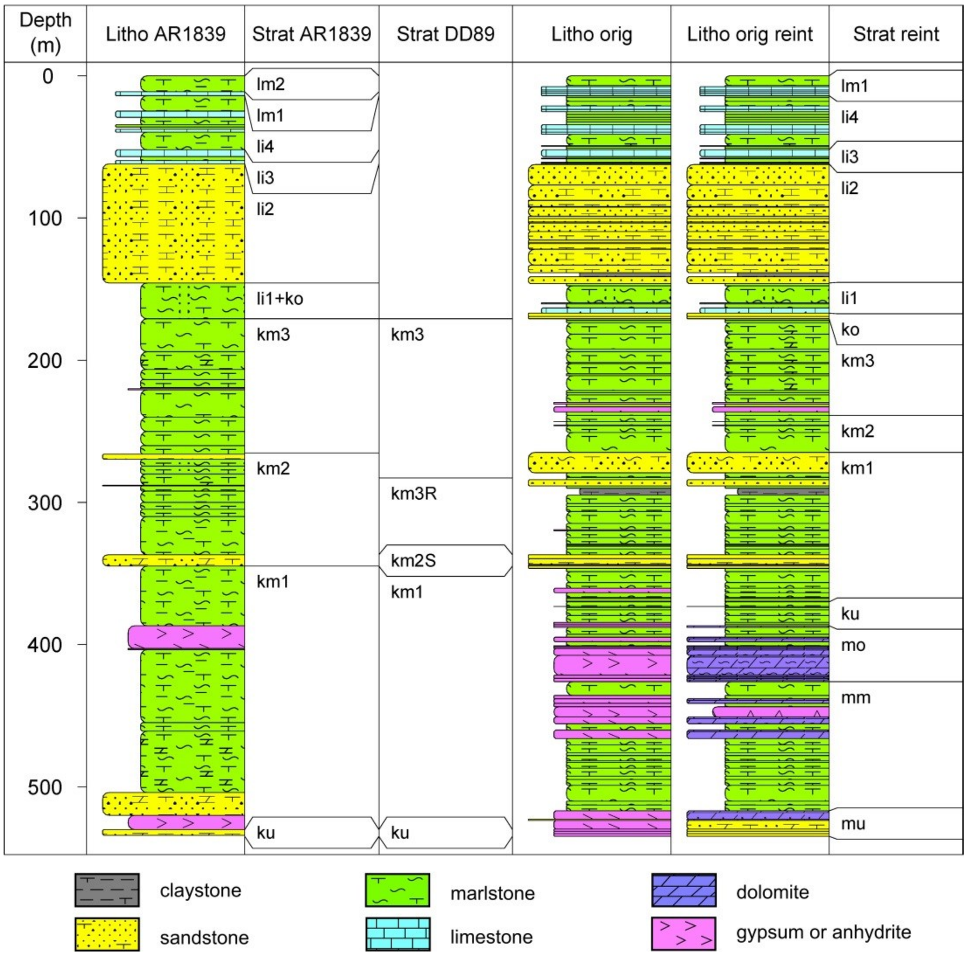


Fig. 4: Various stratigraphic (Strat) and lithologic (Litho) interpretations of the geological section in the Cessange borehole. Strat AR1839: Rost 1839 (after Lucius 1948), Strat DD89: Dittrich 1989, Litho AR1839: Rost 1839 (after Lucius 1948), Strat reint: stratigraphy reinterpreted in this study, Litho orig: lithology as originally reported in the drilling report (Kind, 1842), Litho orig reint: original lithology reinterpreted in this study.

The main problem with the Cessange borehole findings might be associated with a misidentification of specific lithotypes that was associated with the sketchy geological knowledge in the past. Especially the dolomitic rock types, frequently encountered in the Muschelkalk and Keuper, are not recognized or mentioned at that time. Arguing from an improved knowledge of the regional geological history of the TLB it is assumed that parts of the relatively abundant gypsum and anhydrite originally reported actually are dolomite, dolomitic marlstone or dolomitic sandstone, and therefore would require another stratigraphic labelling.

The new interpretation of the Cessange borehole stratigraphy uses the original description of Kind (1842) and centres in the replacement of the remarkable succession of anhydrite and gypsum from 387.02 to 425.90 m depth (38.88 m; Fig. 4) by relatively massive dolomite, typical for the Upper Muschelkalk (mo). The separation of 17.08 m of ku leaves 199.24 m to be classified as Middle Keuper. In contrast to the former interpretations, the occurrence of a sandstone facies, typical for the Schilfsandstein Formation in E- and SE-Guttland, can be excluded. However, the Lower Middle Keuper (Pseudomorphosenkeuper; km1), ranging from 264.72 to 369.94 m depth (105.22 m), is differentiated due to a generally higher sand and sandstone content (Fig. 4). Lucius (1948) also notes a typically higher brine content in that section. The separation of the Steinmergelkeuper (km3) from the Rote Gipsmergel (km2) is more difficult. An alternation of blue and red marl from 224.63 to 238.70 m depth is correlated with the Argiles de Chanville (Table 2), which results in 68 m of km3 and 26.02 m of km2. Below the Upper Muschelkalk, the succession of blue-grey marls underlain by dominantly red marls (425.90 to 516.90 m) is classified as Middle Muschelkalk, resulting in a thickness of 91 m. The apparently sandy, relatively hard “gypsum” down to the bottom of the borehole likely corresponds to Lower Muschelkalk (mu; Fig. 4). In summary, despite the uncertain subdivision of the Middle Keuper, the reinterpretation of the geological section of the Cessange borehole yields relatively conservative thickness values which are also supported by the isopach maps presented in the following section.

3.3 Isopach maps and regional cross sections

To delineate the geology and basin structure of the TLB, several isopach maps were drawn (Fig. 5a–u). They show most of the Triassic and Jurassic geological units and provide an overview of the existing database. Borehole data from Luxembourg (Geological Survey of Luxembourg), France (http://infoterre.brgm.fr), Belgium (Geological Survey of Belgium) and Germany (LGB and LUWG, 2010; Dittrich, 1989; Dittrich and Norbisrath, 2006; Dittrich et al., 1998, 2005; Landesamt für Umwelt und Arbeitsschutz [LUA] Saarland) form the basis on which these maps were generated. Where necessary, the stratigraphic interpretation has been corrected by comparison with nearby borehole data and gamma-ray logs. Due to the variable data density, only the most relevant data points are shown. The isopachs were hand-contoured and honor the data points to show the large-scale morphology of the individual units as well as cumulative thicknesses of subunits first defined by Dittrich (1989). The uncertainty of the layout of the isopachs is obviously strongly dependent on the availability of borehole data, which locally is very restricted. In those areas, the isopachs are concept-based and frequently show a certain structural continuity. Only the major synsedimentary faults are shown. For the sake of clarity, small-scale thickness variations due to local synsedimentary tectonics and sediment deposition (e.g., Dittrich, 1989, 2008, 2009) are not honored. Especially in NW-Guttland, where the stratigraphic interpretation of the Triassic margin facies is difficult and variably addressed by several authors, the isopachs are only indicative. In particular, the individual and largely differing thickness patterns of the subunits of the Middle Middle Keuper (Fig. 5h; Table 2) are summarized and thus extremely simplified because some of these units are locally very condensed or absent (e.g. Dittrich, 1989). Furthermore, there is little data available about the largely concealed pre-Dogger units in SW-Guttland and northern Lorraine. For this reason, relevant maps from the Paris Basin (Mégnien, 1980) were used to guide the isopach contouring. For the Luxembourg Sandstone, a modified version of the existing isopach map (Berners 1985, modified from Bintz and Muller 1966) is suggested by integrating additional data (Fig. 5m). For the ironstone formation, the map in Teyssen (1984) was used. In response to the progressive restructuration at the beginning of the Keuper, the throw at the MF is gradually inverted, which is clearly shown by the contrasting thickness patterns of the Triassic (Mégnien, 1980) and the Liassic deposits (Mouterde et al., 1980), respectively, on either side of the MF.

The Luxemburger Zentralschwelle (LZS; Fig. 2) has repeatedly influenced both thickness and facies patterns at least during the Triassic sedimentation in the TLB (e.g., Dittrich, 1989; Weiler, 1991). As shown on the Bouguer map (Fig. 3), the zone of the LZS is characterized by a positive anomaly (the CLA) which likely corresponds to a buried Caledonian massif. The tendency of passiveness or even relative uplift of the LZS within the overall subsiding basement of the TLB is often reflected by a spatially differentiated, slower increase (e.g., Fig. 5a, b) of thickness or even by no thickness changes (e.g., Fig. 5f–k) above the LZS.

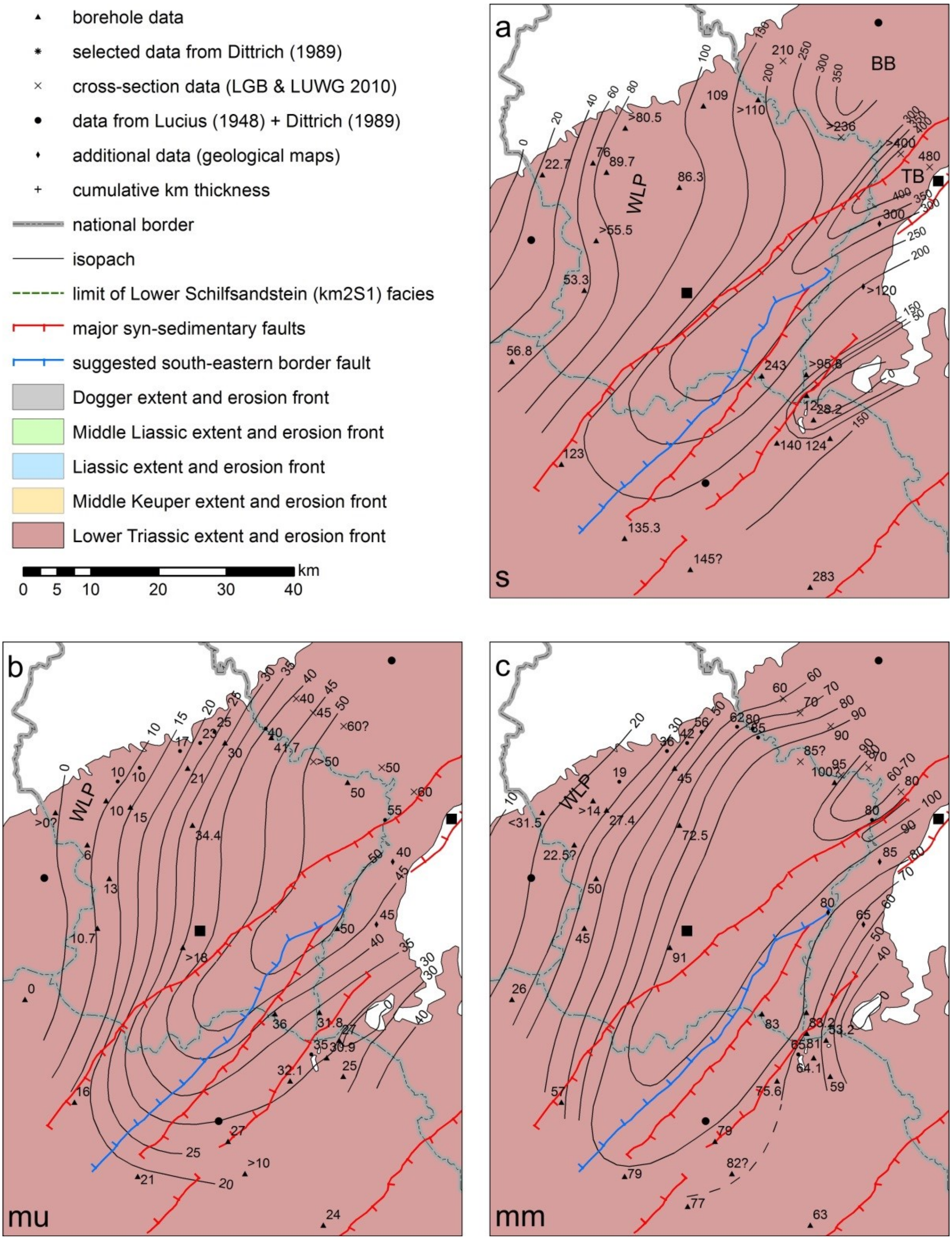
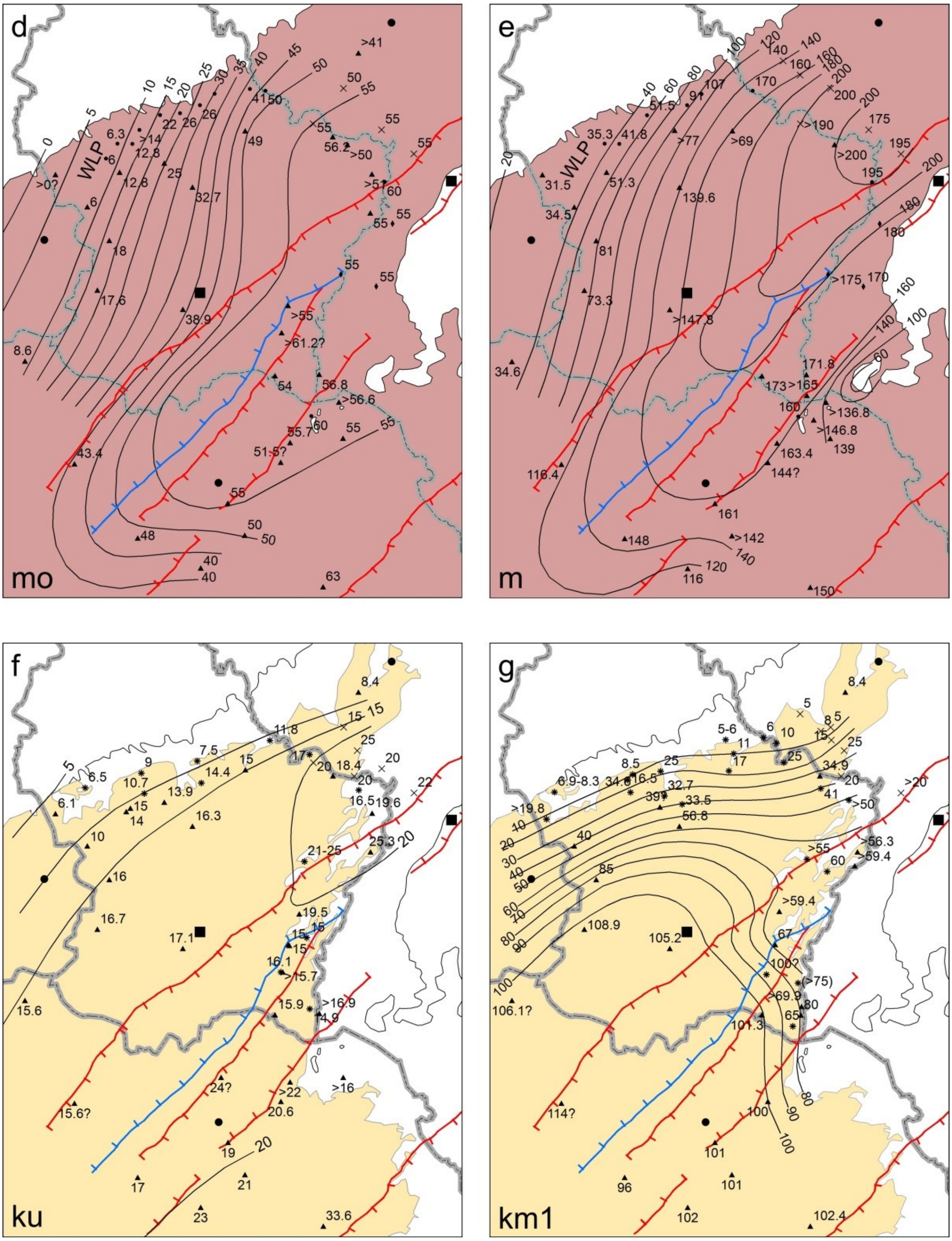


Fig. 5: Isopach maps (thickness values in meters). The indicated localities are the same as in Fig. 1. For the relative placement of the data points the extent and recent erosion front (simplified) of the relevant superordinate succession is indicated. The most important synsedimentary faults are plotted according to their contemporaneous slip tendency.

BB = Bitburg Basin, TB = Trier Basin, WLP = Western Luxembourg Plateau.



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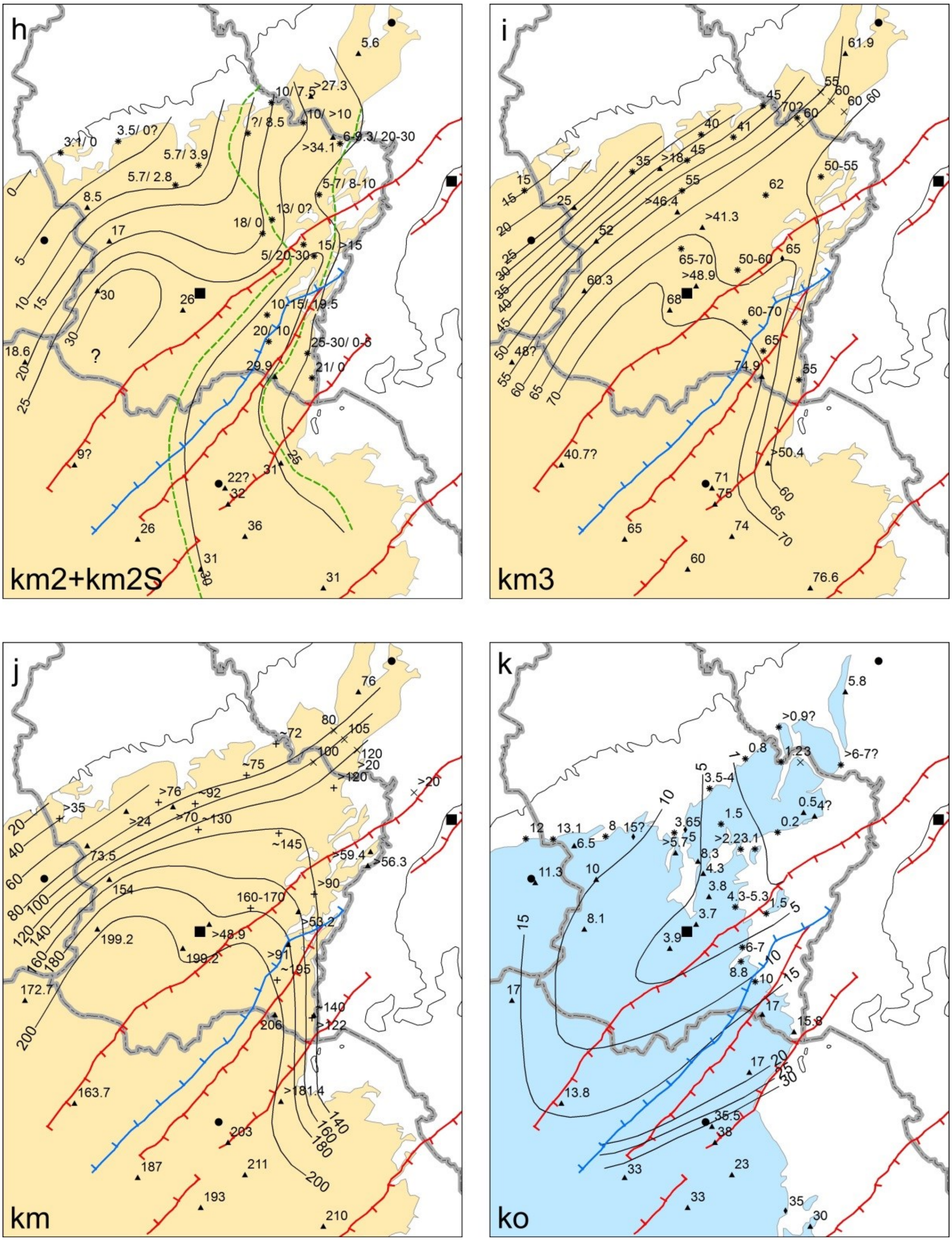

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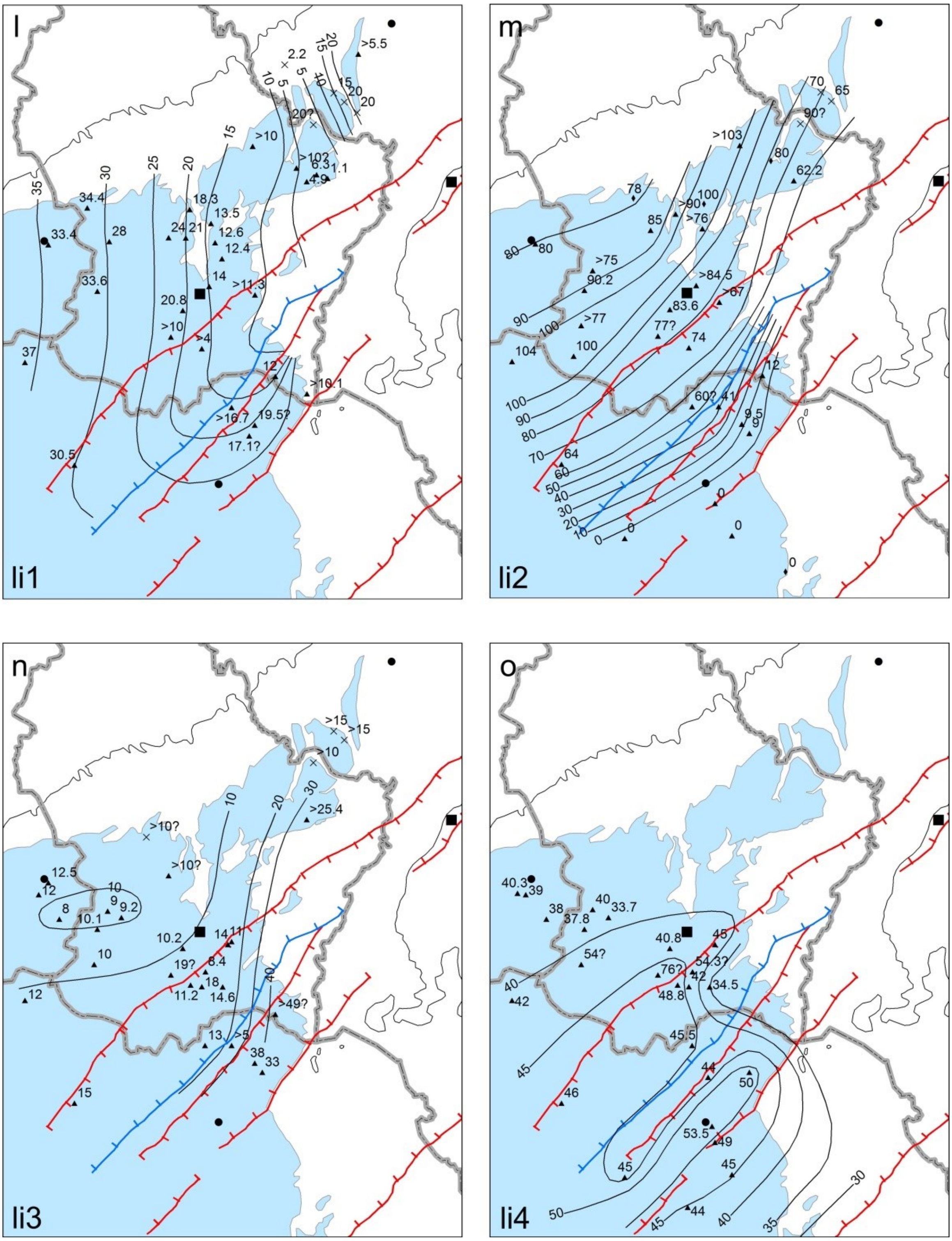
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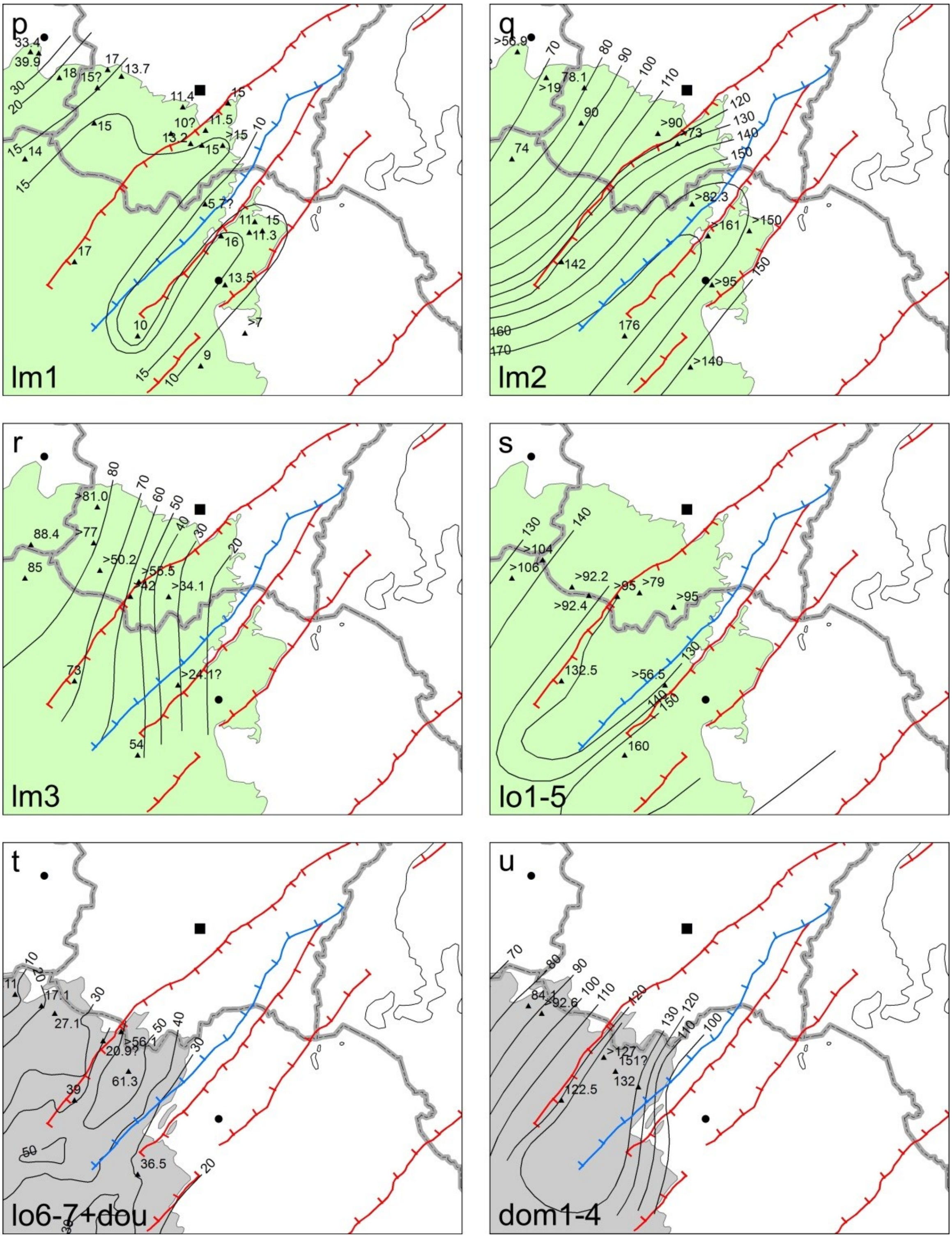

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It is also striking that contrasting thickness patterns in the TLB reflect major changes in the depositional environment. Certainly not all of the changes are of tectonic origin. Some changes may be caused by a coupling between structural processes and sedimentological effects. As an example, erosion obviously was important prior to and during the deposition of the fluvial channels of the Lower Schilfsandstein (km2S1; e.g., Barth et al., 1984; Dittrich, 1989; Dittrich et al., 2005). The transgression at the base of the Liassic, in addition to tectonic restructuration (Dittrich, 1989), then obviously also shapes the deposition of the Rhaetian deposits (Fig. 5k). Furthermore, changes in the thickness pattern are associated with geological formations that are defined by facies boundaries (the Luxembourg Sandstone [li2]) within the Lorrainian facies [li1–li3], the westward sanding up of the lm3, and the diachronous boundary between the lo1–5 and the Minette Fm.). Indeed, the gradation of the Grès supraliasique (lo4–5) into the overlying Minette Formation is progressive and depends on the palaeogeography (Le Roux in Thierry et al., 1980; Muller, 1987). In addition to considerable synsedimentary thickness changes, in particular within the Gipsmergel (mm1; LGB, 2005; Fig. 5c), local dissolution of some of their anhydrite and gypsum layers (e.g., Dittrich, 1989; LGB and LUWG, 2010) adds further complexity.

The regional geological cross sections (Fig. 6A–G), generated based on the information provided by the isopach maps and other geological map data, provide an overview of the geological structure in the TLB. For each cross section, the corresponding data are prepared in spreadsheet format and visualized as graph using Matlab®. The cross sections A to F are perpendicular to the SW–NE-oriented Variscan elements, whereas cross section G is more or less parallel to the Variscan basement structures, primarily showing the tilt from the German Triassic Basin towards the Paris Basin at the beginning of the Keuper. The indicated faults are obtained from the most recent geological maps and extended linearly with a constant dip of 70° assuming an extensional regime, although there is recent evidence of compressional phases in the Tertiary (including strike-slip faults with an offset of up to 3.5 km) in the adjoining Südeifel (Dittrich, 2008, 2009), SE-Luxembourg and the Saargau (Dittrich, 2011b, 2012). In particular, several reverse faults were probably formed due to the reactivation of the LZS during the Tertiary compression (Le Roux, 2000; Fig. 3).

Despite higher erosion levels towards the NE (i.e. towards the NE-Guttland and the Südeifel), the series of cross sections shows the rather homogeneous structure of the TLB. Before uplift, in particular of the Hunsrück in the east and consequent erosion, a transect through the TLB probably would have had much resemblance to cross section F, in which many units are preserved. The cross sections A to F also show the probable location of a Permian graben below the Mesozoic TLB as will be discussed in the next section.

Except for the LZS, the depth of the TLB generally increases from the Ardennes in the NW towards the inferred Permian graben (SELG) and decreases again towards the Hunsrück in the SE. Interestingly, the axis of the TLB, which actually coincides with the location of the inferred Permian graben, is not simply inclined towards the Paris Basin as might be expected. Along the axis, the base of the TLB shows a break similar to the one observed along cross section G showing a relatively sub-horizontal position to the NE of cross section C (depth of about 400 m below mean sea level) and an increasing depth (i.e. 400 to about 900 m below mean sea level) between the cross sections C and F, towards the Paris Basin in the SW. This might have caused the preservation of a consistently larger amount of Liassic sediments in SW-Guttland. In southernmost Luxembourg, in the vicinity of Dudelange (Fig. 6E), the maximum thickness of preserved Mesozoic sediments may be on the order of about 1100 m, which is roughly 400 m greater than known from the Rebierg (Fig. 6E) and Mondorf (Fig. 6D) boreholes. In the same region, the Devonian basement may rest below the Permian deposits at about 2000 m depth.

The isopach maps and cross sections show that the Lower and Middle Buntsandstein have greater thicknesses in the Trier area, which is due to the synsedimentary activity of the Wittlich Main Fault (WMF) (Fig. 2; LGB and LUWG, 2010; Dittrich, 2011a). A contrast in thickness is also suggested on both sides of the Luxembourg Fault (LF). On the Ardennes block, typical Middle Buntsandstein (sm) is mostly restricted to the Bitburg Basin (BB; Fig. 5a), which likely extends roughly 10 km into E-Guttland. Deduced from the gravity map and the absence of typical sm (i.e. in a basin facies) in the Mersch borehole and assuming that the basement of the CLA has a similar synsedimentary behaviour than the basement underneath Mersch (cf. Fig. 3), the occurrences of typical sm are suggested to contour or slightly onlap the CLA, thus delimiting the Eifel Depression to the west. The Eifel Depression is suggested to be structurally bound only to the Ardennes-Eifel block and thus is geographically restricted to NE-Guttland and the Südeifel (Fig. 2). Although the Eifel Depression is only marginally included in this study, it is part of the western margin of the German Triassic Basin and acted as an important channel for river systems respectively sea gate during the Mesozoic sedimentation in the TLB. The interpretation of Wagner (1989), i.e. the existence of limited sm in a margin facies in the form of fluvial channels on the Western Luxembourg Plateau (WLP), hereby remains perfectly possible and is supported by Dittrich and Norbisrath (2006). Unfortunately, all boreholes between the major LF and HHMF faults did not penetrate neither the whole Buntsandstein nor the Permian succession, so that the maximum thicknesses in this crucial area remain unknown. In comparison to the Trier Basin, the highest Buntsandstein thicknesses are to be expected close to the LF. Relatively thick Middle and Upper Buntsandstein along the eastern side of the TLB and the Mondorf Kind borehole (Lucius ,1948) suggest that the sedimentation area likely was far more extended in the Hunsrück area just to the southeast of Trier.

In comparison with the Buntsandstein, the Muschelkalk shows basically a very similar development (Fig. 5b−e). The thickness patterns of these lowermost units, where unconformably overlying the Devonian basement, are influenced by the palaeomorphology of the latter. It affects even the entire Middle Muschelkalk in the vicinity of the Ridge of Mettlach−Sierck (Fig. 5a−d) (e.g.; Müller, 1973; Dittrich, 2011a). A comparison of the Buntsandstein and Muschelkalk maps with the Middle Keuper maps shows the effect of the developing Paris Basin, which passes on to rapid expansion during the Upper Middle Keuper (Haguenauer and Hilly, 1987; Bourquin and Guillocheau, 1993; Guillocheau et al., 1999). The coarse clastics of the Lower Middle Keuper (Pseudomorphosenkeuper), in particular the sandstone- and conglomerate-rich horizons in the northwestern and western Guttland (e.g., Lucius, 1948; Dittrich, 1989), which coincide well with a newly formed high gradient in the latter region (Fig. 5g), very likely reflect the southwestward tilting of the TLB with reduced sedimentation at the northeastern margin and increased erosion of the exhumed lands at the northern and northwestern margins of the basin. Erosion goes along with a considerable westward enlargement with a high sedimentation rate in the direction of the new depocentre in the SW (Fig. 5g). In relation with the destabilization of the western margin of the TLB, the maps of the Keuper (Fig. 5f–j), and to some extent also those of the overlying Liassic, show that the sedimentation area is shifted by up to 10 km to the northwest in SW−Guttland. This evolution, however, is not explained by the formation of a new syncline, but rather is associated with a general northward shift of the sedimentation in the Paris Basin during the Triassic (Courel et al., 1980), whereby existing depressions, notably the SELG, remain active. The actual situation is exemplified by cross section F (Fig. 6F), in which the present-day structure illustrates that the latter process obviously went on beyond the Jurassic sedimentation. A strong argument for the sustained subsidence of the SELG is the distribution of fluvial deposits. The principal Lower Schilfsandstein (km2S1) channels (Barth et al., 1984; Dittrich, 1989; Dittrich et al., 2005) follow the orientation of different depocentres as they are directed first along the Eifel Depression as far as the LF, then turn to the southwest into the new depocentre to the southeast of the LF, i.e. the SELG, and continue in northern Lorraine

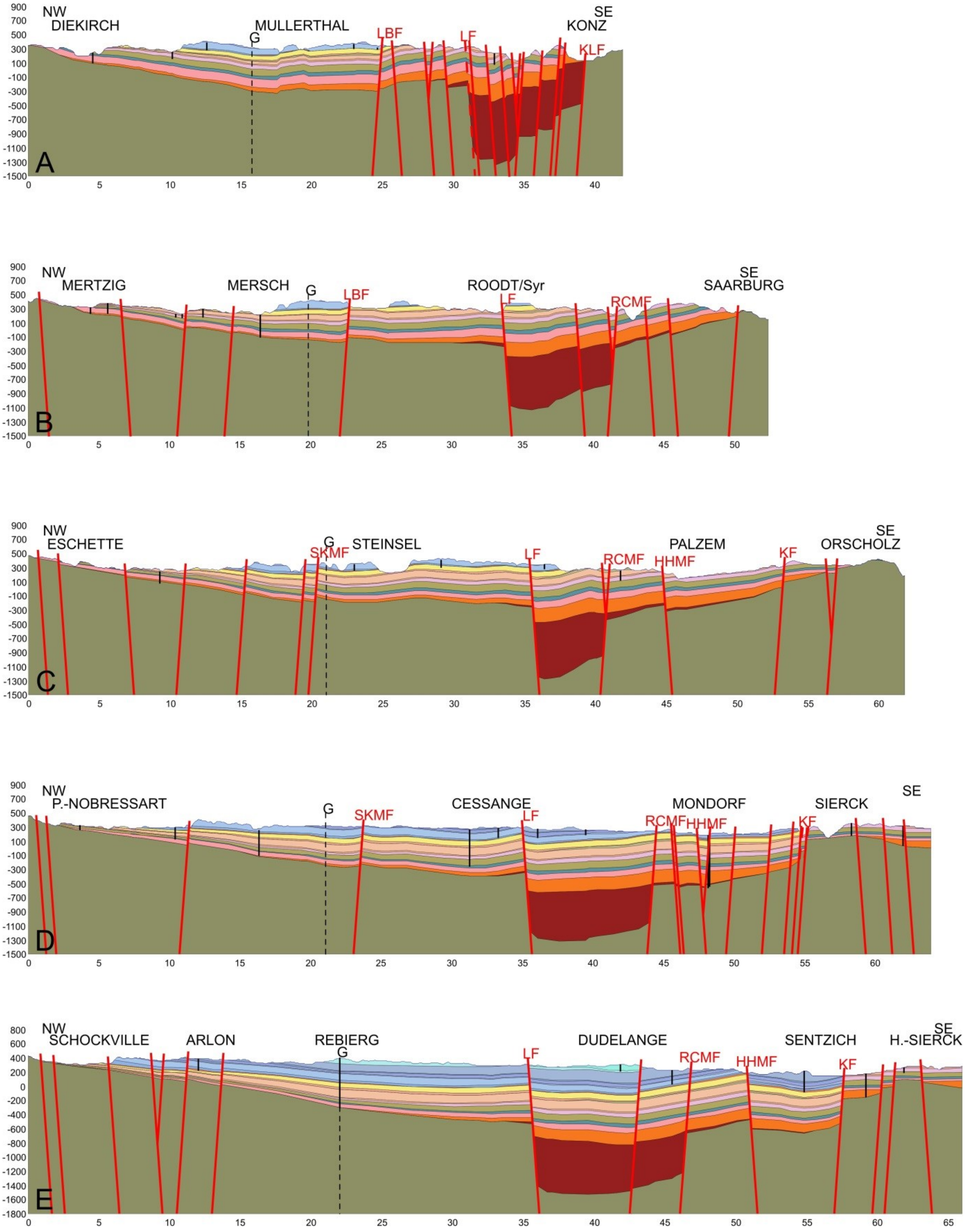

Fig. 6: Regional geological cross sections (horizontal axis in kilometers, vertical axis in meters). Traces of the sections are shown in Fig. 1. The vertical exaggeration is 5-fold for profiles A to E and 7.5-fold for profiles F and G. Black dashed lines correspond to intersection with the indicated cross section.

LBF = Lorentzweiler–Bech Fault, LF = Luxembourg Fault, KLF = Konz–Longuich Fault, SKMF = Schoenfels–Keispelt–Mamer Fault, RCMF = Roussy-le-Village–Canach–Machtum Fault, HHMF = Hayange–Hettange–Mondorf Fault, KF = Koenigsmacker Fault, DF = Differdange Fault, MF = Metz Fault.

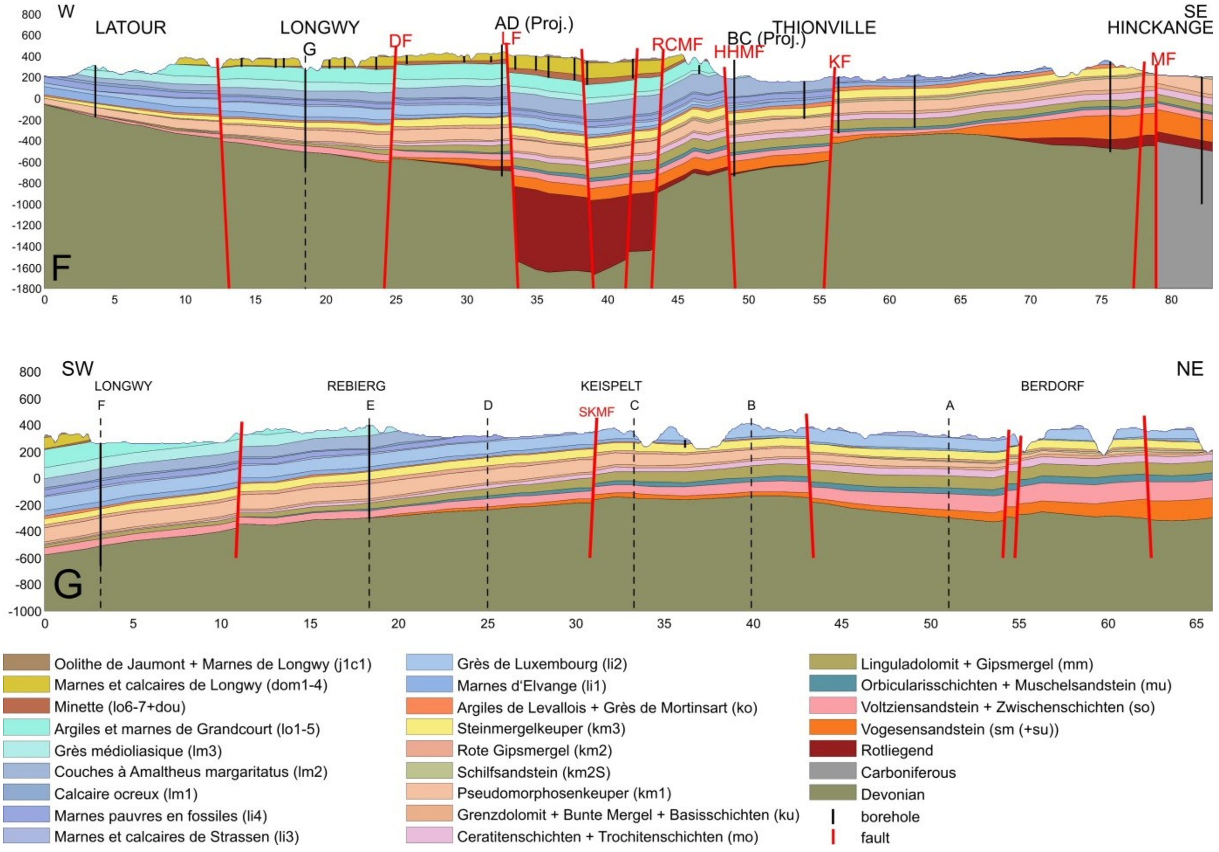

Fig. 6: cont.

as shown by Palain (1966) (Fig. 5h). The SELG corresponds roughly to a combination of two grabens defined by Dittrich (1989), namely the “Grabenzone Schifflange–Alzingen–Uebersyren–Betzdorf” and the “Grabenzone Volmerange–Aspelt–Gostingen”. The southern border likely does not correspond to the HHMF, but rather follows several more or less well expressed fault segments located approximately 2.5−3 km to the northwest of the HHMF. The suggested southeastern border, named RCMF, strikes SW−NE from Bettainvillers, Fontoy, Roussy-le-Village, Canach til Machtum and forms the link with the KLF near Konz (Fig. 2). In the southeastern Guttland, the RCMF likely follows the southeastern border of the narrow grabens of Canach and Machtum, respectively. In the German-Luxembourgish border region, the complex tectonic situation (Dittrich, 2011b, 2012) obscures the connections of both the LF and the RCMF with the WMF and KLF, respectively. However, as the RCMF follows well the isolines in the gravity map (Fig. 3), it is supposed that it is a continuous major fault in the basement. Furthermore, the comparison of the km1 and km3 isopach maps (Fig. 5g, i) indicates a possible reduction of km1 thicknesses (by 20 to 30 m) in E-Guttland through erosional forces related to the deposition of the Lower Schilfsandstein. The Upper Schilfsandstein (km2S2) is subject to a different structuration and therefore more widespread (e.g., Dittrich et al., 2005). In the TLB, the maximum thickness of the Middle Keuper commonly is in the range of 200 m (Fig. 5j). The untypically small Middle Keuper thickness of about 164 m in the AD101 borehole and of 187 m in the Bois-châté borehole (Fig. 5j) are probably artefacts associated with normal faults (the LF and HHMF respectively). Surprisingly, the thickness pattern of the Rhaetian deposits (Fig. 5k) is very different notably from the one of the underlying km3 (Fig. 5i), but resembles much the one of the overlying li1 (Fig. 5l). Berners et al. (1984) and Dittrich (1989) observed this phenomenon and concluded that the old subsidence zones again guided the emplacement of fluvial channels or marine currents through the Eifel Depression and thus the formation of conglomerate under high-energy erosive conditions. A relatively high thickness of the Rhaetian to the southeast of the HHMF may be linked to subsidence in the Thionville Graben (Dittrich, 1989).

The deposition of the Luxembourg Sandstone will be discussed in Section 4.3. The formation of the thick sandstone complex known as Grès médioliasique (lm3a+b; Table 2; Fig. 5r) due to a general regression at the end of the Domerian (Mouterde et al., 1980) to the northwest of the LF, also points to a change in bathymetry resulting from synsedimentary activity of the LF. During the Toarcian, the relatively thick succession (Fig. 5s), compared to frequent hiatuses towards the Ardennes, also reflects the ongoing creation of accommodation space in the centre of the Luxembourg Basin (Mouterde et al., 1980), with a markedly higher subsidence in the area southeast of the LF. This palaeotectonic setting is also strikingly well imaged by the accumulation of ironstone (Fig. 5t) in uppermost Toarcian and Aalenian time, and by the various Bajocian formations (Fig. 5u), detritic as well as calcareous, in northern Lorraine and SW−Luxembourg (Le Roux in Thierry et al. 1980).

Finally, in view of the relatively homogeneous thickness of the Liassic sediment pile in the Luxembourg Basin (Mégnien, 1980: map L7), it is most likely that the contrasting and remarkably complementary accumulation patterns of some formations, instead of reflecting changing subsidence, rather outbalance each other, e.g. the li2 and lm2 as well as the lm3 and lo1−lo5. Indeed, the coarse-grained formations are arranged exclusively close to the margin of the basin whereas clay-silt dominated formations are characterized by a homogenization of the depositional conditions and consequently a larger extension (Mouterde et al., 1980), thus filling up the remaining accommodation space.

4 Discussion

4.1 Permian sediments beneath the TLB

The concept of Permian (more specifically Rotliegend) sediments resting beneath the TLB is old and corroborated by the occurrence of those sediments in the surroundings of the TLB notably in the Wittlicher Senke and in the Saar valley. Although there is no direct confirmation of the presence of these sediments below the TLB by borehole or seismic data, those sediments were inferred in several studies and in numerous regional, relatively large-scale maps therein (e.g., Lucius, 1937; Autran et al., 1980; Mégnien, 1980; Donsimoni, 1981; Schäfer, 1986; Mascle, 1990; Perrodon and Zabek, 1990; Meyer, 1994; Prijac et al., 2000; Stets, 2004a; LGB, 2005). For example, Lucius (1937, 1948) suggests Permian sediments below the Mesozoic sedimentary cover, however playing only a minor role in the Luxembourgish sedimentation area, by linking the main Permian basins, namely the Wittlicher Senke in the north with the Saar-Nahe Senke in the south through the Weilerbach Mulde (see also Muller 1987). As a consequence, Lucius (1948) suspects Permian sediments in the Mondorf area (Fig. 1) and classifies the lowermost 8 m as Permian based on drill cores recovered during the restoration of the Kind borehole. At present, the latter occurrence still is the only indication of Permian sediments on Luxembourgish territory.

In the Longwy borehole (Table 1), which is located immediately to the southwest of Luxembourg (Fig. 1), Joly (1908) defines the 231-m-thick section above the Devonian basement as Permian overlain by only very little Buntsandstein, Muschelkalk and Keuper, which means a drastic reduction in thickness and hiatuses compared to the common regional thicknesses (Maubeuge, 1955). Van Werveke (1908), however, correctly correlates the relatively coarse facies in the Longwy borehole to similarly developed Triassic deposits south of the Luxembourgish Ardennes. Nevertheless, the original interpretation of Joly (1908) was still used in 1980 in a map compiling the Permian basins in France (Mégnien, 1980: map S4). In 1909, the Bois-châté borehole (Fig. 1) revealed the existence of Permian deposits below the high plateau (Pays-Haut) of Lorraine (Nicklès, 1914). However, barely 12 m of Permian deposits were drilled (Fig. 7). In the Audun-le-Roman borehole (Table 1; Mégnien, 1980: map S4) at least 125.7 m of Permian were drilled instead of the Devonian basement indicated in the initial report (Fig. 7). Furthermore, Autran et al. (1980) mention a more than 600-m-thick Permian deposit underneath the Luxembourg Basin, mostly on French territory. It extends some distance north and parallel to the southern boundary of the Rhenohercynian Zone. Autran et al. (1980) point out that except from local, fortuitous identification of

Permian sediments in boreholes, however, their spatial extent remains generally difficult to predict without having seismic data. Except the well-studied Permo-Carboniferous Saar–Nahe Basin (SNB; Fig. 1), the only exposed Permian deposits belong to the more than 1000-m-thick Permian succession of the Wittlicher Senke (WS) just east of the TLB (Fig. 1; for a complete description see Stets 2004a). The sedimentation in the WS began relatively late, namely in the higher Rotliegend (Saxonian, Nahe Sub-group) after termination of the Late Variscan Saalian phase (LGB, 2005; Autran et al., 1980). The depositional gap at the top comprises the uppermost Rotliegend, the Zechstein and variable amounts of the lowermost Buntsandstein (Stets, 2004a; LGB, 2005). For the formation of the WS, Stets (1990) suggests the development of a pull-apart basin in a sinistral regime based on the currently available observations, e.g. the s-shape of the basin and sedimentological aspects.

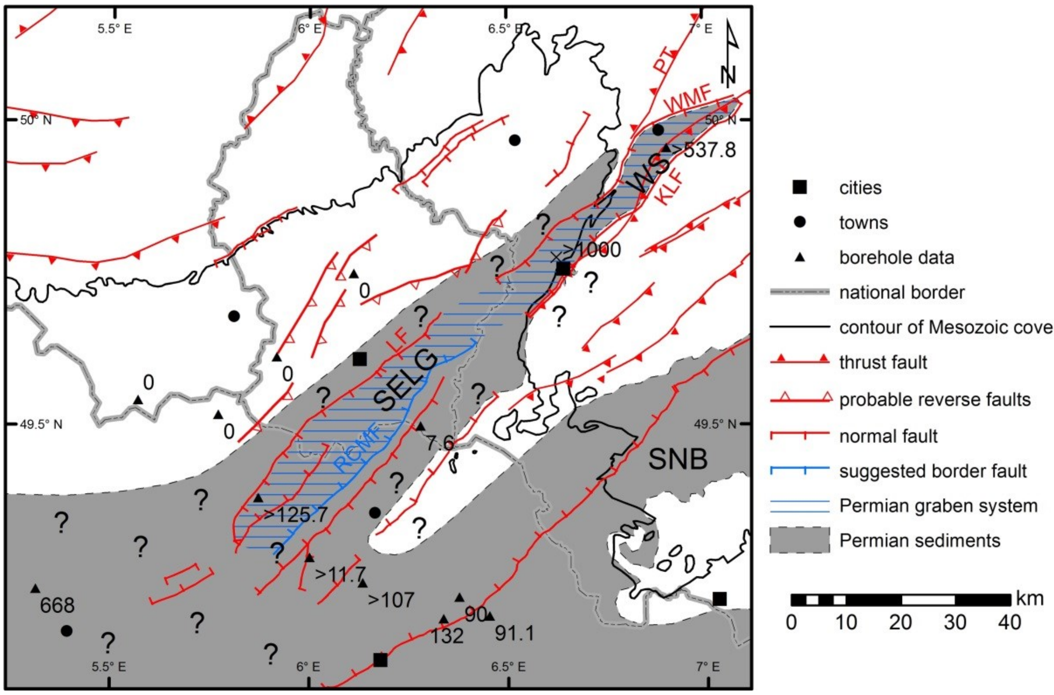

Fig. 7: Map showing the probable extent of preserved Permian deposits on exposure and below Mesozoic cover in Luxembourg and adjacent areas (modified after Mégnien 1980: Map S4 and Prijac et al. 2000, and completed after Dittrich 2011a). Only the deep boreholes that have reached the Permian respectively the Devonian basement are shown. The indicated localities are the same as in Fig. 1. The names of the main faults are the same as in Fig. 2.

According to the structural information deduced from geological and gravity data, the main Permian sedimentation area must be located on top of the elongate negative SELA anomaly (Fig. 3), between the Luxembourg Fault–Wittlich Main Fault system as master faults in the northwest and the BDLA–HHMA lineament in the southeast (Figs. 2 and 7). Indeed, the thickness of preserved Permian sediments to the southeast of the latter lineament, for instance in the lower Saar valley (Lucius, 1948; Stets, 2004a) and in the Kind borehole in Mondorf (Lucius, 1948) is very restricted. Similarly, to the northwest of the WMF, the thin Permian record is known not to overlap largely the Eifel block with thicknesses not exceeding much more than several tens of meters (LGB, 2005; LGB and LUWG, 2010; Dittrich, 2011a).

In view of the new interpretation of the Cessange borehole and the gravity map, specifically the probable absence of an independent depocentre and the occurrence of rather conservative thicknesses, we suggest that possible Permian deposits likely are restricted in that region. The nearest borehole that drilled relatively thick Permian deposits is the French Audun-le-Roman borehole (Fig. 1; Table 1). As a consequence, it appears that the inferred SE-Luxembourg Graben (Fig. 2) has broadly the same structure as the WS. Its southeastern boundary fault is likely located at an unknown distance to the northwest of the HHMF (Fig. 6C–F). In southern Luxembourg the southeastern border fault of the SELG is suggested to be the RCMF, which is located 2–3.5 km to the northwest of the HHMF yielding a roughly 5- to 10-km-wide graben.

Further to the southwest in the Paris Basin, 668 m of Permian sediments were drilled in the Vacherauville borehole (Table 1; Figs. 1 and 6). Starting with an 11-m-thick rhyolite, the sedimentary succession resembles the formations defined in the WS. Field observations in the WS clearly indicate a southwestward sediment transport (Stets, 2004a), which means that the sediments eroded in the northeast were obviously channeled through the SELG–WS (Fig. 7) and may then have joined the Permian basin in the Vacherauville area (Mégnien, 1980). As confirmed by the new interpretation of the Longwy borehole, the Permian sediments however do not reach as far north onto the Ardennes–Eifel block (Fig. 7).

As a conclusion, in the WS and potentially the SELG, up to 1000-m-thick Permian sediments accumulated in a well-defined structure that is delimited by border faults. Considering the lack of convenient boreholes and seismic data, however, the existence of connections between individual Permian basins (e.g. with the Saar–Nahe Basin) is highly speculative and resulted in largely differing maps (e.g., Prijac et al., 2000; Mégnien, 1980). Because no transverse faults or folds are known in the Mesozoic cover and in the underlying basement, which would have an impact on the sediment deposition between the WS and the Vacherauville borehole, the thickness of the Permian sediments in the SELG probably ranges between 668 m (Vacherauville borehole) and more than 1000 m inferred by Stets (1990, 2004a: Abb. 4, 2004b) in the WS underneath Trier.

4.2 Structural concept of the Mesozoic Trier–Luxembourg Basin

The isopach maps, cross sections as well as structural and sedimentological observations in the Mesozoic sedimentary record of the TLB infer the influence of the Permian SELG as a major weakness zone during the development of the TLB. The concept presented by Dittrich (1989) does not consider the possibility of a single major weakness zone such as the SELG. Instead, she distinguished from sedimentological observations in the Upper Triassic (Keuper) three inherited, intersecting sets of faults giving rise to a more or less complex horst and graben structure. For parts of that structure synsedimentary activity is documented and evidence is perceptible in geological maps.

However, the new isopach maps, in particular the less facies-controlled sedimentation patterns of the Triassic, clearly suggest a long-lasting subsidence in the vicinity of the SELG, controlled mainly by a few major faults. The large variation in directions observed in the TLB (e.g., Dittrich, 1989) can actually be explained by heterogeneities in the basement whose tectonic behaviour likely is controlled not only by Variscan structures, but also to some point by the deeper Caledonian structures (e.g., the CLA) as well as the reactivation of those structures by a younger compressional regime (e.g., Guillocheau et al., 1999; Le Roux, 2000). As the superficial structures are often related to the structures of the basement (e.g., Lucius, 1948; Dittrich, 1989; Le Roux, 1971, 1980, 1999, 2000), it is rather unlikely that structures can be followed across the entire basin thereby indifferently cross-cutting major basement structures (Fig. 2), notably the internally differently structured Ardennes–Eifel block and the Hunsrück block (Fig. 2). In addition, the Ridge of Mettlach–Sierck (RMS; Fig. 2), an important synsedimentary high-ground (Courel et al., 1984) in the TLB, is here considered to be a relatively passive structural element in comparison to the actually active Luxembourg and Metz faults, respectively (Courel et al., 1980; Mouterde et al., 1980).

4.3 Implications for the Luxembourg Sandstone

The deposition of the well-studied Luxembourg Sandstone Formation (li2) is usually linked with the existence of the Weilerbach Mulde (e.g., Lucius, 1948; Bintz and Muller, 1966; Muller, 1980; Berners, 1983, 1985; Guérin–Franiatte et al., 1991). However, the existence of the Weilerbach Mulde has been structurally disproven by Dittrich (1989) for the Keuper and the present-day geological situation, which has important implications for understanding the deposition of the Luxembourg Sandstone (Table 2; Fig. 5m) of Lower Liassic age. It consists of a diachronous sandstone body inserted in between Hettangian to Lower Sinemurian marls, clays and limestone pertaining to the Lorrainian facies (li1−3; Table 2). The sanding-up of the Lower Liassic took place along the NE–SW oriented coast of the Ardennes through the action of dominantly southwestward-directed littoral currents arriving through the marine channel of the Eifel Depression into the Paris Basin (Bintz and Muller, 1966; Berners, 1983, 1985). Instead of being fault-related (Berners, 1983), westward shifting of the sedimentation from the Hettangian to Lower Sinemurian can be explained by simple transgression as acknowledged by Guérin−Franiatte et al. (1991). The comparatively low position of the li2, notably in the Weilerbach area in the Lower Sauer valley likely has led to the more general interpretation that the Weilerbach Mulde is the central tectonic element of the "Gulf" of Luxembourg (Lucius, 1948; Muller, 1980, 1987). However, in addition to the arguments presented in Section 3.1 and 3.3, there are more arguments to challenge the existence of the Weilerbach Mulde and its involvement in the deposition of the li2.

The straightforward structural interpretation of the present-day appearance of the sedimentary record is indeed misleading because it ignores a major phase of compression and folding in Upper Eocene and Miocene time related to the distant Alpine Orogeny (Le Roux, 2000). The LZS, which is a prominent feature in central Guttland and has facilitated the erosion of large portions of li2 in the eastern Guttland, likely was reactivated after the Mesozoic. At depth, in the basement, the bulge is well imaged by a positive Bouguer anomaly, namely the CLA. This fact, as well as the unusually arcuate course of the fault segments supports the hypothesis of its reactivation in the Tertiary due to compression of the basement northwest of the Luxembourg Fault along probably pre-existing basement structures and consequent deformation of the thin Mesozoic cover.

Despite only little information on the detailed thickness patterns notably for the Triassic units in central and SW-Guttland, the large-scale thickness pattern of the Steinmergelkeuper (Fig. 5i) is indicative for the basin structure during the formation of the overlying Lower Liassic succession. Indeed, Haguenauer and Hilly (1987) point out that the Paris Basin as a whole acquires already in the Upper Middle Keuper a configuration which is characteristic of the entire Liassic period. Instead of specifically controlling the accumulation of the Luxembourg Sandstone, the subsidence is known to affect the entire LB (Fig. 1) extending from the Metz Fault in the SE to the Ardennes mainland in the NW (Figs. 1 and 2; Mouterde et al., 1980: 92; Mégnien, 1980: map L7; Guillocheau et al., 1999). The lower Liassic transgression rapidly creates a marine environment in which the effects of sequence stratigraphy are even stronger than before. Probably for the first time during the development of the TLB, the accommodation space created largely exceeds the volume of sediments provided. Considering only the thickness of the whole sandstone body irrespective of age, it is therefore significant that the li2, in contrast to the contemporaneous marly Lorrainian facies, is mostly developed in proximity to the Ardennes mainland and principally on the Ardennes block with a rapidly decreasing proportion to the southeast of the LF (Fig. 5m). Further to the SE, i.e. further away from the Ardennes, in the probably deeper parts of the basin, the supply of coarse material weakened and mainly marly and bioclastic material accumulated, resulting in the thinner Lorrainian facies. Comparison of the Lorrainian facies in the Thionville area with a typical Luxembourgish Lower Liassic profile shows that the difference in thickness is readily explained by the additional amount of sand (-stone), in accordance with a differentiated sedimentation and a higher accumulation rate along the Ardennes. The SE-Luxembourg Graben and probably also the Thionville Graben (Fig. 2) possibly contribute to the rapid thinning of the li2 towards the southeast (Fig. 5m). Finally, the occurrence of more than 100-m-thick li2 in a borehole near Medernach (Fig. 5m: > 103 m) further strengthens the strong sedimentological component in the formation of the Luxembourg Sandstone and shows that the maximum sedimentation is not associated with the Weilerbach Mulde as shown by Berners (1985). The regions of maximum thickness apparently imitate the direction of the palaeocurrents arriving from the north through the Eifel Depression.

5 Summary and conclusions

The paper aimed at a comprehensive structural and geological update of the Trier–Luxembourg Basin (TLB) as a first step for a geothermal resources assessment and a thermal model for drillable depths in Luxembourg. The incorporation of new data, e.g., a Bouguer map, and the reinterpretation of the Cessange borehole suggest that the Weilerbach Mulde, which has been disproven since Dittrich (1989) mainly for the Keuper, also does not control the deposition of the Luxembourg Sandstone and the development of a particularly thick Keuper succession in the Cessange area. The Bouguer map shows that the Luxemburger Zentralschwelle is probably related with a buried Caledonian Massif. Its present-day appearance as a structural high results likely from reactivation under a compressional regime in the Tertiary. The basin-wide cross sections, the structural and sedimentological observations in the TLB and the tectonic structures in the exposed basement strongly suggest that the TLB developed along a weakness zone related to a Permian graben. This roughly 5- to 10-km-large and more than 1000-m-deep, SW–NE trending SE-Luxembourg Graben

(SELG), located between the Luxembourg Fault (LF) in the northwest and the Roussy-le-Village–Canach–Machtum Fault (RCMF) in the southeast, corresponds very likely to the southwestern prolongation of the Permian Wittlicher Senke underneath the Mesozoic cover. According to this concept, the SELG, mainly controlled by the synsedimentary active LF, constitutes the central subsiding element of the TLB probably since Permian time.

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