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REGULAR RESEARCH ARTICLE

New data on the biostratigraphy (charophytes, nannofossils, mammals) and lithostratigraphy of the Late Eocene to Early Late Miocene deposits in the Swiss Molasse Basin and Jura Mountains

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Abstract
In the northern Swiss Plateau and Jura Mountains, non marine Paleogene and Neogene deposits of the Swiss Molasse Basin or linked to the Upper Rhine Graben are examined in detail. The Late Eocene (Middle–Late Priabonian) is characterized by charophytes of the Vasiformis–Tuberculata Zone (Diegten Süsswasserkalk) and Vectensis Zone (lower Tuberculata Superzone, Oberdorf Süsswasserkalk, Terre jaune). The Rupelian and Early Chattian appear as little developed and extended. The Rupelian is characterized by charophytes of the Pinguis Zone (upper Tuberculata Superzone, basal Conglomérat de Porrentruy) and Major Zone (Conglomérat de Porrentruy, lower "Molasse alsacienne", Marnes rouges). In the Neuchâtel region of central Jura, a paleokarst marine filling of UMM (Montmollin) yielded nannofossils of Early Rupelian (NP 21) age. Early Chattian sediments are for the first time precisely dated by small mammals (MP 25–26a) and typical charophytes of the Microcera Zone (Calcaire d'eau douce de Trois-Rods). The biostratigraphy of charophytes for the Early Miocene to early Late Miocene (MN 1–9) can also be defined more precisely ranging from Nitida Zone to Etrusca Zone. The biozonation of charophytes for the Swiss Paleogene and Neogene (SPN) is revised and completed by the creation of 11 assemblage zones SPN-EC 1–2 (Eocene charophytes, Late Eocene), SPN-OC 1–2 (Oligocene charophytes, Rupelian), SPN-OC 3–5 (Chattian), SPN-MC 1–2 (Miocene charophytes, Aquitanian), SPN-MC 3 (Burdigalian) and SPN-MC 4 (Langhian–Early Tortonian).

Keywords Cenozoic · Molasse · Charophytes · Biostratigraphy · Lithostratigraphy · Switzerland

Introduction

This study was carried out with samples derived from Late Eocene to Oligocene–Miocene freshwater and marine sediments located between the Swiss Plateau and Swiss-French Jura Mountains (Fig. 1, Table 1). New data are reported from Middle–Late Priabonian to lowermost Tortonian freshwater deposits separated by two marine episodes known as UMM (Untere Meeresmolasse) or Série grise (Rupelian) and OMM (Obere Meeresmolasse, Burdigalian). Until recently, the ages of deposits initially placed in the Early Oligocene (Terre jaune, Oberdorf

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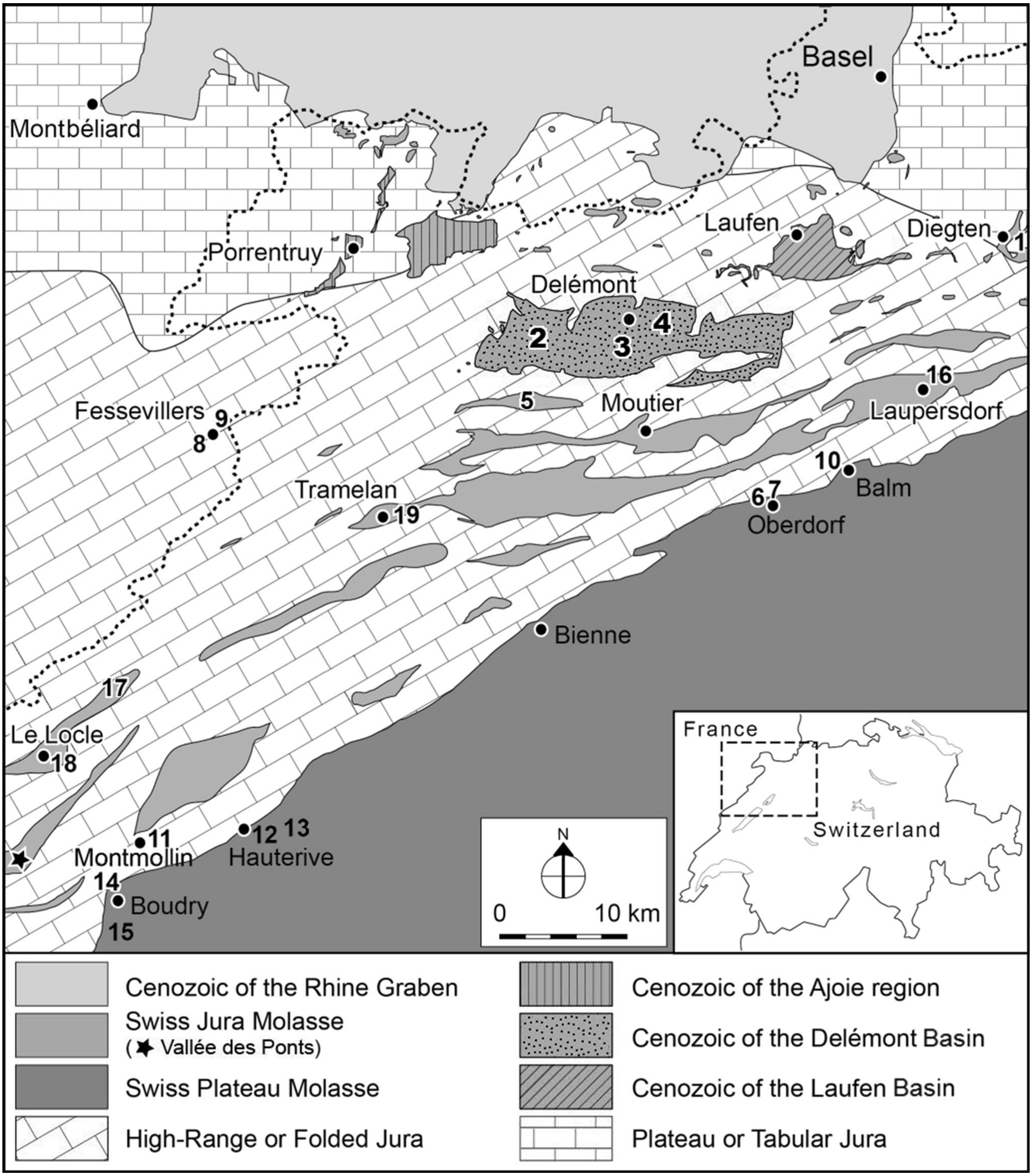


Fig. 1 Location map (modified from Picot et al. 2008). For the localities and sites 1–19, see Tables 1 and 2a, b. For details on the complex contents of the Jura synclines, see Becker (2003, p. 20 and 69–70)

Süsswasserkalk and Calcaire d'eau douce de Trois-Rods) were still poorly known and remained to be investigated. During recent years, new observations and analyses were performed on boreholes, excavations and landslides. New data with charophytes, nannofossils and mammals provide crucial clarifications about the ages and the stratigraphical terminology for the Paleogene and Neogene of Western Switzerland. Our results complement likewise the

Table 1 Listing of the sites (outcrops, excavations, drillings) and samples collected for this study

Localities and sites			Samples	Coordinates (Map of Switzerland 1:25'000)	Groups	Stages	Biostratigraphy	Lithostratigraphy and lithology	Collections
1. Diegten (BL)			DSK-2016 / 1 - 10	2628.645/1251.800	Haguenau	Middle-Late Priabonian	Vasiformis-Tuberculata Z.	Diegten Süsswasserkalk (pinkish-grey marls)	MGL (coll. POM)
2. Delémont Basin (west)	2.1. Boécourt (JU), quarry of Moulin de Séprais		RM 172 FPJ 22679 + RM3 FPJ 22680	2584.200/1246.780	Siderolithic	Early-Middle Priabonian	MP 17-18	Reddish clays (paleokarst fissure filling)	FPJ - JUR. Mus.-NMBE
	2.2. Bassecourt (JU), Longues Royes		LGR 007 / 81, 84	2584.600/1242.870	Stockstadt	Late Rupelian	non basal Major Z., MP 23-24	"Molasse alsacienne" (colorful clays)	JUR. Mus. (Porrentruy)
3. Delémont Basin (south)	3.1. Rossemaison (JU), borehole		Del1-S1-1990	2592.869/1244.478	Pechelbronn	L. Priabon.-E. Rupelian	Tuberculata Spz./Vectensis Z.-bas. Major Z.	Terre jaune (yellow marls)	JUR. Mus. (Porrentruy)
	3.2. Châtillon (JU), Le Bie streambed		CTJ-2013 / 1 - 10	2592.630/1241.290	Pechelbronn	Late Priabonian	Tuberculata Spz./Vectensis Z.	Terre jaune (yellow marls, Fig. 2b)	MGL (coll. POM)
	3.3. Courfaivre (JU)		C-2017 / POM / 1 - 2	2587.850/1243.080	USM-J	Early Aquitanian	Nitida Z.	Calcaires delémontiens (grey marls, Fig. 6a)	MGL (coll. POM)
	3.4. Courtételle (JU), Métairies de Chaux		MCX 008 / 16, 20, 28, 33, 34, 59	2589.595/1243.845	USM-J	Early Aquitanian	Nitida Z.	Calcaires delémontiens (grey marls)	JUR. Mus. (Porrentruy)
			CMCX-2017 / POM / 1	2589.595/1243.845	USM-J	Early Aquitanian	Nitida Z.	Calcaires delémontiens (grey marls)	MGL (coll. POM)
4. Delémont Basin (east)	4.1. Courcelon (JU), Scheulte River		STJ-1983 / MW-JPB	2596.020/1245.870	Pechelbronn	Late Priabonian	Tuberculata Spz./Vectensis Z.	Terre jaune (greenish-beige clayey marls)	MGL (coll. JPB)
	4.2. Courroux (JU)	4.1.1. Le Poillat	POI 007 / 1357, 1953, 2293, 2405, 2503, 2775, 2808, 2942	2594.774-778/1244.519-586	Stockstadt	Late Rupelian	non basal Major Z., MP 23-24	Cyrenenmergel / "Molasse alsacienne" transition	JUR. Mus. (Porrentruy)
			POI 010 / 482	2594.810/1244.519	Stockstadt	Late Rupelian	non basal Major Z., MP 23-24	Cyrenenmergel / "Molasse alsacienne" transition	JUR. Mus. (Porrentruy)
		4.1.2. Pré Chevalier	PRC 004 / 246, 255	2594.654-660/1244.592-603	Stockstadt	Late Rupelian	non basal Major Z., MP 23-24	Cyrenenmergel / "Molasse alsacienne" transition	JUR. Mus. (Porrentruy)
5. Soulce (JU), Côte de Sormont			S-2017 / POM / 1	2586.280/1240.005	Stockstadt	Late Rupelian	non basal Major Z., MP 23-24	"Molasse alsacienne" (beige marls)	MGL (coll. POM)
6-7. Oberdorf (SO)	6. Railway station	6.1. Forest road	OSK-2013-14 / 1 - 7	2604.140/1231.830	Pechelbronn	Late Priabonian	Tuberculata Spz./Vectensis Z.	Oberdorf Süsswasserkalk (yellowish marls, Fig. 2a)	MGL (coll. POM)
		6.2. Weissenstein cableway (trench)	OHSK-2014 / 1	2604.225/1231.760	Stockstadt	Rupelian	Major Z.	Whitish limestone with Hydrobiidae	MGL (coll. POM)
	7. Weissenstein road			2604.300/1231.945	Sid. + Pechel.	Late Priabonian		Bolustone (reddish-grey clays) + Oberdorf Süsswasserkalk (yellowish limestones)	
8-9. Fessevillers (Doubs, France)	8. Village (center)		FCP-2014 / 1 - 5	2560.070/1236.705	Pechelbronn	Early Rupelian	Tuberculata Spz./Pinguis Z. - basal Major Z.	Conglomérat de Porrentruy (various marls, Fig. 2c)	MGL (coll. POM)
	9. Road D 437B		FCP-D437B-2014 / 1	2561.900/1237.350	Pechelbronn	Early Rupelian	basal Major Z.	Conglomérat de Porrentruy (yellow marls)	MGL (coll. POM)
10. Balm (SO)			BM-2013-14 / DK / 1	2608.900/1233.880	USM	Early Rupelian	basal Major Z., MP 22	Dark grey marls (cf. Gander 2013)	MGL (coll. POM)
11. Montmollin (NE), quarry of Bois-Rond			MCBR-1990 / EDK / 1 - 5 (+ MCBR-2017 / POM / 1-7)	2555.735/1204.510	UMM	Early Rupelian	NP 21	Reddish-grey marls (paleokarst marine filling)	Coll. E. de Kaenel; MGL (coll. POM)
12. Hauterive (NE), Rouges-Terres			HRT-2013 / POM / 1 - 7	2564.970/1206.870	USM	Rupelian-Early Chattian	Major Z.-Microcera Z.	Marnes rouges + Calcaire d'eau douce de Trois-Rods (mainly red marls and whitish limestones, Fig. 5c-d)	MGL (coll. POM)
13. Marin-Epagnier (NE), Pré-aux-Andins Street (borehole)			PRA 005 / 12, 14	2566.705/1206.614	USM	Early Aquitanian	Nitida Z.	Grès et marnes bigarrés (black marls)	JUR. Mus. (Porrentruy)
14. Boudry (NE), Trois-Rods			BTR-2016 / POM / 1 - 10	2553.705/1201.130	USM	Early Chattian	Microcera Z., MP 25-26	Calcaire d'eau douce de Trois-Rods with *Eomys* n. sp. 2 (pinkish-grey marls and grey limestones, Fig. 5a-b)	MGL (coll. POM); NMB (leg. POM)
15. Bevaix (NE), Les Vernets (A5 Highway trench, toward "Boudry-Les Tilles")			TIL 004 / 48	2553.410/1198.955	USM	Early Aquitanian	Nitida Z.	Grès et marnes bigarrés (black marls)	JUR. Mus. (Porrentruy)
16. Laupersdorf-Güggelhof (SO)			LG-2014 / DK / 1 - 3	cf. Bläsi et al. (2015)	USM-J	Late Chattian - Early Aquitanian	MP 30 - Nitida Z.	Delsberger Süsswasserkalk (grey-brown clayey marl)	MGL (coll. POM)
17. La Chaux-de-Fonds - Le Locle Basin (east) - La Chaux-de-Fonds (NE)		17.1. Borehole Cridor S3	LCF-CS3	cf. Kälin et al. (2001)	OSM-J	Serravallian	"Ginsburgi" / Etrusca Z. transition, MN 6	"Oeningian" (red marls)	MGL (coll. POM)
18. La Chaux-de-Fonds - Le Locle Basin (west) - Le Locle (NE)		18.1. Les Varodes (La Grecque)	LL-LV-2017 / POM / 1 - 3	2546.745-790/1210.290-370	OSM-J	Serravallian	Basal Etrusca Z., upper MN 6 - MN 7	"Oeningian" (dark coloured marls, Fig. 6e-f)	MGL (coll. POM)
		18.2. Combe Girard 33 / L33	LL-CG33	cf. Kälin et al. (2001)	OSM-J	Serravallian	Basal Etrusca Z., upper MN 6 - MN 7	"Oeningian" (dark coloured marls)	MGL (coll. JPB)
		18.3. Combe Girard 20 / L20	LL-CG20	cf. Kälin et al. (2001)	OSM-J	Serravallian	Basal Etrusca Z., upper MN 6 - MN 7	"Oeningian" (dark coloured marls)	MGL (coll. JPB)
		18.4. Combe Girard 10	LL-CG10	cf. Kälin et al. (2001)	OSM-J	Serravallian	Basal Etrusca Z., upper MN 6 - MN 7	"Oeningian" (dark coloured marls with *Megacricetodon gersi*)	MGL (coll. JPB - POM); NMB (leg. POM)
		18.5. Borehole Tours Dixi S13	LL-TDS13	cf. Kälin et al. (2001)	OSM-J	Serravallian	Basal Etrusca Z., MN 7+8	"Oeningian" (dark coloured marls)	MGL (coll. JPB)
		18.6. Combe des Enfers 24	LL-CE24	cf. Kälin et al. (2001)	OSM-J	Serravallian	Basal Etrusca Z., MN 7+8	"Oeningian" (dark coloured marls)	MGL (coll. JPB)
		18.7. J.J. Huguenin Street	LL-JJHS	cf. Kälin et al. (2001)	OSM-J	Serravallian	Basal Etrusca Z., MN 7+8	"Oeningian" (dark coloured marls)	MGL (coll. JPB)
		18.8. Haut-du-Crêt 12	LL-HC12	cf. Kälin et al. (2001)	OSM-J	Serravallian	Basal Etrusca Z., MN 7+8	"Oeningian" (dark coloured marls)	MGL (coll. JPB)
		18.9. Pied-du-Crêt 2	LL-PC2	cf. Kälin et al. (2001)	OSM-J	Serravallian	Basal Etrusca Z., MN 7+8	"Oeningian" (dark coloured marls)	MGL (coll. JPB)
		18.10. La Claire	LL-LC-2013 / POM / 1 - 4	2547.820/1211.010	OSM-J	Serravallian	Basal Etrusca Z., MN 7+8	"Oeningian" (dark coloured marls)	MGL (coll. POM)
19. Tramelan (BE)			TR-2015 / DK / 1 - 2	cf. Aufranc et al. (2016)	OSM-J	Serravallian	Basal Etrusca Z., MN 7+8	"Oeningian" (dark coloured marls)	MGL (coll. POM)
Localities and sites outside the Fig. 1									
20. La Rippe (VD), borehole			LRS03-2009 / MW / 1	2501.950/1138.680	USM	Rupelian	Major Z.	Marnes rouges (red marls)	MGL (coll. MW)
21. Crissier (VD), La Mèbre streambed (= sample Mèbre 446, Berger 1983)			Mèbre-1997 / POM / 1	2534.360/1550.910	USM	Middle Aquitanian	Nitida / Berdotensis Z. transition, MN 1-2a	Molasse grise de Lausanne (black marls)	MGL (coll. POM)
22. Mamand (VD), streambed (cf. samples Mamand Pont; Berger 1983, 1985)			MR-2017 / POM / 1	2559.385/1178.060	USM	Late Aquitanian	Berdotensis Z., MN 2a-b transition	Molasse grise de Lausanne (grey marls, Fig. 6b) (red marls with *Ritteneria* sp., 2559.425/1178.030)	MGL (coll. POM); NMB (leg. POM)
23-24. Cheyres (FR)	23. Roadside (= sample CH I-6 / Cheyres 29; Berger 1983, 1985)		CR-2017 / POM / 1	2550.980/1185.720	USM	Late Aquitanian	Berdotensis Z., MN 2b	Molasse grise de Lausanne (red marls, Fig. 6c)	MGL (coll. POM)
	24. Pathway (= sample Béthanie 2; Berger 1983, 1985)		CB-2017 / POM / 1	2551.185/1185.657	USM	Late Aquitanian	Berdotensis Z., MN 2b	Molasse grise de Lausanne (yellow and green marls)	MGL (coll. POM)
25. Arrissoules (VD), forest path			ARR-2017 / POM / 1 - 2	2549.180/1183.570	USM	Late Aquitanian	Berdotensis Z.	Molasse grise de Lausanne (greenish-beige marls)	MGL (coll. POM)
26. Hauteville - Le Ruz (FR), streambed			HLR-2017 / POM / 1 - 2	2575.735/1169.425	UMM	Middle-Late Rupelian	Major Z.	Grès de Vaulruz (lacustrine limestone + lignite, Fig. 13a)	MGL (coll. POM)
27. Hasle-Entle (LU)			HE-2017 / POM 1	2647.540/1203.430	OMM I	Late Aquitanian	Berdotensis Z.	Luzern Formation (palustrine marls, Fig. 13b)	MGL (coll. POM)
28. Auw (AG), Mariahaldetobel			AMHTBL-2017 / DK / 1	2667.880/1228.900	OSM	Serravallian	"Ginsburgi" / Etrusca Z. transition, upper MN 6	"Oeningian" (dark coloured marls)	MGL (coll. POM)
29. Beinwil (Freiamt), (AG), Brandtobel			BBDTBL-2017 / DK / 1	2667.655/1230.840	OSM	Serravallian	"Ginsburgi" / Etrusca Z. transition, upper MN 6	"Oeningian" (dark coloured marls)	MGL (coll. POM)
30. Hungerbol (Germany), near Stein am Rhein (SH)			TDH-2016 / DK / 1	2708.095/1282.505		Early Pleistocene	Obtusa Z.	Tiefere Deckenschotter (fine silty green sand)	MGL (coll. POM)

charophyte biozonation and taxonomy for the Swiss Molasse Basin published by Berger (1983, 1986, 1992, 1999, *in*: Reichenbacher et al. 1996; Kälin et al. 2001; Berger et al. 2005b; Charollais et al. 2007), as well as the otolith-zonation for the brackish and lacustrine deposits of the western Paratethys (Reichenbacher and Weidmann 1992; Reichenbacher 1999, p. 376). Some additional data are also reported about other non marine microfossils as ostracods (identified from Carbonnel et al. 1985; Pirkenseer and Berger 2011), gastropods and plant remains.

Materials and methods

For this study, 170 marl samples of about 1–2 kg and partly up to 20 kg dry weight were collected from 45 sites (data reported on Fig. 1, Table 1), wet-sieved (mesh width ranging from 250 µm to 2 mm) and sorted using a binocular loupe. The samples were collected between 1981 and 2017 by M. Weidmann and J.-P. Berger [Le Locle, with B. Engesser and J. Hürzeler (1981–1996), La Scheulte (1983), Del 1 borehole (1990)], E. De Kaenel [Montmollin (1990)], D. Kälin [Le Locle (1990–1996), Châtillon and Fessevillers (exploratory samples, 2013), Balm (2013–2014), Laupersdorf (2014), Tramelan (2015), Tiefere Deckenschotter Hungerbol (2016), Diegten Süsswasserkalk (2016), Mariahaldetobel and Brandtobel (2017)], B. Hostettler et K. Ramseyer [Séprais (1997)], M. Weidmann [La Rippe borehole (2009)], the Paléontologie A16 team [A16 construction sites in the Delémont Basin (2001–2010) and sites near Neuchâtel (Bevaix and Marin-Epagnier, 2004–2005)], K. Ramseyer [Oberdorf Süsswasserkalk (2013)] and P.-O. Mojon [La Mèbre (1997), Le Locle (2011–2017), Châtillon and Hauterive/Rouges Terres (2013), Oberdorf Süsswasserkalk/USM and Fessevillers (2014), Trois-Rods/

Table 2 Framework and lithostratigraphic terminology with references for the Paleogene and Neogene of the Swiss Molasse Basin and Jura Mountains. **a** NW-Jura border and Jura Mountains with synclines of the Neuchâtel High-Range, northern Plateau. **b** NE-Jura border and Jura Mountains with the distal basins of Ajoie, Delémont and Laufen within the Upper Rhine Graben tectonic province. Inferred datings (mammals, charophytes and nannofossils) are indicated by brackets

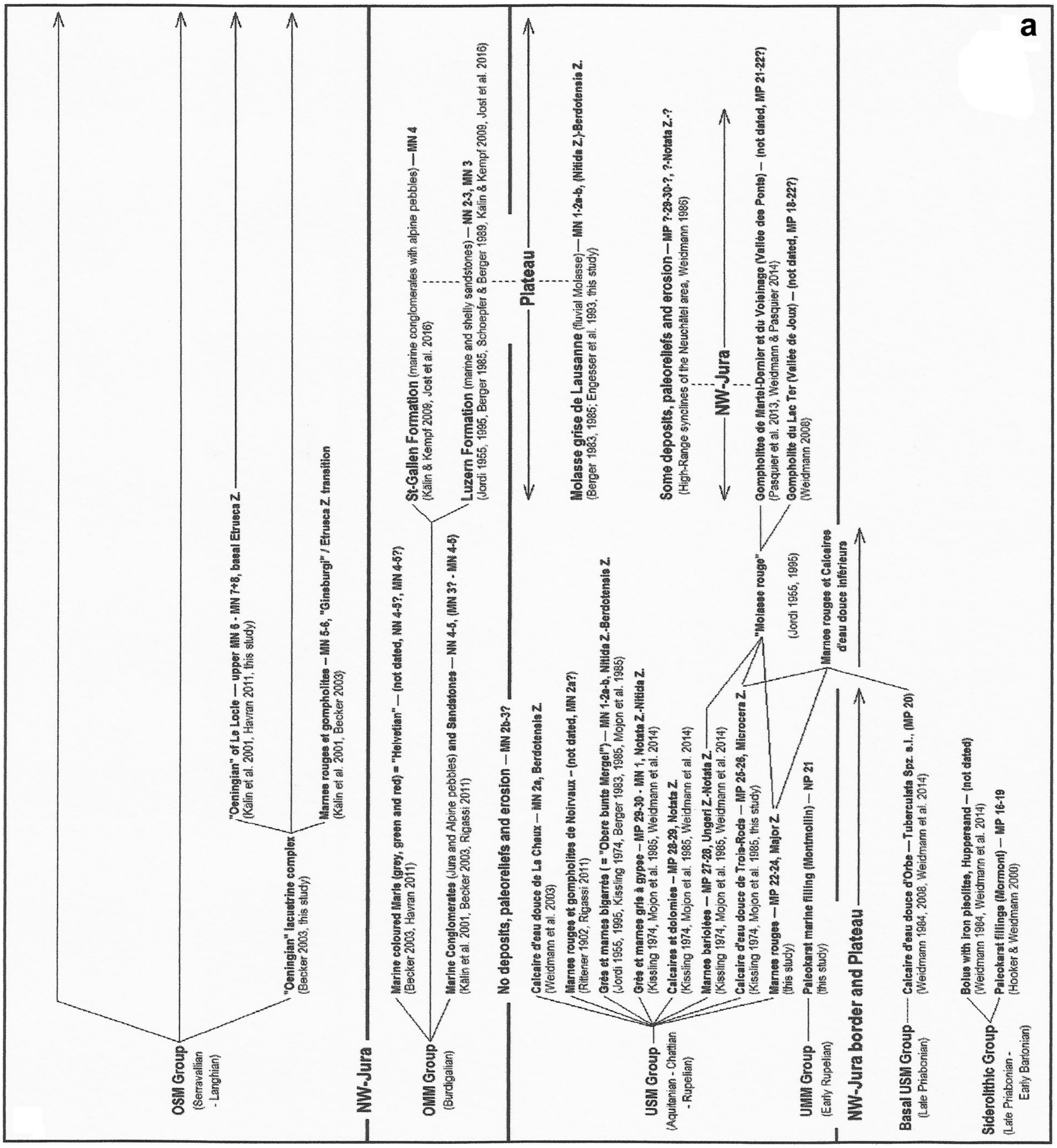


Table 2 continued

b

Jura

- **OSM Group** (Serravallian - Langhian)
  - **Bois de Raube Formation** Alluvial conglomerates with Jura and Vosges pebbles, sands and lower lacustrine marls — (Kälin 1997)
    - **Ajoie Member** – Hipparion Sands (Charmoille) with *Hippotherium primigenium* (von Meyer 1829), (Becker 2003) — **MN 9** (Idem)
    - **Bois de Raube Member** (Idem) / **Montchaibeux Member** (Idem) — Deinotherium Sands and marls with leaves of mediterranean trees (Kälin 1997) — **MN 7**
  - **Nebelberg Süsswasserkalk — MN 9, Etrusca Z.** (Kälin & Engesser 2001, Becker 2003)
  - **Anwil Süsswasserkalk — MN 8, Etrusca Z.** (Engesser 1972)
  - **"Oeningian" (Tramelan) — MN 7+8, basal Etrusca Z.** (Aufranc et al. 2016a)
  - **Vermes Süsswasserkalk — MN 5-6/7** (Kälin 1993, Bläsi et al. 2015)

- **OMM Group** (Burdigalian)
  - **Paleokarst marine fillings of Glovelier** (Jura and Vosges pebbles) — **MN 4** (Hug et al. 1997, Becker 2003)
  - **Marine Conglomerates** (Jura and Vosges pebbles) **and Sandstones (Corban) — (not dated, MN 3-4?)** (Becker 2003)
  - **Marine Conglomerates** (Jura and Alpine pebbles) **and Sandstones (Tavannes) — MN 3** (Beaumont et al. 1984, Becker 2003)

- **USM Group** (Aquitanian - Late Chattian)
  - **Gray-beige Sandstones and Marls (Tavannes) — MN 2** (Aufranc et al. 2016a)
  - **Calcaires delémontiens — MP 29-30 - (MN 1), Notata Z.-Nitida Z.** (Picot 2002, Becker 2003, this study)

- **Stockstadt Group** (Grimm 2004, Grimm et al. 2011; Late Chattian - Early Rupelian)
  - 2 **Elsass Subgroup** (Idem)
    - **"Molasse alsacienne"** (incl. Marnes noires de la Birse) — **MP 23-29, non basal Major Z.- Notata Z.** (Clément 1998, Picot 2002, Becker 2003, Becker et al. 2004, Picot et al. 2008, this study)
    - **Niederroedern Formation — non basal Major Z.-Microcera Z., (MP 24-26, NP 24-25)** (Pirkenseer et al. 2013)
  - 1 **Froidefontaine Subgroup** (Idem) — **Série grise** (Cyrenenmergel, Cyathula-Bank, Cyathulamergel, Septarienton, Meeressand) — **NP 22-24, MP 22-26** (Sittler 1965, Berger et al. 2005a-b, Roussé 2006, Picot et al. 2008, Pirkenseer & Rauber 2014, 2015)
  - **Gompholite d'Ajoie** (marine conglomerate) — **(MP 22)** (Picot 2002)

- **Pechelbronn Group** (Sittler & Schuler 1988; Early Rupelian - Late Priabonian)
  - **Conglomérat de Porrentruy** (fresh- to brackishwater conglomerate) — **Tuberculata Spz./Pinguis Z. - basal Major Z. (MP 21-22)** (Picot 2002, Picot et al. 2008, this study)
  - **Terre jaune — Tuberculata Spz./Vectensis Z. - basal Major Z. (MP 20-22)** (Picot 2002, Picot et al. 2008, this study)

- **Haguenau Group** (Grimm 2004; Middle-Late Priabonian)
  - **Diegten Süsswasserkalk — Vasiformis-Tuberculata Z., (MP 18-19)** (Cloos 1910, Jenny 1928, this study)
  - **Calcaires d'eau douce de Moutier — Vasiformis-Tuberculata Z., (MP 18-19)** (Reichenbacher et al. 1996, this study)

- **Siderolithic Group** (Middle Priabonian - Early Bartonian)
  - **Bohnerz-Konglomerat, Huppersand, Gompholite/Calcaire d'eau douce de Daubrée — MP 16-18 + Vasiformis-Tuberculata Z., (MP 18-19)** (Stehlin 1903, Picot 2002, this study)
  - **Paleokarst fillings — MP 16-18** (Picot 2002, Becker et al. 2013b, this study)

NE-Jura border and Plateau

- **OMM Group** (Burdigalian)
  - **St-Gallen Formation** (marine conglomerates with Alpine pebbles) — **MN 4** (Kälin & Kempf 2009, Bitterli et al. 2011, Bläsi et al. 2015, Jost et al. 2016)
  - **Luzern Formation — MN 3** (Kälin & Kempf 2009, Bitterli et al. 2011, Jost et al. 2016)
- **No deposits, paleoreliefs and erosion — MN 3** (Bläsi et al. 2015)
- **No deposits, paleoreliefs and erosion — MN 1-2** (Bläsi et al. 2015)

- **USM Group** (Early Aquitanian - Late Chattian)
  - **Delsberger Süsswasserkalk — MP 29-30 - MN 1, Notata Z.-Nitida Z.** (Bitterli et al. 2011, Bläsi et al. 2015, this study)
  - **Obere bunte Molasse — MN 1**
  - **Kalksandsteinserie — MP 30**
  - **Untere bunte Molasse — MP 29**
  - **Matzendörfer Süsswasserkalk — (not dated, MP 27-28?)**
  - **"Elsässer"/Aarwanger Molasse** (with Boninger Süsswasserkalk) — **MP 27-28**
  - **Oensinger bzw. Wynauer Süsswasserkalk — MP 26**
  - (Bitterli et al. 2011, Bläsi et al. 2015)

- **Stockstadt Group** (Early Chattian - Rupelian)
  - **Fossilreiche Süsswasserkalke und -mergel — Major Z. - ?, (MP 22-24-?)** (Bläsi et al. 2015)

- **Haguenau Group** (Late Priabonian)
  - **Bräunlichrote Bolustone z.T. mit Bohnerz — (not dated)** (Bläsi et al. 2015)
  - **Oberdorf Süsswasserkalk — Tuberculata Spz./Vectensis Z., (MP 20)** (Bläsi et al. 2015, this study)

- **Siderolithic Group** (Late Priabonian - Late Lutetian)
  - **Bohnerz Formation** (Boluston, Bohnerz, Huppererde, Krustenkalk) — **(not dated)** (Bläsi et al. 2015)
  - **? Conglomérat de Daubrée — (not dated)** (Bläsi et al. 2015)
  - **Paleokarst fillings — MP 14-19** (Schmidt-Kittler 1987)

Boudry and Diegten Süsswasserkalk (2016–2017), Marnand, Cheyres and Arrissoules (2016–2017), Montmollin, Hasle-Entle, Hauteville-Le Ruz and Soulce (2017)]. The reference material for this study (micropaleontological cells with the whole harvested material and figured specimens) is deposited at the Musée géologique de Lausanne (MGL, Unil, Dorigny) in the collections P.-O. Mojon (POM), J.-P. Berger (JPB) and M. Weidmann (MW), as well as at the JURASSICA Museum (JUR. Mus., Porrentruy, collection Paléontologie A16), the Fondation paléontologique jurassienne (FPJ, Glovelier) and the Naturhistorisches Museum Bern (NMBE, teeth of Eocene mammals from Moulin de Séprais) and the Naturhistorisches Museum Basel [NMB, leg. POM, teeth of small mammals from the Calcaire d'eau douce de Trois-Rods, the Marnand streambed (Molasse grise de Lausanne) and the "Lower Oeningian" of Le Locle]. As the sedimentation is notably influenced in the northern Swiss Jura Mountains by the tectonic activity of the Upper Rhine Graben (URG), the lithostratigraphical terminology includes major subdivisions with names of groups defined in the URG (Tables 1, 2b) and does not follow the traditional nomenclature for the Swiss Molasse previously published by the Schweizerisches Komitee für Stratigraphie und Landesgeologie (2014).

Results

Several Paleogene freshwater deposits of the Swiss Jura cannot be placed in the Siderolithic or in the UMM/USM; they are, therefore, considered as parts of the Haguenau, Pechelbronn and Stockstadt Groups defined within the URG tectonic province (Table 2b, cf. "Haguenau Group", "Pechelbronn Group", "Stockstadt Group").

Siderolithic Group

In Switzerland, the Siderolithic Group is formally defined in the Alps for the non-marine Eocene deposits (Menkveld-Gfeller et al. 2016). In the Jura Mountains and the border of the Swiss Plateau, major Siderolithic deposits are well known from the Lutetian to Priabonian (MP 14–20, Tables 1 and 2a, b). The Siderolithic sediments are altered and rubefied terrestrial sediments as sands and clays, prior to the Alpine folding and, therefore, not part of the Oligocene–Miocene Molasse. Among recent finds yet unpublished, a karstic fissure filling of the Reuchenette Formation in the quarry of Moulin de Séprais (Kimmeridgian limestones above the Marnes du Banné) yielded some teeth of Artiodactyls as *Mouillacitherium* sp. ($M^{1/2}$ dext.) and *Pseudamphimeryx* sp. (M^3 dext.) of the Early-Middle Priabonian mammal biozones MP 17–18 (det. J. Hooker, 1997; collection samples RM 172 FPJ 22679 and RM3 FPJ 22680, NMBE).

Haguenau Group

Diegten Süsswasserkalk

This site is a hill covered by forest and does not show currently a well visible section, but only few restricted and scattered outcrops of freshwater deposits as yellowish massive limestones and overlaying marls. These sediments constitute the Diegten Süsswasserkalk (= Mitteldiegten Limneenkalk) and their thickness is estimated at 10 m (Cloos 1910). In 2016, it was exceptionally possible to sample a thin upper layer of pinkish-grey marls with a rich assemblage of gastropods (Jenny 1928), limnic ostracods (*Metacypris*, *Virgatocypris* and *Heterocypris* spp.) and Middle–Late Priabonian charophytes of the Vasiformis–Tuberculata Zone (Feist-Castel 1971, 1977a; Riveline 1984, 1986) as *Harrisichara* gr. *vasiformis-tuberculata*, *Nitellopsis (Tectochara)* gr. *aemula-latispira*, *Gyrogona wrighti*, *Gyrogona wrighti-medicaginula*, *Gyrogona medicaginula*, *Gyrogona* gr. *caelata*, *Grovesichara distorta*, *Psilochara* gr. *bitruncata-conspicua* (Fig. 10.1–40). Other examples of similar Late Eocene freshwater limestones are known in the Tabular Jura, near Aesch, Lausen und Hochwald (Gutzwiller 1906, Picot 2002), but these ones have not been precisely dated so far. According to the facies of the Upper Rhine Graben (Grimm 2004; Grimm et al. 2011) and their Paleogene flora of charophytes (Schwarz 1997), the nearby lacustrine marls of the Diegten Süsswasserkalk can be considered as an equivalent of the Lymnäenmergel (upper part of the Haguenau Group).

Oberdorf Süsswasserkalk

At the eastern Swiss Jura border, the Oberdorf Süsswasserkalk (Fig. 2a) represents an isolated Late Eocene lacustrine deposit located near faults marking a southern extension of the Rhine Graben and previously considered as Early Oligocene (Bläsi et al. 2015). The Oberdorf section according to the original drawing of Rollier (1910) remains accessible, though mostly covered by vegetation. Part of the 22 m thick Oberdorf Süsswasserkalk crops out on the slope above the railway station and contains Late Priabonian charophytes of the Tuberculata Superzone [*Harrisichara tuberculata*, *Nitellopsis (Tectochara)* gr. *latispira-wonnacotti* (Fig. 11.76–81), *Rhabdochara* gr. *stockmansi-major*, *Sphaerochara* gr. *headonensis-parvula*] in thin marly layers of the lower part of the sections (5–10 cm thick, on ferruginous surfaces) and in massive limestone at the top (Fig. 3a). The species *N. (T.)* gr.

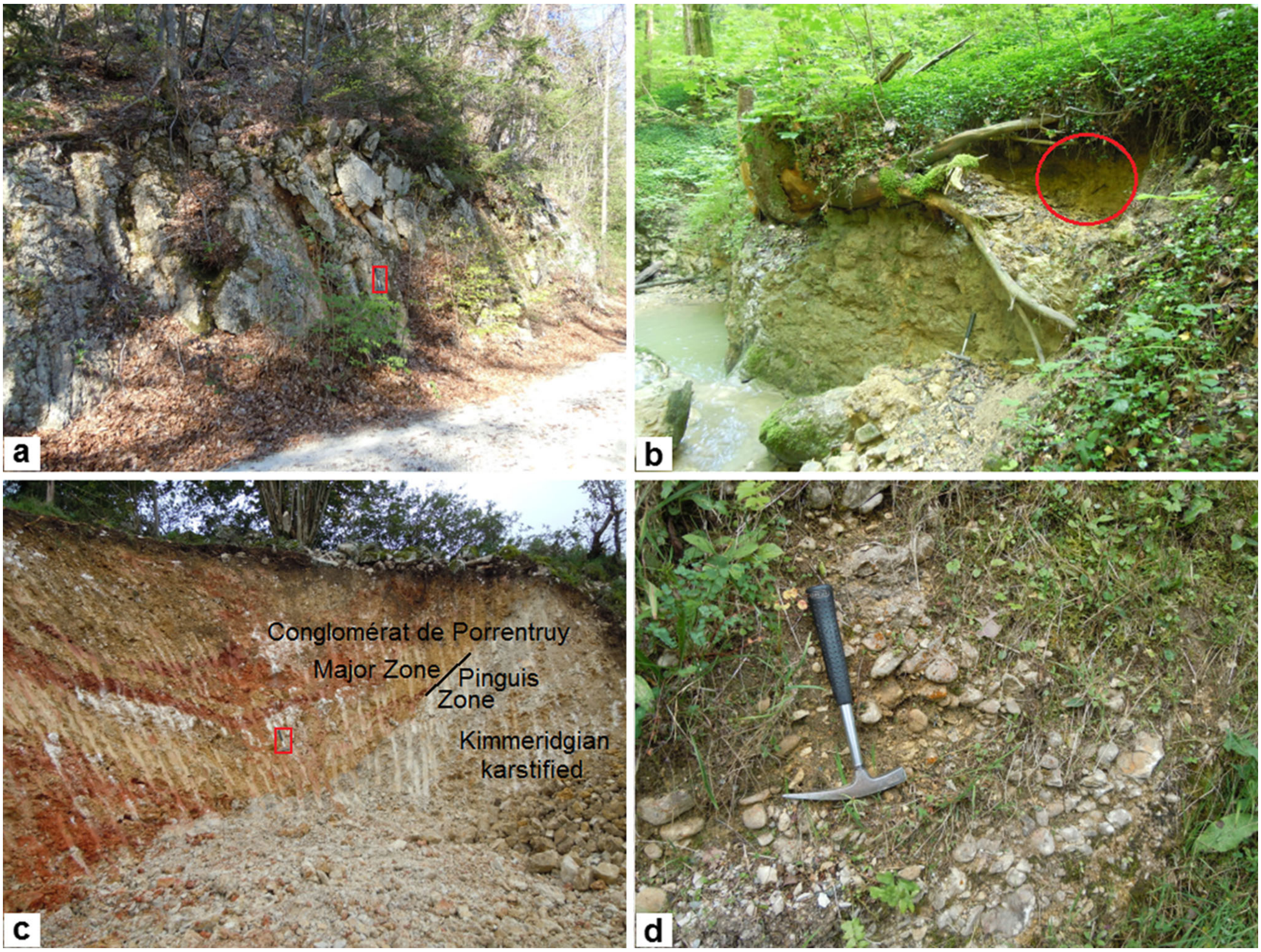


Fig. 2 **a** Oberdorf outcrop of freshwater limestone above the railway station. **b** Châtillon outcrop of Terre jaune (red circle) overlying Kimmeridgian limestones. **c** Fessevillers excavation in the Conglomérat de Porrentruy and its Kimmeridgian substratum. **d** Roadside Goumois–Fessevillers outcrop of Conglomérat de Porrentruy. The hammer is 31.5 cm long (red frame in **a**, **c**). Photos by P.-O. Mojon (2013–2014)

latispira-wonnacotti is particularly common in the marly levels of the lower part, while the massive limestone at the top is mainly characterized by *H. tuberculata* and *Rhabdochara* gr. *stockmansi-major*. Some layers of the Oberdorf Süsswasserkalk may contain up to 40% of kaolinite reworked from Siderolithic clays (e.g. marly layers with charophytes; K. Ramseyer, comm. pers. 2016) and the outcrop is covered by thick redbrown clays with iron pisolites and large quartz grains (bräunlichrote Bolustone, z.T. mit Bohnerz) likewise reworked from the Siderolithic. Another small outcrop with the kaolinite-rich clays (= Bolustone with iron pisolites or Bohnerz) of the Siderolithic and the overlying basal part of the Oberdorf Süsswasserkalk can be observed along the Weissenstein road. Near the railway station of Oberdorf and in the mostly covered upper part of the section, whitish 2 m thick lacustrine limestone beds are characterized by abundant small gastropods (Hydrobiidae) and yielded charophytes of the Major Zone (*Rhabdochara* gr. *stockmansi-major*, *Rhabdochara* gr. *praelangeri-major*). Intercalated between the lacustrine limestones of the Vectensis and Major Zones, the well-known laminated and bituminous layer (Dysodile) with well-preserved fishes (Fröhlicher and Weiler 1956; Gaudant 1977) belongs rather to Rupelian "Molasse alsacienne" (cf. very similar series of Soulce) than to basal USM (Bläsi et al. 2015). A comparison with the Paleogene charophytes of the Upper Rhine Graben (Schwarz and Griessemer 1994; Schwarz 1997) and northern Jura Mountains (this study, cf. "Assemblage zone SPN-EC 2") attests that the Oberdorf Süsswasserkalk can be placed between the Lymnäenmergel and the Mittlere Pechelbronn Schichten. Comparatively to the facies of the URG (Grimm 2004; Grimm et al. 2011), the thick Bräunlichrote Bolustone of Oberdorf could correspond in the URG to the Rote Leitschicht at the top of the Haguenau Group. The age indicated by the charophytes is coherent with this

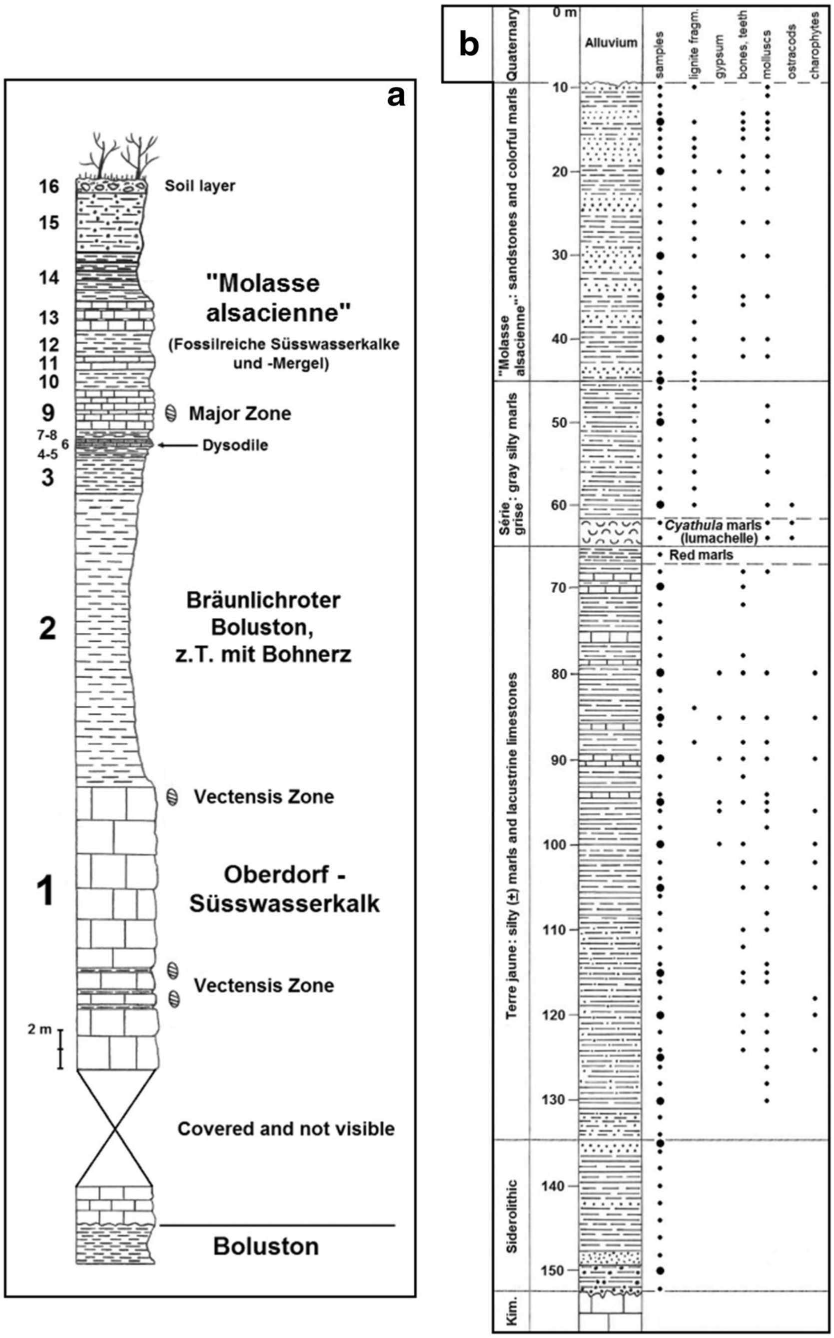


Fig. 3 **a** Oberdorf section above the railway station and along the road to the Weissenstein (survey 2014 by P.-O. Mojon, amended and redrawn from fig. 13 of Rollier 1910). Bolustone: reddish-grey calcareous clays with iron pisolites (Bohnerz). 1: Yellowish ferruginous lacustrine limestone and some thin marly layers with charophytes (Oberdorf Süsswasserkalk). 2: Red-brown clays with iron pisolites (Bräunlichrote Bolustone, z.T. mit Bohnerz). 3: Grey clayey marls. 4–5: Lower calcareous marl and greenish-grey marls with pisolites. 6: Dysodile: thin laminated calcareous layer with fossil fishes and ostracods. 7–8: Lower thin calcareous layers and blue-grey marls. 9: Whitish lacustrine limestones with charophytes and gastropods (Hydrobiidae). 10: Blue-grey marls. 11: Grey limestone. 12: Greenish-grey marls. 13: Lacustrine limestones and marly layers, upper part with lignitic interbeds (14) containing compressed lacustrine and terrestrial gastropods (Planorbidae, Lymnaeidae, Helicidae). 15: Sandy marls. 16: Moraine of the last glaciation with alpine blocks and topsoil. **b** Log of the Del 1/Rossemaison borehole (survey 1990 by M. Weidmann, detailed description in the text)

hypothesis placing the Oberdorf Süsswasserkalk as equivalent to the late Lymnäenmergel of the Haguenau Group.

Pechelbronn Group

Terre jaune

The designation of Terre jaune (syn. Gelbe Erde or Gelberde) was defined and described by Greppin (1855). This yellowish marly facies rarely crops out and is restricted almost exclusively to the central part of the Delémont Basin bordered by the faults of Develier and Vicques (Suter 1978; Clément and Berger 1999; Kälin 2013). It is a local lacustrine formation that ranges from the Late Eocene to the Early Oligocene (Picot et al. 2008; this study). The Terre jaune is constituted mainly by yellow argillaceous marls and yellowish-grey to orange limestones, with iron pisolites and Huppersand (quartzitic sands) reworked from prior Siderolithic deposits, millimetric to centimetric nodules of alumina silicate and some neoformed gypsum. Lenticular beds of conglomerates with pebbles of Jurassic limestones (gompholites) may also be intercalated near the basin margins. The main lithofacies is clayey at the base and becomes increasingly calcareous at the top of the series, with alumina silicate nodules also more frequent. Freshwater limestone intercalations of 1–5 m (Raitsche, Greppin 1870) and fibrous gypsum veins appear towards the top (Liniger 1925; Stalder and Rykart 1990). The Terre jaune clays consist of approximately 50% smectite and nearly 25% kaolinite (Becker 2003; Gander 2013), which implies reworked kaolinite from the Siderolithic and reworked clays from the eroded Lower Cretaceous according to the presence of some marine microfossils (ostracods, orbitolinids). Sittler (1965) concludes that the accumulation of Terre jaune deposits in the central part of the Delémont Basin was a result of poor drainage with smectite and gypsum neoformation in shallow ephemeral freshwater lakes, particularly towards the top of the series. The highest thickness of 50–140 m is recorded over the central fault block of the Delémont Basin (Greppin 1870). The Terre jaune is, however, absent (Clément 1998) or reduced to a few metres (Liniger 1925) in the basin areas east and west of the main faults. According to Greppin (1855, 1870), Rollier (1910) and Liniger (1925), the fossil content of the Terre jaune is poor. A summary in Antenen (1973, p. 74) provided no reliable dating, an issue revised more recently by Berger (1992) and Clément and Berger (1999). In this study three sites are discussed below to accurately determine the age of the Terre jaune. Heer (1856, 1859) reports the first discoveries of charophytes in the Terre jaune, describing and naming several important taxa. This abundant and well-preserved material was available conjointly with new collections of charophytes for a re-evaluation, in order to establish the synonymy with various genera and species created a century later. In samples of ETH-Zürich collected by J.-B. Greppin and studied by Heer (1856, 1859), Berger (1992) identified *Harrisichara tuberculata*, *Nitellopsis (Tectochara) latispira* and "*Chara siderolithica*" (cf. Table 4 and "Assemblage zone SPN-EC 2" for the taxonomy and synonymy).

Châtillon The Terre jaune in the streambed of the Bie creek near Châtillon (Fig. 2b) provided a rich charophyte assemblage (Fig. 11.16–75] with *Harrisichara tuberculata*, *Stephanochara vectensis*, *Nitellopsis (Tectochara)* gr. *latispira-wonnacotti*, *Nitellopsis (Tectochara)* gr. *aemula-latispira*, *Rhabdochara* gr. *stockmansi-major*, *Sphaerochara* gr. *headonensis-parvula* and *Tolypella pumila*. These charophytes indicate the Tuberculata Superzone and the Vectensis Zone (Feist-Castel 1977a; Riveline 1984, 1986) corresponding to the Late Priabonian small mammal zone MP 20 with the Grande Coupure event (major cooling and drying episode with vegetation change and migration of Asian mammals in Europe), below the limit with the Earliest Oligocene defined by the small mammal zone MP 21 and the *Pinguis* Zone of the charophytes (Hooker et al. 2004, 2009; Sille et al. 2004; Costa et al. 2011; Vandenberghe et al. 2012). According to this study (cf. "Assemblage zone SPN-EC 2"), a comparison with the Paleogene charophytes of the Upper Rhine Graben (Breuer and Feist 1986; Schwarz and Griessemer 1992, 1994; Schwarz 1997) indicates that the Terre jaune is an equivalent of the Pechelbronn Schichten of the URG (Pechelbronn Group, Sittler and Schuler 1988; Grimm 2004; Grimm et al. 2011).

Del 1 borehole The borehole Del 1, also named S 1 or Rossemaison borehole (Fig. 3b), was drilled in 1990 (Flury et al. 1991). The 432 m deep drilling revealed 12 m of Quaternary and 141 m of Cenozoic sediments overlying Jurassic strata of the Reuchenette Formation (Kimmeridgian). 85 samples of Cenozoic cuttings were collected [dry weight 1–2 kg (small dots) or 10–20 kg (large dots)]. Stratigraphic and geochemical preliminary data from this borehole were already published in Berger (1992), Todorov et al. (1993), Clément and Berger (1999), Picot (2002), Becker et al. (2004) and Picot et al. (2008). The investigated material allows a reliable interpretation of the stratigraphic units (top to bottom).

"*Molasse alsacienne*" or "*Elsässer Molasse*" from 9.5 to 45 m: fine-medium to coarse-grained sandstones, siltstones and yellow to grey-beige silty marls. Fragments of lignite, molluscs, bones and teeth are common. At 20 m, a deciduous premolar fragment of Gliridae (?left D4) identified as cf. *Peridyromys* sp. (det. B. Engesser & C.

Mödden, 1994) possibly indicates small mammal zones MP 27–29.

Série grise: from 45 to 65 m, mainly silty grey marls, rich in fragments of lignite and molluscs. The lower part corresponds to a facies variation of Meeressand with a rich profusion of *Cyathula* oysters (Pirkenseer and Rauber 2014), a 2–3 m thick lumachelle with molluscs, sea urchins and crabs, fish remains, foraminifers and marine ostracods (Clément 1998). In core boreholes BIR 16–17–18 from Courrendlin, the Série grise is correlated with calcareous nannofossil zones NP 23–24 (Berger 1992, p. 11; Clément 1998), corresponding overall to the small mammal zones MP 23–25.

Terre jaune: from 65 to 135 m, ocher or russet silty to sandy marls, with abundant reworked fragments of Boluston and Bohnerz between 96 and 135 m. From 65 to 110 m ocher, pink or white argillaceous marls, occasionally containing gypsum, caliche nodules and several intercalated beds of lacustrine limestones (Raitsche). The sediments between 95 and 138 m yielded abundant charophytes as *Harrisichara tuberculata*, *Nitellopsis (Tectochara)* gr. *latispira-wonnacotti*, *Nitellopsis (Tectochara)* gr. *aemula-latispira*, *Rhabdochara* gr. *stockmansi-major* and *Stephanochara vectensis* indicating the Tuberculata Superzone and Vectensis Zone of the Late Priabonian. Unfortunately, the mesh size of the sieves used for treating the samples of the Del 1 borehole was too large to collect very small charophytes as in Châtillon. Layers between 85 and 90 m are characterized by *Rhabdochara* gr. *stockmansi-major* and the occurrence of some new Early Rupelian taxa of the Major Zone as *Rhabdochara* gr. *praelangeri-major* and *Sphaerochara* gr. *hirmeri* (Fig. 12.44). A single gyrogonite of *Harrisichara tuberculata* was found (Fig. 12.28), probably resedimented or reworked by the drilling process. Rare fragments of small mammal tooth were also collected. A nonspecific Theridomyidae at 124 m and an incomplete upper molar of ?*Theridomys* cf. *aquatilis* at 100 m (det. B. Engesser & C. Mödden, 1990) would indicate rather the small mammal zone MP 21. According to the data of charophytes and small mammals, the Eocene–Oligocene boundary is placed around 100 m deep in the Del 1 borehole and the upper part of the Terre jaune can be, therefore, considered as Early Rupelian.

Siderolithic: lower limit at 152 m. About 5 m of red clay (Boluston) rich in iron pisolites (Bohnerz) is covered by white and red sands (Huppersand), followed by 10 m of red to yellow Boluston with coarse sandstone layers. These deposits are fossil barren. At about 135 m, transition to the Terre jaune. These observations confirm those of former reports (Quiquerez 1852; Greppin 1855; Fleury 1909; Baumberger 1923; Liniger 1925; Kürsteiner et al. 1990).

La Scheulte In the Delémont Basin, short sections of Siderolithic and Terre jaune are periodically exposed on the banks of the Scheulte River near Courcelon. These outcrops, whose extension varies with floods, were described by Greppin (1855, 1867, 1870), Rollier (1893, 1910), Fleury (1909), Baumberger (1923), Liniger (1925), Sittler (1965) and Hamel (1998). Marls characteristic of the Terre jaune are associated with small lenticular beds of freshwater limestone (Raitsche). Liniger (1925, p. 12) correlates the limestone layers of the Scheulte River with those encountered in the upper part of the Terre jaune in mine shafts located to the south of Courroux and near Delémont. One of these outcrops along the Scheulte River (Fig. 4a, layers 2 and 3) yielded well-preserved and abundant specimens of *Harrisichara tuberculata*, *Nitellopsis (Tectochara)* gr. *latispira-wonnacotti*, *Nitellopsis (Tectochara)* gr. *aemula-latispira* and *Stephanochara vectensis*, which indicate the Late Priabonian. For the washing–sieving of the samples made in the NMB, the mesh size of the sieves was too large to collect very small charophytes, as for the Del 1 borehole.

Conglomérat de Porrentruy

The studied section was located in a construction site within the village of Fessevillers (Doubs, France), near the Swiss border and just outside the western limit of the geological map drawn by Suter (1976). This site is reported by Aufranc et al. (2016a, b) and exposed in autumn 2014 the Conglomérat de Porrentruy and its substratum of karstified Kimmeridgian (Figs. 1, 2c).

Description of the section (top to bottom, Fig. 4b):

1—Topsoil, reworked and altered marl matrix containing blocks and pebbles (approx. 50 cm).

2–5—Conglomérat de Porrentruy (approx. 2 m) consisting of pebbles up to 10 cm diameter with intercalated marls and lacustrine limestones. This formation represents the interface between fluvio-lacustrine and brackish lagoonal to marine coastal paleoenvironments of the first and second marine incursion into the Upper Rhine Graben (i.e. marginal Middle Pechelbronn Beds and Série grise) and the Ajoie region (Picot 2002; Picot et al. 2008; Pirkenseer et al. 2013). Detailed sampling of the excavation site revealed a rich assemblage of microfossils as charophytes, ostracods and gastropods. Common reworked elements like Purbeckian authigenic quartz (Lower Cretaceous) and iron pisolites from Siderolithic (Eocene) are documented in this fluvio-lacustrine deposit.

2a, b—Conglomérat de Porrentruy with yellow and red marls (approx. 1 m) showing pedogenesis (root traces, paleosols) and containing charophytes of the basal Major Zone (cf. layer 4).

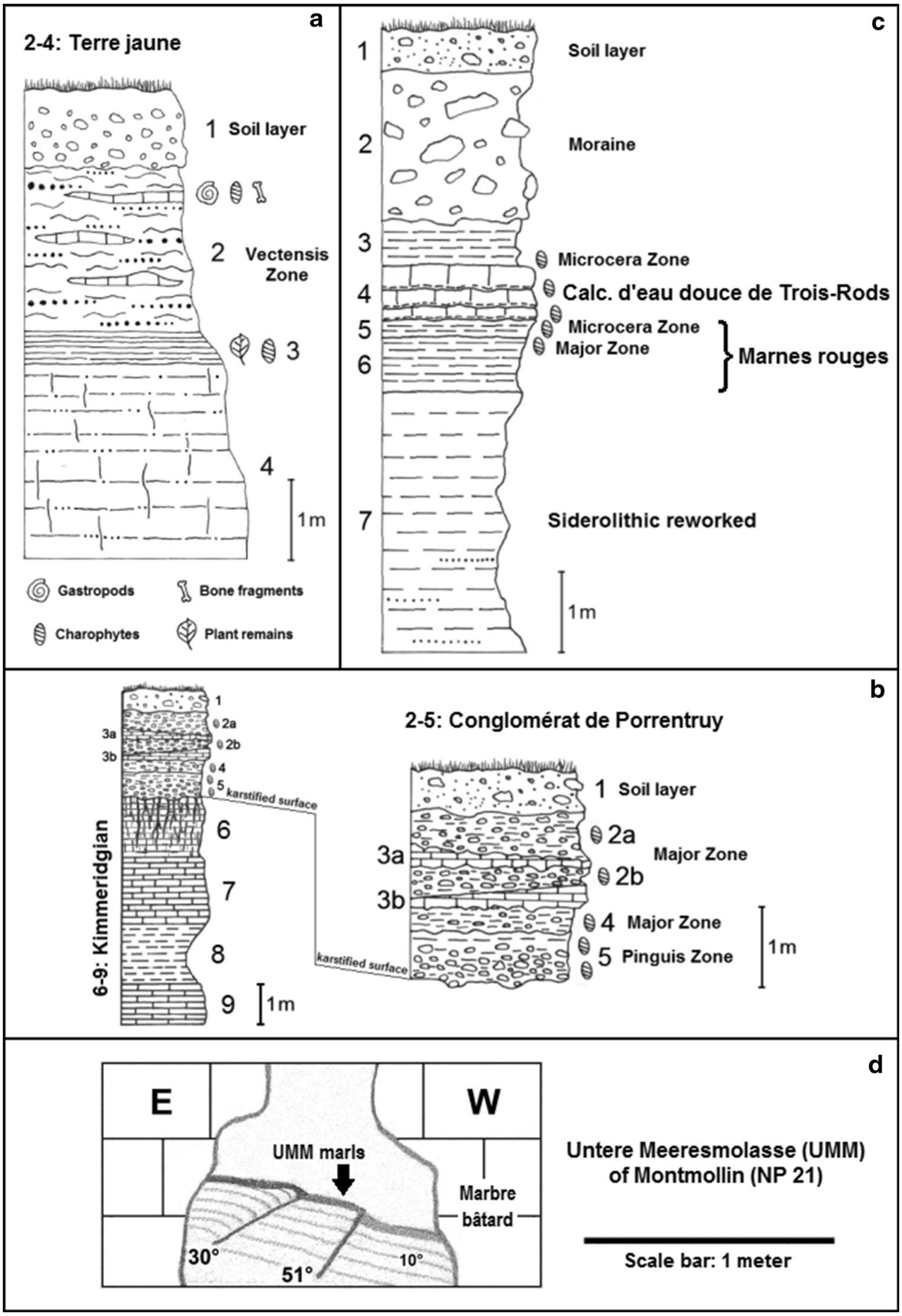


Fig. 4 **a** Scheulte River partial section of the Terre jaune (survey 1983 by M. Weidmann). 1: Alluvium. 2: White, beige or greenish clayey marls, with silty layers and small lenticular beds of chalky freshwater limestone containing planorbids (Raitsche), frequent pebbles of reworked Boluston, charophytes and undeterminable bone fragments. 3: Greenish-beige clay with charophytes and undeterminable plant remains. 4: Yellow, pink or orange silty homogeneous marls with inconspicuous stratification. **b** Fessevillers section in the Conglomérat de Porrentruy and its Kimmeridgian substratum (survey 2014 by P.-O. Mojon, detailed description in the text). **c** Hauterive/Rouges-Terres section (survey 2013 by P.-O. Mojon, detailed description in the text). **d** Scheme of a former large paleokarst filling of UMM in the Bois-Rond quarry at Montmollin (redrawn from a sketch of 1990 by X. Tschanz, detailed description in the text)

3a, b—Discontinuous lenticular beds of whitish lacustrine limestone (approx. 10–30 cm).

4—Yellowish conglomeratic marl (approx. 30 cm) with charophytes of the basal Major Zone [Fig. 12.1–10/29–32, *Rhabdochara* gr. *stockmansi-major*, *Rhabdochara* gr. *praelangeri-major*, *Nitellopsis (Tectochara)* gr. *meriani*, *Chara tornata*] and reworked Vasiformis–Tuberculata Zone [*Harrisichara* gr. *vasiformis-tuberculata* (Fig. 11.4–6), *Nitellopsis (Tectochara)* gr. *aemula-latispira*]. Some poorly preserved ostracods co-occur (*Virgatocypris* cf. *virgata* and *Cyprinotus*, *Hemicyprideis*, *Ilyocypris* spp.).

5—Argillaceous and conglomeratic grey marl (approx. 60 cm) with a microflora characteristic of the Tuberculata Superzone and Pinguis Zone [Fig. 11.1–3/7–15, *Harrisichara* gr. *lineata-tuberculata*, *Stephanochara pinguis*, *Nitellopsis (Tectochara)* gr. *aemula-latispira*, *Rhabdochara* gr. *stockmansi-major*, *Sphaerochara* gr. *headonensis-parvula* (rare)]. Scarce ostracods (*Pseudocandona* cf. *fertilis*, *Candona* and *Cypridopsis* spp.) and more frequent gastropod remains as abundant opercula of *Bithynia* sp. (Hydrobiidae) or some shells of *Hippeutis* sp. (Planorbidae), Lymnaeidae, Valvatidae and fluvio-lacustrine *Theodoxus* sp. (Neritidae) are also present. The karstification of the underlying Kimmeridgian is enhanced by pedogenesis indicated by large calcitic root casts.

6–9—Jurassic bedrock (topmost part of the Late Kimmeridgian, Comment et al. 2015), approx. 6 m.

6, 7—Basal part of the Twannbach Formation (approx. 3 m), small banks of beige limestone (7) karstified in the upper part (6).

8, 9—Highest part of the Reuchenette Formation (approx. 2.5 m), Marnes à *virgula* supérieures corresponding to yellowish coquinoid marls (8) with *Nanogyra virgula* and whitish limestone (9).

At the side of the road D437B from Goumois to Fessevillers the Conglomérat de Porrentruy (Figs. 1, 2d) overlies directly the uppermost Kimmeridgian (basal Twannbach Formation). The yellow marls mentioned by Suter (1976) are readily visible and provided typical *Rhabdochara* specimens of the Major Zone, as well as reworked authigenic quartz and iron pisolites. According to a comparison with the Paleogene charophytes of the Upper Rhine Graben (Schwarz and Griessemer 1992; Schwarz 1997), the Conglomérat de Porrentruy is an equivalent of the Obere Pechelbronn Schichten (this study, cf. "Assemblage zone SPN-EC 2") and can be placed at the upper part of the Pechelbronn Group.

Stockstadt Group

In the distal basins of Ajoie, Delémont and Laufen, the marine Froidefontaine Subgroup (Série grise) is closely imbricated with the non-marine Elsass Subgroup ("Molasse alsacienne" or "Elsässer Molasse", Niederroedern Formation, Fig. 1, Table 2b). In the northern Jura, the sedimentation of these deposits is alternatively influenced by the boreal sea inlet of the Upper Rhine Graben or by the rivers of the Alps. So the Froidefontaine Subgroup must be differentiated from the Rupelian UMM of the southern Swiss Plateau and northern Alps, as separate deposits of the western Paratethys or Perialpine Sea (Keller 1992; Gorin 1992; Matter and Weidmann 1992; Pictet et al. 2013). The "Molasse alsacienne" named also USM-J (USM des Juras, Schweizerisches Komitee für Stratigraphie und Landesgeologie 2014) is also quite different from the classical USM of the Swiss Plateau (Table 2a, b with references).

"Molasse alsacienne" (= "Elsässer Molasse")

In the Delémont Basin, charophytes were collected in construction sites of the Transjurane Highway A16 near Courroux, from small sections (2–3 m thick) in the strongly detrital lower part of the "Molasse alsacienne" (greenish-grey marly sands), just above the regressive marine Cyrenenmergel at the top of the Série grise (Fig. 1, Tables 1 and 2b). These sections are correlated with the Late Rupelian small mammal zones MP 23–24 at La Beuchille (Becker et al. 2004) or early MP 24 at Le Poillat (Becker et al. 2013a) and yielded mixed charophyte assemblages of the reworked Vasiformis–Tuberculata Zone [Fig. 12.54–64/66, *Nitellopsis (Tectochara)* gr. *aemula-latispira*, *Gyrogona wrighti-medicaginula* (large hybrid specimens), *Gyrogona wrighti*, *Psilochara* cf. *conspicua casselensis*, *Psilochara* gr. *bitruncata-conspicua*] and non basal Major Zone [Fig. 12.38–43/65, *Nitellopsis (Tectochara)* gr. *meriani*, *Rhabdochara* gr. *stockmansi–major*, *Rhabdochara* gr. *praelangeri-major*, *Chara minutissima*, *Sphaerochara* gr. *hirmeri*]. In the adjacent Soulce syncline, the "Molasse alsacienne" includes freshwater deposits of little thickness (Rollier 1910) with lower fluvio-lacustrine marls overlying lacustrine limestones characterized by stems of Characeae (*Rhabdochara* spp.) and various vertebrates comprising fishes, amphibians and large mammals as *Iberomeryx minor* (Gaudant 1979; Mennecart et al. 2011). The marls have provided very rare gyrogonites of charophytes indicating the Major Zone [*Nitellopsis (Tectochara)* gr. *meriani*, *Rhabdochara* gr. *stockmansi-major*], coherently with the small mammal zones MP 23-lower MP 24 pointed out by *Iberomeryx minor* like in the Delémont Basin.

USM Group (Untere Süsswassermolasse)

Marnes rouges

In the Molasse of the Swiss Plateau and Jura Mountains, the Swiss reference locality for small mammal zone MP 22 is Balm, where dark grey marls (1 m thick, sample BM-2013-14/DK, cf. Marnes rouges, Tables 1 and 2a) yielded typical charophytes of the basal Major Zone [*Rhabdochara* gr. *stockmansi-major*, *Rhabdochara* gr. *praelangeri-major*, *Nitellopsis (Tectochara)* gr. *meriani*].

Marnes rouges and Calcaire d'eau douce de Trois-Rods

The Marnes rouges and Calcaire d'eau douce de Trois-Rods are located between the Lake Neuchâtel and the first chain of the Jura Mountains. They belong to the basal USM of the NW-Swiss Plateau and Jura border (Fig. 1, Tables 1 and 2a). The first site of the Neuchâtel region is the reference locality of the Calcaire d'eau douce de Trois-Rods at Boudry (Mojon et al. 1985). Interbedded pinkish-grey marls in a small cliff of freshwater limestone (Fig. 5a, b) yielded typical charophytes of the Microcera Zone [*Chara* gr. *praemicrocera-microcera*, *Rhabdochara* gr. *praelangeri-major* (frequent), *Nitellopsis (Tectochara)* gr. *meriani*, *Sphaerochara* gr. *hirmeri*] and ostracods (*Metacypris danubialis*, *Moenocypris ingelheimensis*, *Pseudocandona* cf. *fertilis*), as well as gastropods from various freshwater paleoenvironments such as lacustrine, palustrine (Planorbidae, Lymnaeidae, Hydrobiidae, Valvatidae) or terrestrial (Helicidae, Pupilloidea and others indet. gen. and spp.). Large Helicidae as the land snail *Helix (Wenzia) ramondi* are especially common in the Calcaire d'eau douce de Trois-Rods and can be reported to the proximity of a well-developed landform. Eggshells of birds, plant seeds (*Carpolithus* sp., *Boraginocarpus*? sp.) and small mammal teeth are also present. The newly collected material with the small species *Eomys* nov. sp. 2 (P^4 sin., M_1 sin.) and two other fragmentary teeth of unidentified Gliridae and primitive Theridomyidae (det. D. Kälin, 2017) indicates clearly

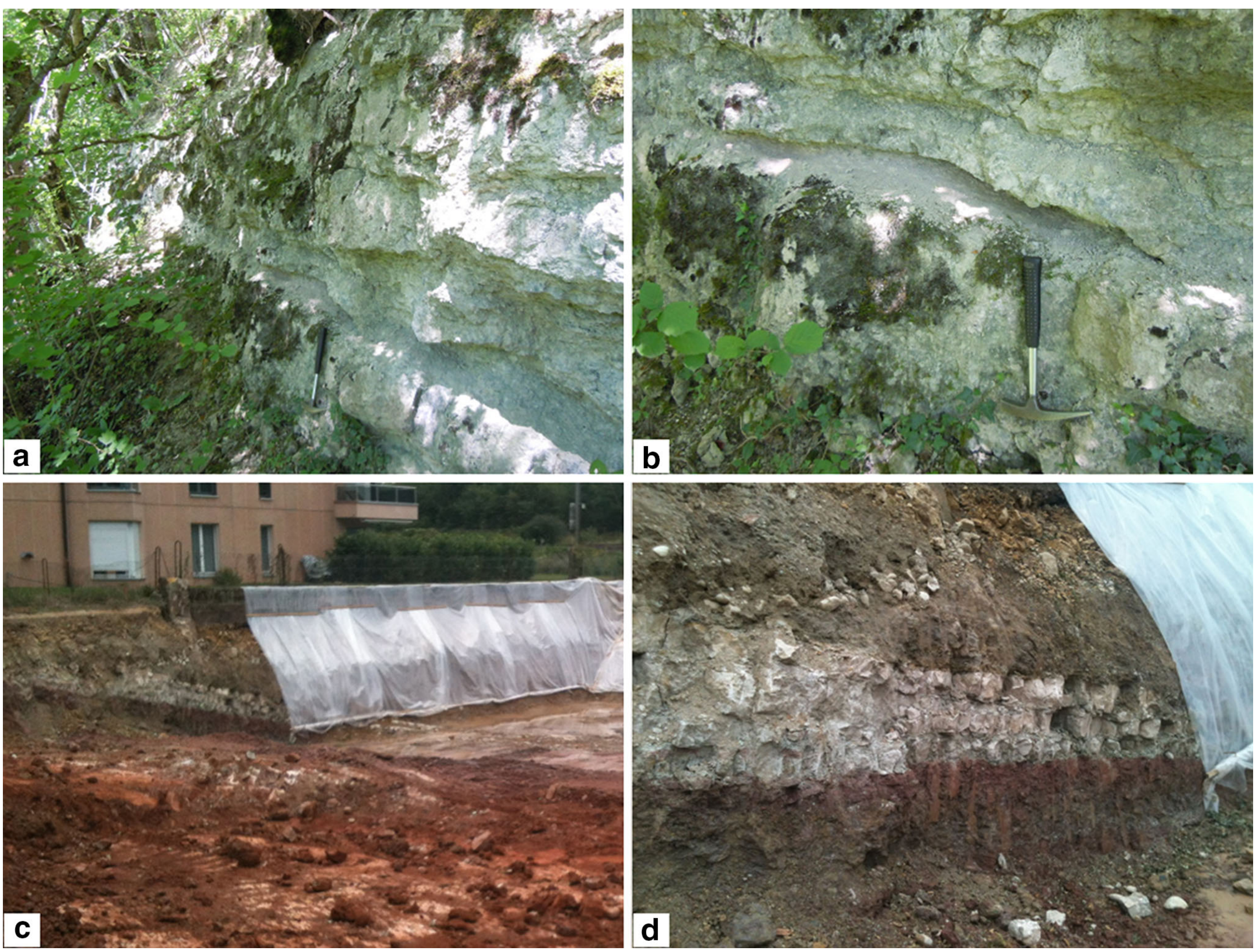


Fig. 5 **a**, **b** Boundary outcrop of the Calcaire d'eau douce de Trois-Rods (**b** detailed view of the main fossiliferous marly layer). The hammer is 31.5 cm long. **c**, **d** Rouges-Terres (Hauterive) excavation with reworked Siderolithic in the foreground, Marnes rouges and Calcaire d'eau douce de Trois-Rods (**d** detailed view of the Marnes rouges and Calcaire d'eau douce de Trois-Rods measuring approximately 60 cm thick). Photos by P.-O. Mojon (**a**, **b** 2016) and M. Affolter (**c**, **d** 2014)

the biozones MP 25–26a (Engesser 1990; Weidmann et al. 2014; Engesser and Kälin 2017) a partly contemporary age with the Oensinger bzw. Wynauer Süsswasserkalk (MP 26, Table 2b). In both cases, Eocene premolassic Siderolithic and Early Oligocene basal USM overlie a partly folded Mesozoic substratum (eroded and karstified) of Early Cretaceous at Trois-Rods or Late Jurassic (Malm) for the Oensinger Süsswasserkalk. The marly layers investigated contain also profusion of vadose pisoids (rounded smooth grains with an inner laminated structure) presumably formed in streams by strongly calcareous waters from vauclusian springs.

The currently covered basal USM below the Calcaire d'eau douce de Trois-Rods is about 20 m thick and was still undated (Mojon et al. 1985). This series was described by Desor and Gressly (1858) as marly sandstones and coloured marls ("marnes bigarrées/bariolées") with thin beds of lacustrine limestones, above red marls ("marnes rouges inférieures") overlying the Barremian substratum of white Urgonian limestones. In late November 2017, a drainage trench allowed finally to sample and to date precisely this basal USM (microslide deposited in the MGL with the samples POM from Trois-Rods). The coloured marls have provided charophytes of the Microcera Zone [*Chara* gr. *praemicrocera-microcera*, *Rhabdochara* gr. *praelangeri-major*, *Nitellopsis (Tectochara)* gr. *meriani*, *Sphaerochara* gr. *hirmeri*] with some ostracods (*Ilyocypris essertinensis*, *Cyprinotus parvus*, *Moenocypris ingelheimensis*) and gastropods (Planorbidae, Lymnaeidae, Valvatidae). The red marls correspond to reworked Siderolithic with iron pisolites and large quartz grains; they are characterized by large opercula of terrestrial gastropods and charophytes of the upper Major Zone [*Rhabdochara* gr. *praelangeri-major* (evolved), *Rhabdochara* gr. *stockmansi-major* (rare), *Nitellopsis (Tectochara)* gr. *meriani*]. So, the age for the basal USM of Trois-Rods is comprised between Late Rupelian and Early Chattian, in an interval corresponding to the small mammal zones MP 23–25.

The name Rouges-Terres of the second studied section in Hauterive hints at red marls presently covered, but formerly visible before the urbanization of the area. However, this is not mentioned in the geological map (Bourquin et al. 1968) and literature (Tribolet 1877). At 20 m northwest of the Neuchâtel–Bern railway line, an excavation for a residential building again provided access to these spectacular red marls in September 2013 and allowed the exceptional observation of the Rupelian–Early Chattian transition (Middle Oligocene) at the base of the USM (Fig. 5c, d). The studied section exposed from top to bottom (Fig. 4c):

1—Moraine of the last glaciation and soil of backfill.

2—Coloured marls (= Marnes bariolées, purplish, yellowish, reddish, approx. 50 cm), greenish at the base with charophytes indicating the Microcera Zone, ostracods and gastropods (cf. layer 4).

3—Whitish lacustrine limestone (= Calcaire d'eau douce de Trois-Rods, approx. 60 cm), three banks separated by interbeds of greenish marls with charophytes indicating the Microcera Zone and gastropods (cf. layer 4).

4—Red Marls (= Marnes rouges, approx. 20 cm) with very abundant charophytes of the Microcera Zone [Fig. 12.67–99, *Chara* gr. *praemicrocera-microcera*, *Rhabdochara* gr. *praelangeri-major*, *Nitellopsis (Tectochara)* gr. *meriani*, *Sphaerochara* gr. *hirmeri*], some ostracods (*Metacypris danubialis*, *Moenocypris ingelheimensis*, *Cyprinotus parvus*, *Pseudocandona* cf. *fertilis*, *Darwinula* sp.), gastropods (Planorbidae, Lymnaeidae, Valvatidae, scarce Helicidae) and pharyngeal teeth of fishes.

5—Coloured marls (= Marnes rouges, greenish-grey and reddish, approx. 70 cm). The upper part yielded very abundant charophytes of the Major Zone (Fig. 12.11–27/33/36–37/45–53), *Rhabdochara* gr. *stockmansi-major*, *Rhabdochara* gr. *praelangeri-major*, *Nitellopsis (Tectochara)* gr. *meriani*, *Chara minutissima*, *Sphaerochara* gr. *hirmeri*, *Stephanochara* aff. *martinii*, stem fragments of *Rhabdochara* spp.] with scarce ostracods (*Ilyocypris* cf. *essertinensis*), gastropods (planorbids) and bone fragments.

6—Argillaceous red marls with scattered reworked iron pisolites from Siderolithic (Eocene) deposits (> 3 m), the basal part exposed also yellow marls with purplish veins and lenticular interbeds of yellow–brown, strongly glauconitic hard sandstones. According to the geological map of Bourquin et al. (1968), the Urgonien blanc (Late Barremian) outcrops about 60 m northwest of the excavation with a dip of about 15° SE. The Urgonian was not reached by the deepest borehole of the construction site (7 m) nor those of the nearby A5 Highway. The total thickness of the layer 6 and the depth of the basal limit of the USM remain, therefore, unknown.

Calcaires delémontiens (= Delsberger Süsswasserkalk, USM-J)

In the northeastern Jura Mountains, the Calcaires délémontiens (MP 29–30–MN 1, Fig. 6a) are constituted by grey lacustrine limestones with marls and clays of various colours (greenish-grey, brown, black, grey or beige sometimes with reddish stripes). Locally, marls of the basal part can contain gypsum (Gypsmergel, Tüllinger Süsswasserschichten at Birsfelden, marnes à gypse in a borehole near Sonceboz, Picot 2002). Typical charophytes of the Nitida Zone [*Rantzieniella nitida*, *Stephanochara* gr. *oodea-praeberdotensis*, *Stephanochara* gr. *ungeri*, *Nitellopsis (Tectochara)* gr. *meriani*, *Chara* gr. *molassica-notata*, *Sphaerochara* gr. *hirmeri*, *Rhabdochara* gr.

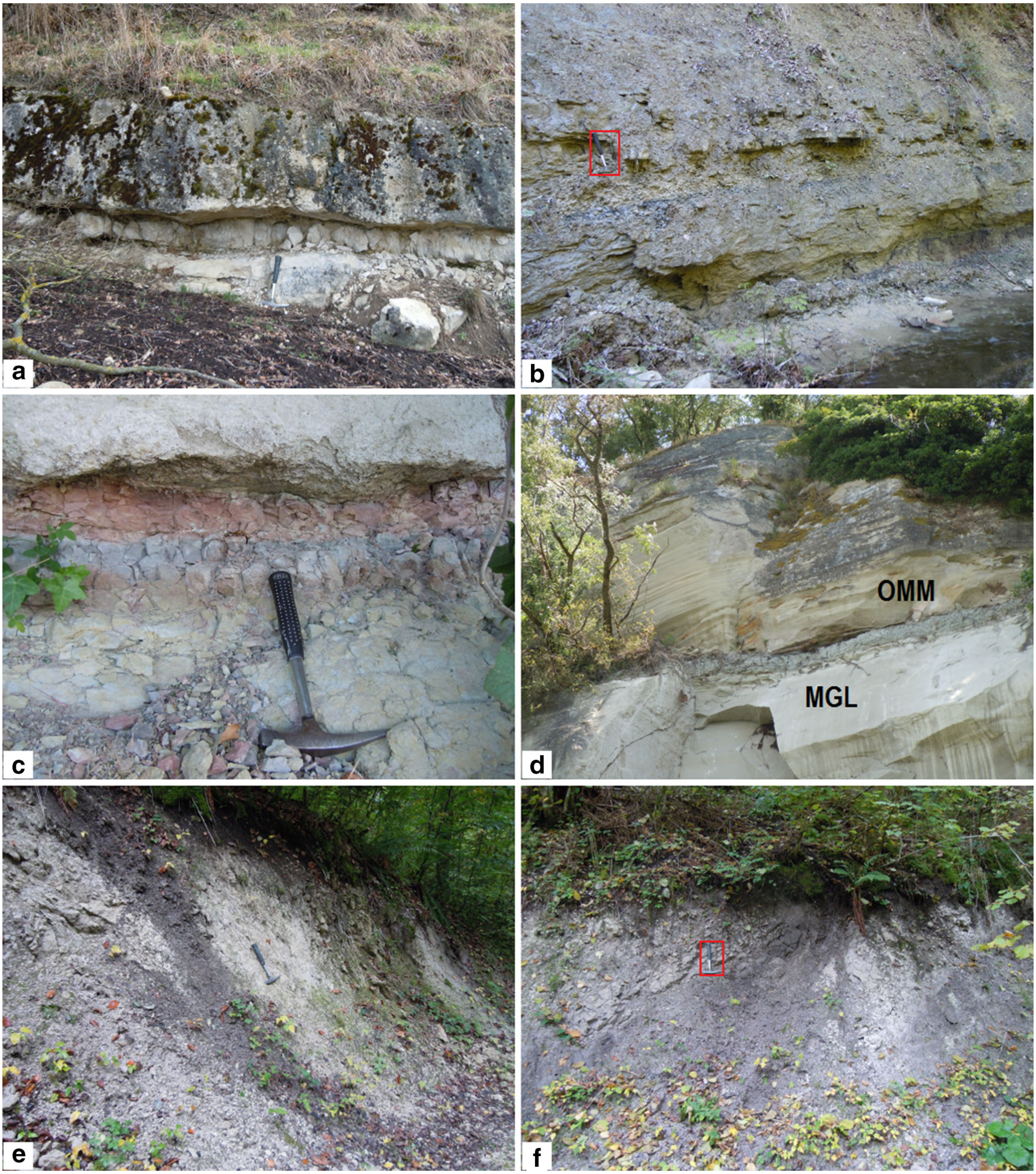


Fig. 6 Outcrops in the Early and Middle Miocene freshwater Molasse of the Swiss Jura and Plateau. **a** Calcaires delémontiens (USM, Early Aquitanian), small section in Courfaivre (Jura). **b**, **d** Molasse grise de Lausanne/MGL (USM, Late Aquitanian, Plateau), sections of Marnand streambed (**b** palustrine grey marls below the hammer in red frame, MN 2a-b transition) and Cheyres (**c** roadside section with palustrine red marls of MN 2b; **d** Château de Font section with contact of clayey marls of floodplain between MGL and OMM, upper part of the cliff about 6 m thick, coord. 2552.180/1187.160 from the map of Switzerland 1:25'000). **e**, **f** Lower "Oeningian" (OSM-J) of La Grecque section, Les Varodes nearby Le Locle (Jura), palustrine dark marls with lacustrine whitish and chalky limestones of the Langhian–Serravallian transition (strongly straightened beds in the edge of the syncline). The hammer (red frame in **b**, **f**) is 31.5 cm long. Photos by P.-O. Mojon (2017)

langeri] were identified recently (2016) in several marly layers (Figs. 1, 14.1–7/16–18, Tables 1 and 2b) from the Delsberger Süsswasserkalk of the Welschenrohr–Balsthal syncline at Laupersdorf (sample LG-2014/DK attributed to the small mammal zone MP 30, Bläsi et al. 2015) and the Calcaires delémontiens of the Delémont Basin (samples MCX008, CMCX-2017/POM, CN-2017/POM). In the Neuchâtel area, very thinned beds equivalent to the Calcaires delémontiens are interbedded in the Grès et marnes bigarrés of the Early Aquitanian (small mammal zone MN 1); they are notably characterized in the Boudry-Viaduc section by *Rantzieniella nitida* and small mammals as *Dimyloides stehlini* (Mojon et al. 1985; Weidmann et al. 2014). Two new localities with charophytes of the Nitida Zone were also found during the years 2004–2005 in the A5 Highway trench near Bevaix and in a borehole at Marin-Epagnier (Fig. 1, Table 1). The section of Bevaix was in a reddish-yellow series of sandstones and silty clays with dark marls [60–70 cm, sample TIL004 with *R. nitida, St.* gr. *oodea-praeberdotensis* (Fig. 14.12–15) and *N. (T.)* gr. *meriani*] between two layers of thin lacustrine beige limestones (15–20 cm). The borehole of Marin-Epagnier was 8 m thick and mainly through greenish-grey sandstones, with black marls (10 cm) at 3.5 m depth (sample PRA005-12 with *R. nitida* and *St. gr. oodea-praeberdotensis*) between a thin beige-brown bituminous limestone (10 cm) and greenish-grey clayey marls (60 cm) below. The lower part of the borehole included reddish-yellow to beige marly sandstones (1.5 m) with grey marls (20 cm) at 6.1 m depth [sample PRA005-14 with *N. (T.) gr. meriani* and numerous *Sph.* gr. *hirmeri*]. The Early Aquitanien deposits in Marin-Epagnier are precisely mentioned and described by Schardt (1901).

Molasse grise de Lausanne

Charophytes are rare in the mainly fluvial deposits of Molasse grise de Lausanne (MN 1–2). South of Lake Neuchâtel, three interesting sections near Marnand and Cheyres were investigated recently (2017) in order to illustrate them (Table 1, Figs. 6b–d, 14.8–11/22–44) and to complete previous data (Berger 1983, 1985). In Marnand, a deciduous molar of *Ritteneria* sp. (det. D. Kälin, 2017) was found with termite coprolites in red marls forming an irregular paleosol (5–15 cm) about 2 m above palustrine grey marls with *Stephanochara berdotensis*. In Cheyres, *Rantzieniella nitida* and typical *Stephanochara berdotensis* were collected together at the top of the MGL (Berdotensis Zone, MN 2b) just below the OMM, about 40 m above a red layer with *Lychnothamnus rhabdocharoides* (localities MN 2b of Béthanie 2 and CH I-6, respectively; Berger 1983; 1985, p. 149). In the same area, the transition USM-OMM at the top of the MGL was formerly reported from four currently partly covered sections near Arrissoules (Weidmann 1982; Berger 1983) with charophyte-rich greenish-beige marls (*Stephanochara berdotensis*) above a thin lacustrine limestone.

UMM Group (Untere Meeresmolasse)

Near Neuchâtel, paleokarst fillings of UMM with a very rich nannoflora (det. E. De Kaenel) were known since 1990 in a quarry of Marbre bâtard (Berriasian limestones) at the NW-Jura border (carrière du Bois-Rond, Montmollin, Fig. 1, Tables 1 and 2a), but not yet published. Paleokarst fillings can be observed from 3 to 8 m below the top of the quarry, with UMM fillings located at the bottom of the paleokarst (Fig. 7a–c). Before the destructive progression of the quarry, initial sections in the southern part near the road to Montmollin showed large karstic cavities half-filled with UMM marls deformed and fractured by the folding of the surrounding Marbre bâtard (Figs. 4e, 7c, d).

The UMM sediment is nannofossil rich and mainly constituted of very finely laminated grey marls, with some reddish thick bands (Fig. 7d). The laminations may be seasonal and indicate a very slow and regular deposition containing exclusively nannofossils. The ocher bands are massive and rip-up clasts of laminated grey marls indicate periodical erosive deposits by gravity flows. The reddish layers provided reworked clasts from the Early Cretaceous and Eocene (Purbeckian authigenic quartz, Berriasian trocholines and rare teeth of pycnodont fishes, Albian limonitic fragments of gastropods and ammonites, iron pisolites from the Siderolithic), including two fragments of possibly Rupelian shark teeth. According to the geology and lithostratigraphy of the central Jura, the paleokarst can, therefore, be considered as originally formed during the Eocene (Siderolithic) and subsequently filled by mainly reworked sediments of the central Jura (texture and colours mainly inherited from Albian marls, Eocene Terra rossa and Lower Marine Molasse).

The assemblage of nannofossils represents a mixture of 117 Paleogene and Cretaceous taxa (Table 3a, b and Fig. 8). The oldest species is *Cruciellipsis cuvillieri* from the Early Hauterivian (Hauterive blue marls of the Jura). The lowermost Rupelian age of the deposit can be inferred from the First and Last Appearance Data (FAD and LAD) of accurate markers as, amongst others, *Coccolithus pelagicus*, *Coccolithus formosus*, *Reticulofenestra celtica*, *Reticulofenestra dictyoda*, *Reticulofenestra samodurovii*, *Reticulofenestra rupeliensis*, *Reticulofenestra umbilicus*, *Clausicoccus quadriperforatus*, *Clausicoccus subdistichus*, *Dictyococcites perplexus*, *Dictyococcites bisectus*, *Dictyococcites stavensis*, *Dictyococcites pseudolockeri*, *Dictyococcites erbae*, *Dictyococcites filewiczii, Dictyococcites helianthus* and *Sphenolithus moriformis*,

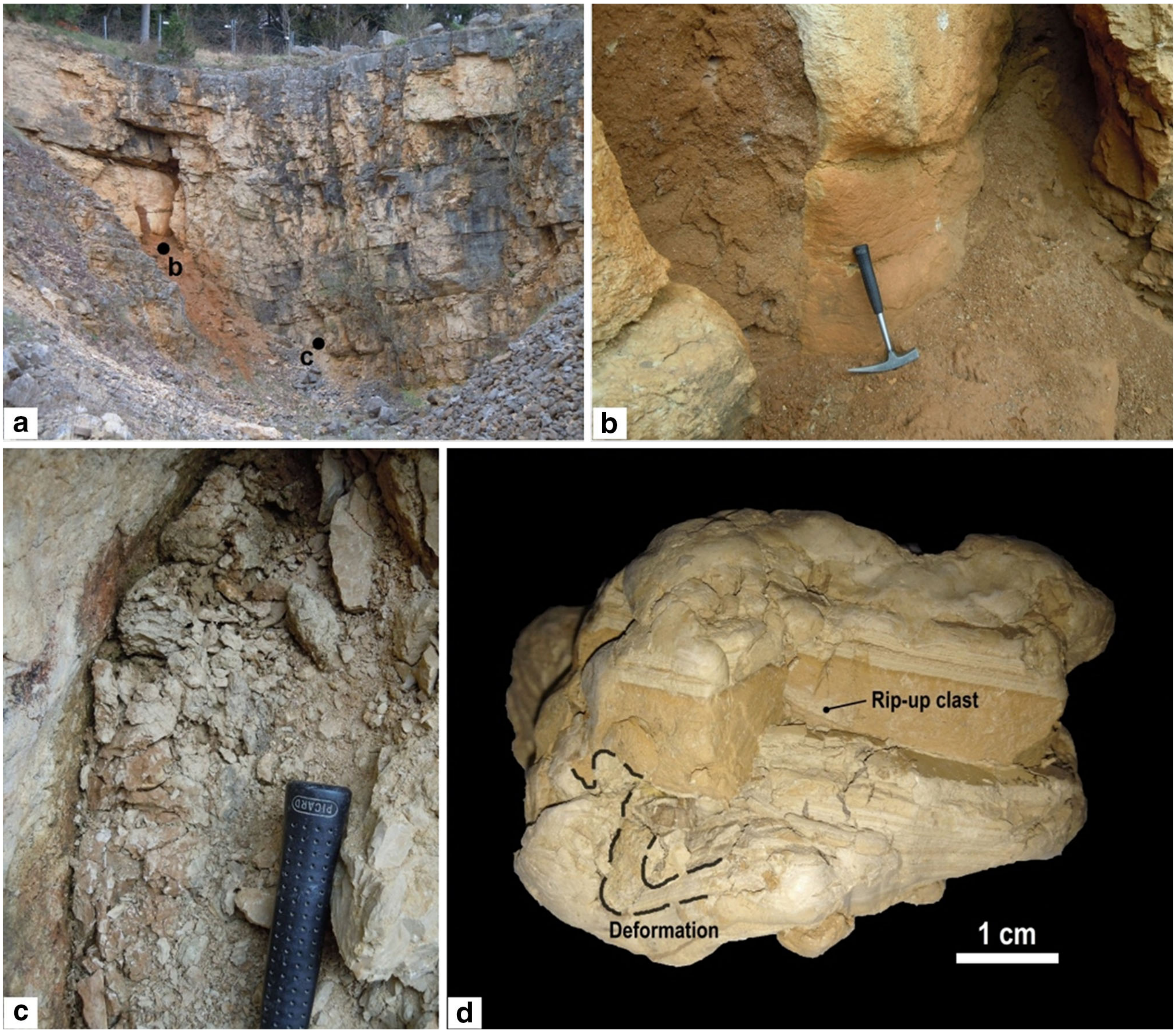


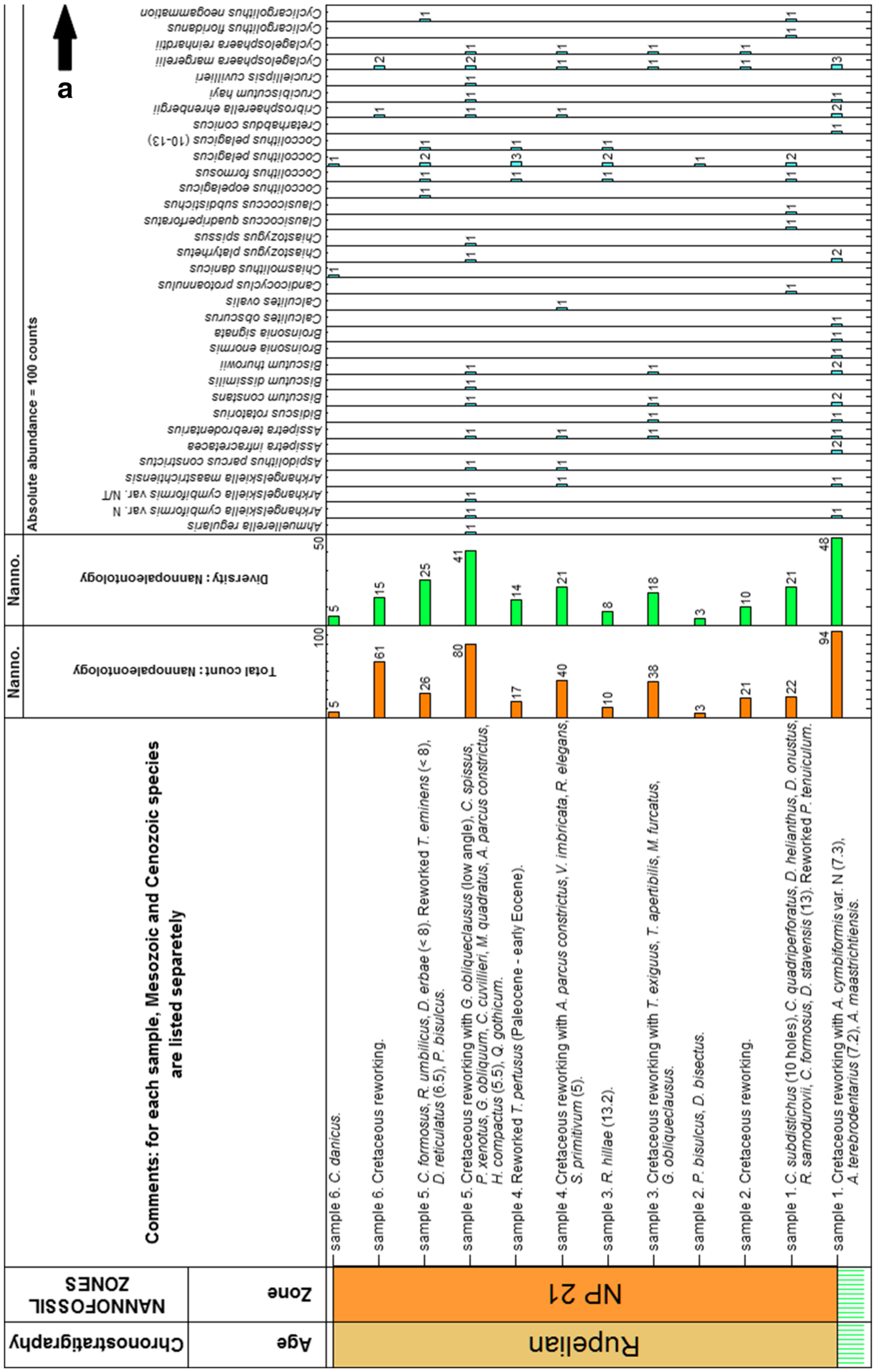
Fig. 7 **a** Quarry of Bois-Rond at Montmollin (2017), north-east part with karstified massive Berriasian limestones (Marbre bâtard, in part, approximately 11 m thick). **b** Upper part of the karstic fillings with coarse reddish sandstone (not dated, age undetermined). **c** Bottom of the paleokarst with UMM filling. **d** Sample of UMM collected in 1990 by E. De Kaenel from a former paleokarst filling (Fig. 4e, description and details in the text). The hammer is 31.5 cm long. Photos by P.-O. Mojon (**a**–**c**) and E. De Kaenel (**d**)

Zygrhablithus bijugatus. The biozone NP 21 is precisely pinpointed by the LAD of *Coccolithus formosus* (NP 12–21), the zonal marker for the NP 21/NP 22 boundary. *Isthmolithus recurvus* and *Dictyococcites daviesii*, which LAD's occur in lower part of zone NP 21, were not observed. Based on the species recorded, samples 1–6 (Table 3a, b) are placed in upper part of zone NP 21.

OSM Group (OSM-J, Obere Süsswassermolasse des Juras)

The Upper Freshwater Molasse (OSM-J) of La Chaux-de-Fonds—Le Locle syncline (Fig. 1, Tables 1, 2a) was primarily reported as "Oeningian" by the authors of nineteenth and twentieth centuries. Many of the most interesting paleontological data for this OSM-J and the underlying OMM (ostracods, charophytes, large mammals) still partially unpublished or unrevised are introduced more comprehensively hereafter. New data of this study concern small mammals from the upper part of "Lower Oeningian" [M^1 dext. and M^2 dext. of *Megacricetodon gersi* from Combe Girard 10, upper MN 6 (Oeschgraben marker bed)—basal MN 7 + 8 (Helsighausen marker bed), cf. Fig. 9; det. D. Kälin, 2017] and charophytes of the basal Etrusca Zone illustrated on Fig. 15.1–57 [*Nitellopsis (Tectochara) ginsburgi*,

Table 3 **a**–**b** Paleogene and reworked Cretaceous nannofossils from the UMM of Montmollin (for the taxonomy and detailed biostratigraphy, see Internet website http://www.mikrotax.org)



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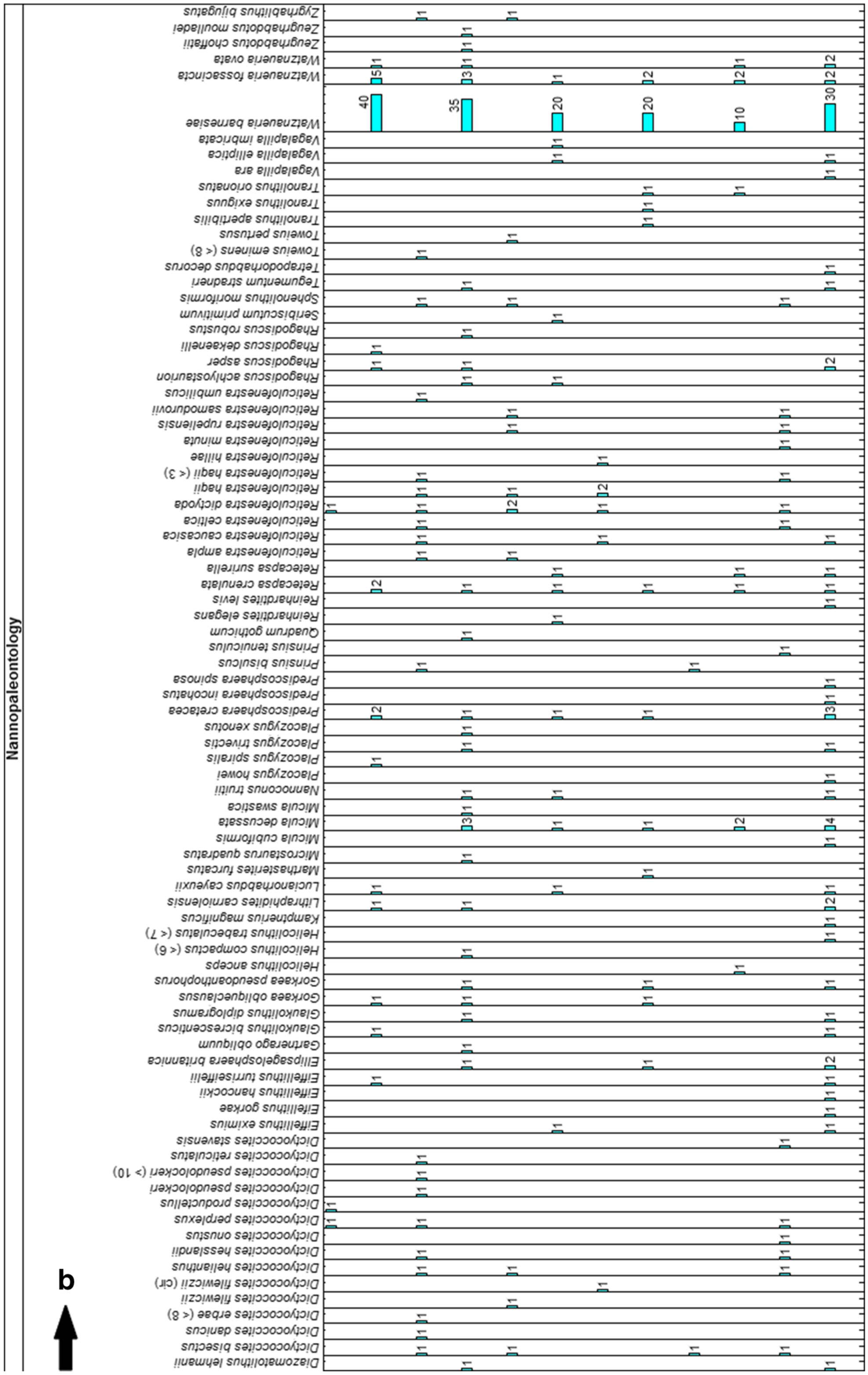


NB: Some data are unpublished as the Late Cretaceous species *Tranolithus apertibilis* (nomen provisorium, British Petroleum unpublished data) and the genus name *Dictyococcites* is considered by many authors as synonym of *Reticulofenestra* (E. De Kaenel, comm. pers. 2017)

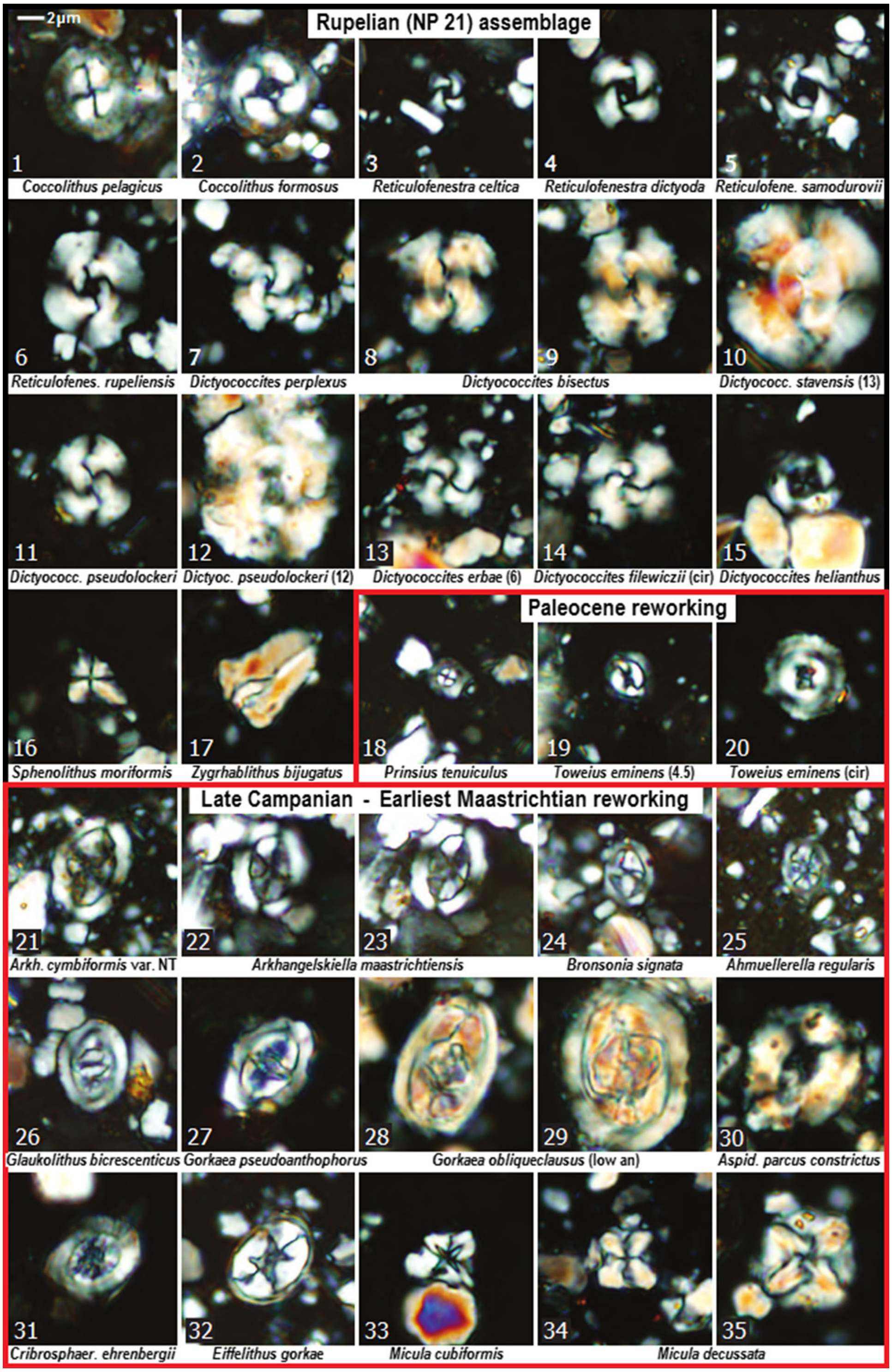


Fig. 8 Some Paleogene and reworked Cretaceous nannofossils from the UMM of Montmollin

Nitellopsis (Tectochara) etrusca, *Nitellopsis (Tectochara)* gr. *meriani*, *Lychnothamnus antiquus*, *Lychnothamnus duplicicarinatus*, *Lychnothamnus barbatus*, *Chara* gr. *molassica-notata*]. The laguno-lacustrine sediments of the Langhian–Serravallian OSM-J were deposited during a short period of approximately 500,000 years (14–13.5 Ma) with a progressive climate cooling during MN 6–7 (Kälin et al. 2001) and mainly in a short period of aridity pointed out during MN 4–7 (Becker 2003). These OSM-J deposits are nearly 200 m thick and can be

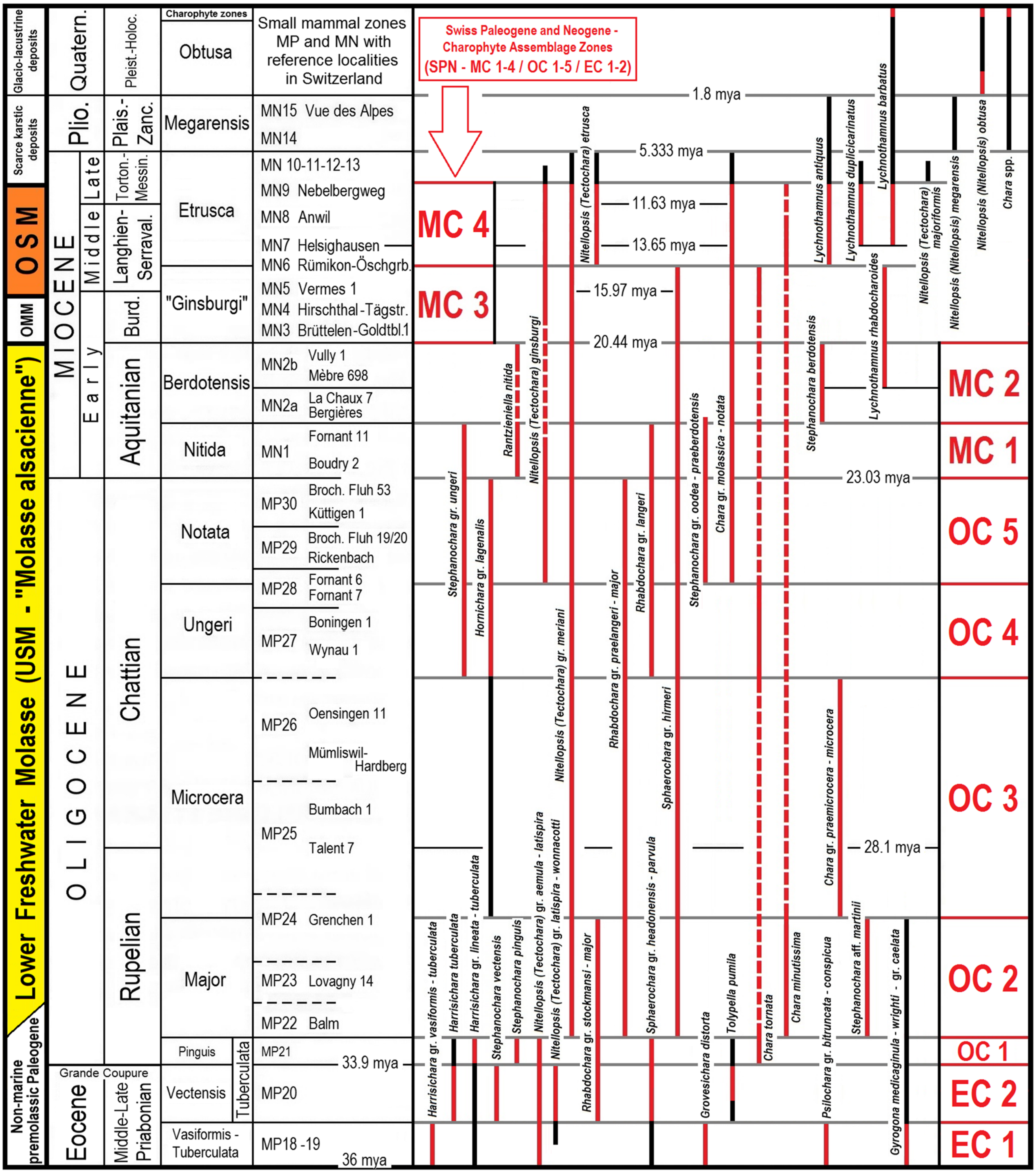


Fig. 9 Charophyte biostratigraphy from Late Eocene to Quaternary with stratigraphic ranges for the taxa of the SPN-assemblage zones (cenozones) in red and complemented in black for other European countries (discontinuous lines for transitional or very rare taxa not observed directly). Chattian–Aquitanian data mainly reported from Berger (1983, 1986, 1992, 1999; *in* Charollais et al. 2007), Berger et al. (2005b) and Weidmann et al. (2014). OSM small mammal zones with reference localities from Kälin and Kempf (2009) and absolute ages from the International Commission on Stratigraphy (International Commission on Stratigraphy 2014), Berger et al. (2005b) and Kälin et al. (2001, OSM-J/Le Locle)

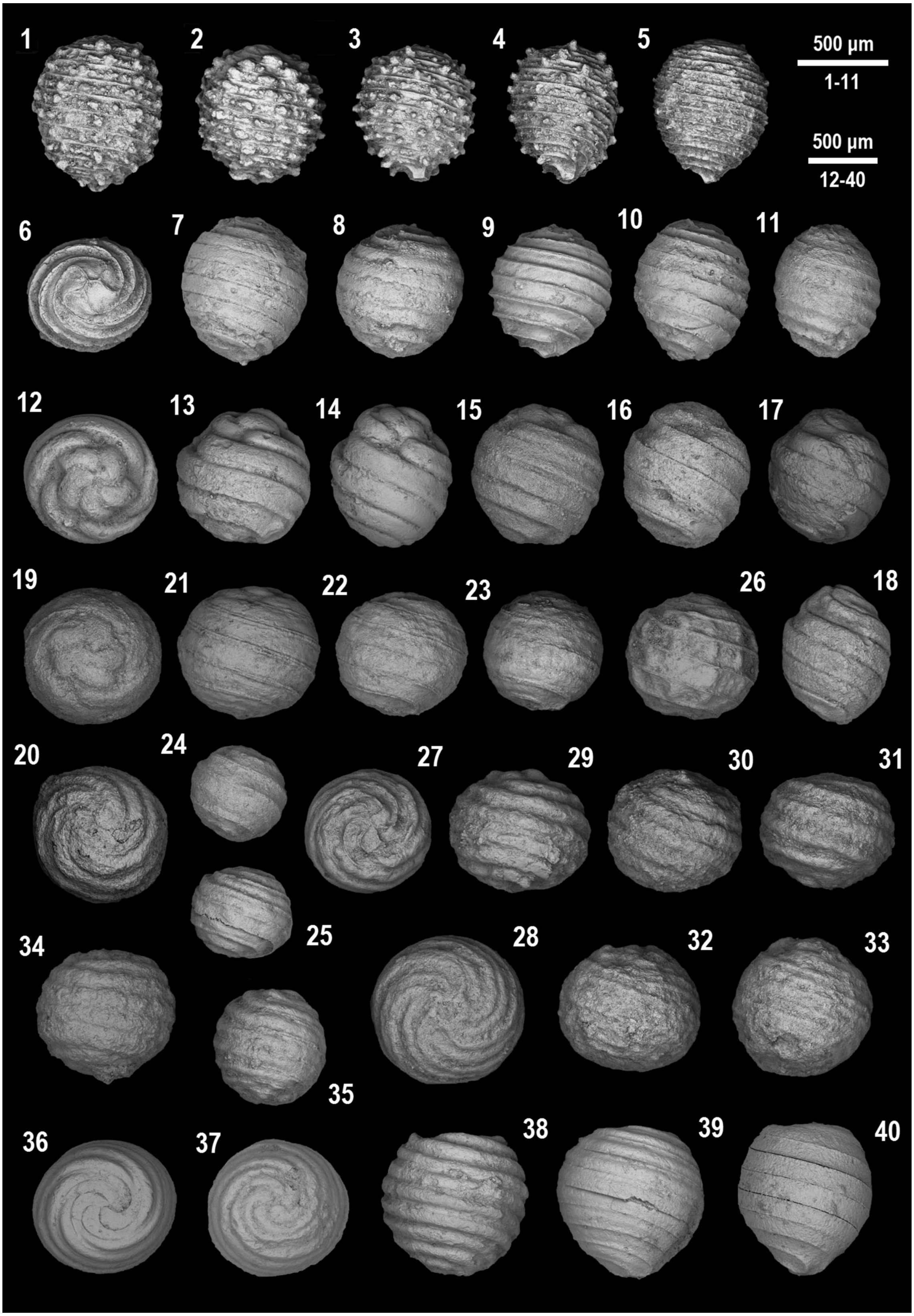
separated into three main units (Kübler 1962) dated by small mammals (Kälin et al. 2001):

Unit 1 Gompholites (river conglomerates) and greenish-grey/black or red brackish marls (approx. 35 m, MN 5–6), transitional with the Burdigalian OMM. The gompholites are developed only locally and characterized by *Microcodium*, fossil microstructures generated in paleosols by saprotrophic fungi and actinobacteria (Kabanov et al. 2008). Reworked Siderolithic pisolites and Purbeckian authigenic quartz may be frequent, as gypsum rosettes most likely generated by leaching and precipitation of Purbeckian gypsum (6 m thick near Le Locle, Jaccard 1883a, b) under hot semi-arid climate conditions. These brackish marls have provided some badly preserved freshwater and terrestrial gastropods, marine and brackish to freshwater ostracods, charophytes and mammal remains (Kälin et al. 2001). The microfloras of charophytes collected are poor and include *Lychnothamnus* sp. [*L. rhabdocharoides* from the Villers-le-Lac section, middle MN 5 and *L.* aff. *antiquus* from the Cridor boreholes, middle-upper MN 6], *N. (T.)* gr. *meriani* and *C.* gr. *molassica-notata*. The new data about the *Lychnothamnus* species attest the lateral substitution of facies between "Lower Oeningian" freshwater limestones and brackish red marls, as previously mentioned by Kälin et al. (2001, p. 93). The transition downwards with Late Burdigalian ("Helvetian") marine coloured marls (greenish-grey and red alternations) and banks of greenish-grey sandy limestones is progressive; no limit can be defined precisely. The red colour of the marls is attributed to eroded and reworked Siderolithic sediments (Kübler 1962, p. 37). These Late Burdigalian deposits are very fossiliferous with a rich invertebrate fauna (Nicolet 1839; Bourquin-Lindt 1909; Favre 1911) and microfauna (Becker 2003; Havran 2011) comprising forams (mainly benthic *Elphidium* and *Cibicides*, rare planktonic *Globigerina*) and ostracods (*Aurila* cf. *cicatricosa*, *Callistocythere* cf. *canaliculata*, *Costa tricostata*, *Cytherella* cf. *compressa*, *Cytherelloidea* sp., *Cytheridea* cf. *acuminata*, *Echinocythereis* cf. *scabra*, *Flexus* cf. *triebeli*, *Grinioneis* cf. *haidingeri*, *Henryhowella asperrima*, *Leguminocythereis* sp., *Loxoconcha punctatella*, *Loxoconcha* cf. *diversapunctata*, *Loxoconcha* cf. *scabra*, *Loxoconcha* cf. *subovata*, *Loxoconcha* cf. *wannai*, *Loxocorniculum*? sp., *Olimfalunia plicatula*, *Rectotrachyleberis edwardsi*, *Ruggieria* sp., *Schizocythere* sp., *Urocythereis*?/*Nonurocythereis*? sp., *Verrucocythereis* cf. *verrucosa*, *Xestoleberis* sp.). The lower part of OMM includes transgressive sandstones and thin basal conglomerate overlying directly limestones of the Mesozoic substratum, on Berriasian or Hauterivian surfaces perforated by pholads

Unit 2–3: Chalky limestones with marly interbeds (unit 2 or "Lower Oeningian", approx. 65 m, upper MN 6—MN 7, Fig. 6e–f) and marls intercalated by chalky limestones and smectite (bentonite) or lignite layers (unit 3 or "Middle-Upper Oeningian", approx. 90 m, MN 7 + 8). These units 2 and 3 correspond to the "Oeningian lacustrine facies", which is highly fossiliferous with remarkable remains of vertebrates (fishes, reptiles, large land mammals) and plants (Jaccard 1869, 1888). The units 2–3 relate to the rich ecosystem of a large lake in the developing syncline surrounded by karstic reliefs. In the upper unit (3), layers with leaves delivered very well-preserved fossil plants from freshwater swamp forest in hot, humid subtropical climate (Heer 1855, 1856, 1859; Berger 1992). Furthermore, thick dark palustrine layers yielded bones and teeth of large extinct mammals (Nicolet 1839; Jaccard 1888; Stehlin 1914; Favre et al. 1937; Van der Made 1998; Kälin et al. 2001; Becker 2003). The herbivorous fauna is represented by Proboscideans (Deinotheres: *Deinotherium giganteum* and *Deinotherium levius*, cf. Böhme et al. 2012 and Aiglstorfer et al. 2014; Mastodons: *Gomphotherium angustidens*), Artiodactyls with Suidae (prehistoric pigs: *Listriodon splendens*, *Hyotherium soemmeringi*, *Lophiochoerus blainvillei*) and Ruminantia (Moschidae: *Micromeryx flouriensanus*; Tragulidae: *Dorcatherium crassum*; Cervidae: *Dicrocerus elegans* and *Euprox furcatus*; Bovidae: small antelope or gazelle *Caprotragoides potwaricus*; Palaeomerycidae: *Palaeomeryx eminens*, *Paleomeryx bojani*, *Lagomeryx* sp.), Perissodactyls with primitive Equidae (*Anchitherium aurelianense*) and Rhinocerotidae (*Brachypotherium brachypus*, *Dicerorhinus sansaniensis*). The Carnivora include large Barbourofelidae *Sansanosmilus palmidens* (popularly known as "Machairodonts" or "saber-toothed cats") and Amphicyonidae (bear-dogs: *Amphicyon steinheimensis*, *Pseudocyon sansaniensis*). Remains of upper canines firstly considered as belonging to *Sansanosmilus palmidens* (Jaccard 1888; Stehlin 1914) were contested afterwards by Stehlin (*in* Favre et al. 1937), who attributed them rather to those rounded conical of Ruminantia ("Cervidae"). However, the accurate comments of Jaccard (1888, p. 54: "*Machairodus*. J'ai découvert deux canines appartenant à ce genre de Carnassier. Elles sont remarquables par leur petite taille et leur forme tranchante, en lame de couteau.") describe perfectly the flattened and sharp-cutting upper canines of *S. palmidens* (cf. Morlo 2006; Robles et al. 2013) and, therefore, leave no doubt about the presence of such Barbourofelidae in the OSM-J of Le Locle. Remains of turtles, crocodilians, snakes and eggshells of birds were also found, as well as frequent small mammal teeth supporting the fine biostratigraphy (Kälin et al. 2001). Freshwater limestones (lacustrine chalks) and marls have also yielded freshwater bivalves (Unionidae), gastropods (for the taxonomy and references see Jaccard 1869; Favre et al. 1937; Mojon et al. 2015; Salvador et al. 2016) from various

Table 4 Taxonomical listing for the charophytes mentioned in this study (cf. Fig. 9), according to the reference classification (Feist et al. 2005) and previous data (Berger 1983, 1992; Charollais et al. 2007; Weidmann et al. 2014). Only the most relevant references are reported in the bibliography, for the others see Feist et al. (2005)

Genus	Sub-genus	Species	Sub-species/var.	First author(s), year(s)	Revising author(s), year	Synonymy
Harrisichara				Grambast, 1957		
Harrisichara		*tuberculata*		(Lyell, 1826)	Grambast, 1957	(= *Chara greppini* Heer, 1859)
Harrisichara		*vasiformis*		(Reid & Groves, 1921)	Grambast, 1957	
Harrisichara		*lineata*		Grambast, 1957		
Grovesichara				Horn af Rantzien, 1959		
Grovesichara		*distorta*		(Reid & Groves, 1921)	Horn af Rantzien, 1959	
Nitellopsis				Hy, 1889		
	(Tectochara)			(L. & N. Grambast, 1954)	Grambast & Soulié-Märsche, 1972	
Nitellopsis	*(Tectochara)*	*aemula*		(Grambast, 1972)	Grambast & Soulié-Märsche, 1972	
Nitellopsis	*(Tectochara)*	*wonnacotti*		(Grambast, 1972)	Grambast & Soulié-Märsche, 1972	
Nitellopsis	*(Tectochara)*	*latispira*		Feist-Castel, 1977a		
Nitellopsis	*(Tectochara)*	*meriani*		(Al. Braun ex Unger, 1850)	Grambast & Soulié-Märsche, 1972	
Nitellopsis	*(Tectochara)*	*ginsburgi*		Riveline, 1986		
Nitellopsis	*(Tectochara)*	*etrusca*		(Tongiorgi, 1956)	Grambast & Soulié-Märsche, 1972	
Nitellopsis	*(Tectochara)*	*majoriformis*		(Papp, 1951)	Schwarz, 2002 (*in* Kovar-Eder et al., 2002)	
	(Nitellopsis)			(Hy, 1889)	Grambast & Soulié-Märsche, 1972	
Nitellopsis	*(Nitellopsis)*	*megarensis*		Soulié-Märsche, 1979		
Nitellopsis	*(Nitellopsis)*	*obtusa*		(Desvaux *in* Loiseleur-Deslongchamps, 1810)	Groves, 1919	
	(Campaniella)			Grambast, 1972		
Nitellopsis	*(Campaniella)*	*helicteres*		(Brongniart, 1822)	Grambast & Soulié-Märsche, 1972	
Gyrogona				Lamarck, 1804 ex Lamarck, 1822	emend. Grambast, 1956	
Gyrogona		*medicaginula*		Lamarck, 1804		
Gyrogona		*wrighti*		(Salter, 1856 ex Reid & Groves, 1921)	Pia, 1927	
Gyrogona		*caelata*		(Reid & Groves, 1921)	Grambast, 1956	
Psilochara				Grambast, 1959		
Psilochara		*bitruncata*		(Reid & Groves, 1921)	Feist-Castel, 1971	
Psilochara		*conspicua*		Grambast, 1958 ex Riveline, 1986		
Psilochara		*conspicua*	*casselensis*	Feist & Riveline ex Riveline, 1986		
Tolypella				(Braun, 1849)	Braun, 1857	
Tolypella		*pumila*		Grambast, 1958		
Chara				Vaillant, 1719		
Chara		*tornata*		Reid & Groves, 1921		
Chara		*praemicrocera*		Schwarz & Griessemer, 1992		
Chara		*microcera*		Grambast & Paul, 1965		
Chara		*minutissima*		(Mädler, 1955)	Schwarz, 1984	
Chara		*molassica*		Straub, 1952		
Chara		*notata*		Grambast & Paul, 1965		
Chara		*globularis*		Thuillier, 1799		
Chara		*globularis*	var. *rousseaui*	Mojon, 2015 (*in* Mojon et al., 2015)		
Hornichara				Maslov, 1963		
Hornichara		*lagenalis*		(Straub, 1952)	Huang & Xu, 1978 (*in* Wang et al., 1978)	
Hornichara		*blayaci*		(Feist, 1977), (*in* Feist & Ringeade, 1977)	Feist & Grambast-Fessard, 2005 (*in* Feist et al., 2005)	
Sphaerochara				Mädler, 1952	emend. Horn af Rantzien & Grambast, 1962	
Sphaerochara		*headonensis*		(Reid & Groves, 1921)	Grambast, 1958	
Sphaerochara		*parvula*		(Reid & Groves, 1921)	Grambast, 1957	
Sphaerochara		*hirmeri*		(Rasky, 1945)	Mädler, 1952	
Rhabdochara				Mädler, 1955	emend. Grambast, 1957	
Rhabdochara		*stockmansi*		Grambast, 1957		
Rhabdochara		*major*		Grambast & Paul, 1965		
Rhabdochara		*praelangeri*		Castel, 1967		
Rhabdochara		*langeri*		(Ettingshausen, 1872)	Mädler, 1955	
Stephanochara				Grambast, 1959		
Stephanochara		*vectensis*		(Groves, 1926)	Grambast, 1958 ex Riveline, 1986	(= *Chara siderolithica* Greppin *in* Heer, 1859)
Stephanochara		*lychnothamnoides*		Feist, 1977 (*in* Feist & Ringeade, 1977)		
Stephanochara		*pinguis*		Grambast, 1958 ex Riveline, 1986		
Stephanochara		*martinii*		Schwarz, 1997 (*in* Reichenbacher & Schwarz, 1997)		
Stephanochara		*ungeri*		Feist-Castel, 1977b		
Stephanochara		*oodea*		Feist-Castel, 1977b		
Stephanochara		*pseudoodea*		Berger, 1983		
Stephanochara		*praeberdotensis*		Berger, 1983		
Stephanochara		*berdotensis*		Feist, 1977 (*in* Feist & Ringeade, 1977)		
Lychnothamnus				(Ruprecht, 1845)	Von Leonhardi, 1863 emend. Braun *in* Braun & Nordstedt, 1882	
Lychnothamnus		*rhabdocharoides*		(Berger, 1983)	Mojon, nov. comb. (this study)	
Lychnothamnus		*duplicicarinatus*		(Papp, 1951)	Soulié-Märsche, 1978	
Lychnothamnus		*antiquus*		(Soulié-Märsche, 1989)	Mojon, nov. comb. (this study)	(= *Lychnothamnus breviovatus* Lu & Luo, 1990)
Lychnothamnus		*barbatus*		(Meyen, 1827)	Von Leonhardi, 1863	
Lychnothamnus		*barbatus*	var. *bicarinatus*	Soulié-Märsche, 1979		
Rantzieniella				Grambast, 1962		
Rantzieniella		*nitida*		Grambast, 1962		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◀**Fig. 10** Charophytes from the Late Eocene (SPN-EC 1) of the Swiss Tabular Jura. 1–5: ***Harrisichara* gr. *vasiformis-tuberculata***. 5–11: ***Psilochara* gr. *bitruncata-conspicua***. 12–18: ***Grovesichara distorta***. 19–25: ***Gyrogona wrighti***. 26: ***Gyrogona* gr. *caelata***. 27/29–31/34–35: ***Gyrogona wrighti–medicaginula***. 28/32–33: ***Gyrogona medicaginula***. 36–40: ***Nitellopsis (Tectochara)* gr. *aemula-latispira***. **DSK-2016/1**: Middle–Late Priabonian/EC 1. **Lateral views** (1–5/7–11/13–18/21–26/29–35/38–40), **apical views** (6/12/19/27/36–37), **basal views** (20/28)

paleoenvironments as lacustrine (Planorbidae: *Gyraulus* and *Planorbarius*; Lymnaeidae: *Radix* and *Galba*; Hydrobiidae: *Hydrobia*, *Pseudamnicola* and *Bithynia*; Valvatidae: *Valvata*; Melanopsidae: *Melanopsis*), fluvio-lacustrine (Neritidae: *Theodoxus*) and terrestrial (Helicidae: *Cepaea*), as well as ostracods (*Cyclocypris* sp., *Cypridopsis biplanata*, *Darwinula flandrini*, *Fabaeformiscandona kirchbergensis*, *Ilyocypris* cf. *boehli*, *Paralimnocythere rostrata*, *Physocypria* sp., *Potamocypris gracilis*, *Potamocypris pastoiri*, *Pseudocandona compressa*; det. by G. Carbonnel, P. Schäfer and C. Pirkenseer *in* Carbonnel et al. 1985; Kälin et al. 2001; Havran 2011).

Discussion

Swiss Paleogene–Neogene assemblage zones of charophytes and taxonomical remarks

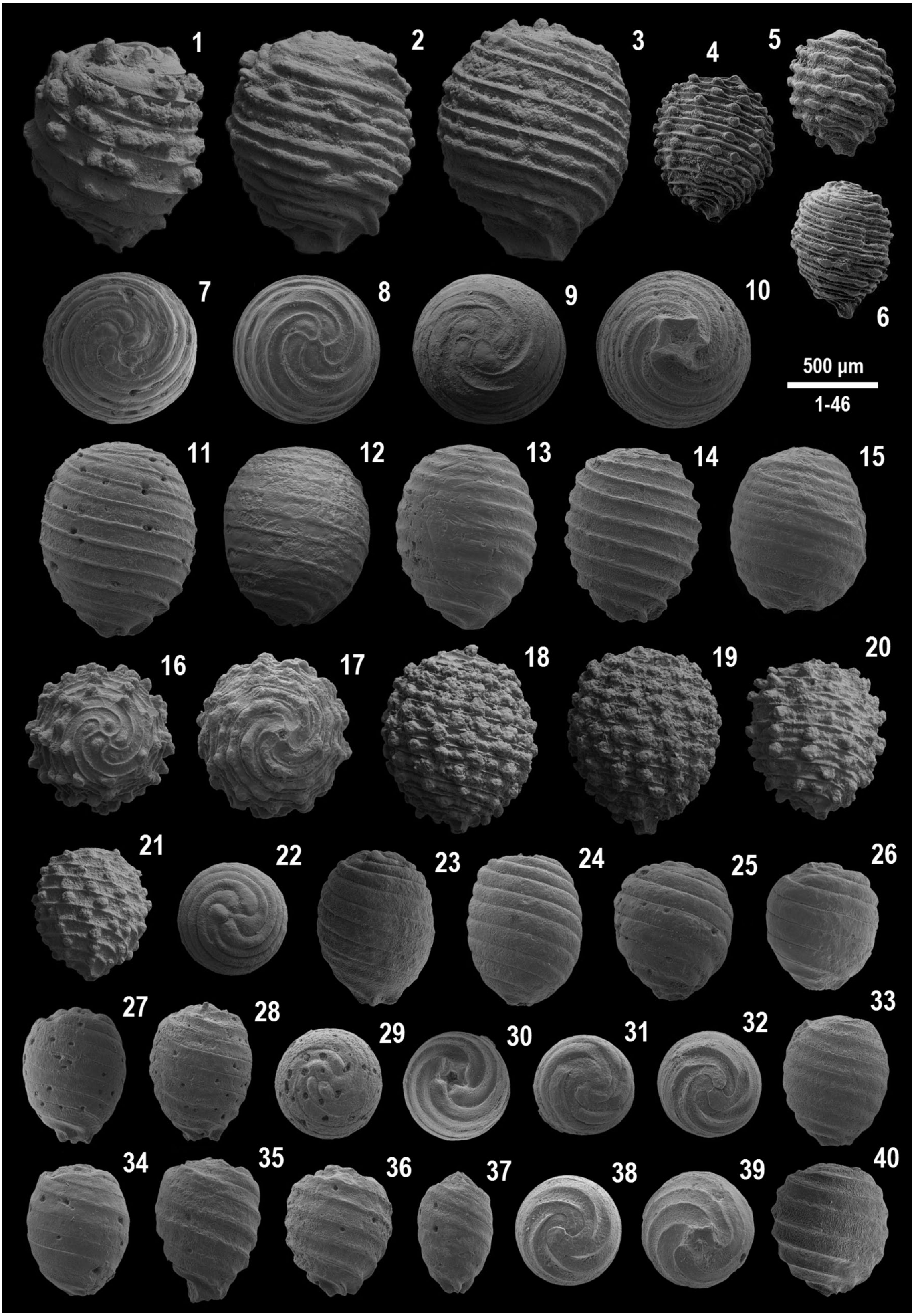
In order to simplify the text, the reference names, author names and synonymy of the cited charophyte taxa from the Swiss Paleogene and Neogene (abbreviated SPN) are listed in Table 4. Evolution and distribution of the charophytes in the SPN result mainly from geological and biological events. According to the data of this study in the SPN, 11 charophytes assemblage zones (cenozones) can be defined complementary to the classical charophyte biozonation of the Eocene (small mammal zones MP 18–20), Oligocene (small mammal zones MP 21–30) and Miocene (small mammal zones MN 1–9). These charophyte assemblage zones are, therefore, abbreviated SPN-EC 1–2 (SPN-Eocene Charophytes 1–2) for Eocene, SPN-OC 1–5 (SPN-Oligocene Charophytes 1–5) for Oligocene and SPN-MC 1–4 (SPN-Miocene Charophytes 1–4) for Miocene (Fig. 9). The definition of assemblage zones is a useful and practical tool to replace biozones, if the marker taxa are missing in the samples (e.g. *R. nitida* or *C.* gr. *praemicrocera-microcera* generally rare) or badly preserved in drill cores and cuttings. Some biozones are also unusable [e.g. "Ginsburgi" Zone (Riveline et al. 1996) with a range of the index-species *N. (T.) ginsburgi* extending from Late Oligocene/MP 28 to Late Miocene/MN 10] or can be problematic (e.g. Microcera and Notata Zones, *C. microcera* is often rare and closely similar to *C. notata*). The peculiarities of morphotypes in many charophytes species can also provide specific informations. The polymorphism is frequent in most of the charophyte assemblages and may allow reliable dating of samples in stratigraphic units [e.g. *N. (T).* gr. *aemula-latispira* – *N. (T.)* gr. *latispira-wonnacotti*, *Rh.* gr. *stockmansi-major* – *Rh.* gr. *praelangeri-major*, *St.* gr. *ungeri* - *St.* gr. *oodea-praeberdotensis*; Mojon *in* Weidmann et al. (2014), this study]. This is carried out at a regional biostratigraphic scale, where the stratigraphic ranges of marker species may vary compared to other Tertiary basins of Europe [e.g. especially for *R. nitida* and *N. (T.) ginsburgi*]. The charophyte assemblage zones of the Swiss Molasse are defined according to revised and supplemented data, as following:

Assemblage zone SPN-EC 1

(= Vasiformis–Tuberculata Zone, small mammal zones MP 18–19). With *Harrisichara* gr. *vasiformis-tuberculata* (very common), *Gyrogona wrighti* (very common), *Gyrogona medicaginula*, *Gyrogona wrighti-medicaginula*, *Gyrogona* gr. *caelata*, *Grovesichara distorta*, *Psilochara* gr. *bitruncata–conspicua* and *Nitellopsis (Tectochara)* gr. *aemula-latispira*. In the reference site of the Isle of Wight (Southern England), the assemblage of charophytes with *H.* gr. *vasiformis-tuberculata*, *G. wrighti*, *G.* gr. *caelata*, *G. distorta*, *P.* gr. *bitruncata-conspicua* and *N. (T.)* gr. *aemula-latispira* characterizes the Headon Hill Formation (Middle and Upper Headon Beds, Osborne Beds) and the Bembridge Beds of the overlying Bembridge Limestone Formation (Feist-Castel 1977a; Riveline 1984, 1986) in a Middle–Late Priabonian interval defined by the Late Eocene small mammal zones MP 18–19 (Sille et al. 2004).

Harrisichara* gr. *vasiformis-tuberculata includes gyrogonites of small to middle size and more or less ornamented by tubercles, the morphotypes attributed to *H. vasiformis* are typically rather small with tubercles little developed (Figs. 10.3–5, 11.4–6) and those of *H. tuberculata* are larger with strong tubercles (Figs. 10.1, 2 and 11.16–21). *H. vasiformis* appears in the Early Bartonian of the Paris Basin (Riveline 1984, 1986) and its derived morphotypes as *H.* gr. *vasiformis-tuberculata* are widely distributed in the Middle–Late Priabonian of Europe (including in Eastern Europe, Baciu and Feist 1999, Baciu and Hartenberger 2001), while *H. tuberculata* characterizes the Late Priabonian–Early Rupelian of Western Europe (Feist-Castel 1977a, b; Riveline 1984, 1986; Sanjuan and Martín-Closas 2014).

Gyrogona wrighti shows big rounded gyrogonites with 5–6 broad and slightly concave or convex convolutions (Figs. 10.19–25 and 12.60–63); this very typical species is very common in the Priabonian (Tuberosa Z., Vasiformis-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◀**Fig. 11** Charophytes from the Late Eocene (SPN-EC 1–2) and Early Oligocene (SPN-OC 1) of the NE-Swiss Plateau border and Folded Jura. 1–3: ***Harrisichara* gr. *lineata-tuberculata***; 4–6: ***Harrisichara* gr. *vasiformis-tuberculata***; 7–15: ***Stephanochara pinguis***; **FCP-2014/1**: Early Rupelian/OC 1 (1–3/7–15) with reworked Late Priabonian/EC 1 (4–6). 16–21: ***Harrisichara tuberculata***; 22–37: ***Stephanochara vectensis*** (22–23: same specimen); 38–46: ***Rhabdochara* gr. *stockmansi-major***; 47–54: ***Sphaerochara* gr. *headonensis-parvula*** (morphotypes *headonensis*: 47–50, morphotypes *parvula*: 51–54); 55–61: ***Tolypella pumila***; 62–65: ***Nitellopsis (Tectochara)* gr. *latispira-wonnacotti***; 66–75: ***Nitellopsis (Tectochara)* gr. *aemula-latispira***; **CTJ-2013/1**: Late Priabonian/EC 2. 76–81: ***Nitellopsis (Tectochara)* gr. *latispira-wonnacotti***, **OSK-2013-14/1**: Late Priabonian/EC 2 (third thin marly layer from the bottom, Fig. 3a). **Lateral views** (1–6/11–15/18–21/23–28/33–37/40–46/49–50/53–54/57–61/64–70/73–75/79–81), **apical views** (7–9/16/22/29/31–32/38/47–48/51/55/62/71/76–77), **basal views** (10/17/30/39/52/56/63/72/78)

Tuberculata Z., Tuberculata Spz./Vectensis Z.) and scarcer in Early Rupelian (Tuberculata Spz./Pinguis Z., Major Z.) of Northwest Europe (Riveline 1984, 1986; Schwarz 1997).

Gyrogona medicaginula is characterized by big rounded or flattened gyrogonites with 6–7 convolutions showing typically a median band and corrugated sutures (Fig. 10.28/32–33); this species is common in Middle–Late Priabonian (Vasiformis-Tuberculata Z., Tuberculata Spz./Vectensis Z.) and scarcer in Early Rupelian (Tuberculata Spz./Pinguis Z. to basal Microcera Z.) of continental Western Europe (Riveline 1984, 1986; Feist et al. 1994). Sometimes, an interbreeding or hybridization is attested by mixed features of intermediate specimens of ***G. wrighti-medicaginula*** (Feist-Castel 1977b; Riveline 1984, 1986) as those figured in this study (Figs. 10.27/29–31/34–35, 12.54–59). In Switzerland, *Gyrogona* gr. *caelata* (Fig. 10.26) is also known with *Harrisichara* gr. *vasiformis-tuberculata* in the Middle–Late Priabonian of the Alps (Weidmann et al. 1991; Berger 1992). The *G. caelata* species group shows large more or less flattened gyrogonites with 5–6 concave convolutions and high ornamental variability of tubercles or convex spiral stripes, it is well known from Upper Lutetian to Upper Priabonian in the Middle–Late Eocene (Sanjuan and Martín-Closas 2014) and vanishes in the Major Zone of the Early Oligocene (Riveline 1984, 1986; Feist et al. 1994). The variations of *G.* gr. *caelata* are considered as varieties without very precise stratigraphical value (Riveline 1984, 1986); the specimen figured in this study shows an ornamentation of large and flat tubercles evoking the Priabonian var. *rhabdita* (Grambast and Grambast-Fessard 1981). The last occurence of ***Psilochara* gr. *bitruncata-conspicua*** (Figs. 10.6–11, 12.66) is usually pinpointed in the Pinguis Zone of lowermost Rupelian (Feist-Castel 1977a; Riveline 1984, 1986). ***Psilochara conspicua casselensis*** (reworked in the "Molasse alsacienne" of the Delémont Basin, Fig. 12.64) is also known in Late Priabonian (MP 19) of the Rhine Graben (Riveline 1984, 1986; Schwarz 1997).

In boreholes of the Moutier syncline, the Calcaires d'eau douce de Moutier [= Calcaires de la Verrerie, de la Charrue (Charruekalk) et du Tirage] yielded Paleogene charophytes and were attributed to the Rupelian by Reichenbacher et al. (1996). These authors considered notably the common *G. medicaginula* and *G. wrighti* of the Calcaire de la Verrerie as last Early Oligocene representatives of these species from the Major and basal Microcera Zones. But, an isolated gyrogonite of *Harrisichara* (fig. 8A *in* Reichenbacher et al. 1996) found nearby in coeval levels of colourful marls upon conglomerate and breccia (cf. Gompholite de Daubrée) corresponds rather to *Harrisichara* gr. *vasiformis-tuberculata* (Figs. 10.1–5, 11.4–6), in comparison clearly smaller and less ornamented than typical *Harrisichara tuberculata* (Fig. 11.16–21). According to the recent data about the Diegten Süsswasserkalk and the Terre jaune without *Gyrogona*, the Calcaires d'eau douce de Moutier and Gompholite de Daubrée can be certainly reported, therefore, to the Vasiformis–Tuberculata Zone. In the Stockstadt Group of Ajoie and Delémont Basin, the reworked charophytes of SPN-EC 1 attest previous eroded freshwater deposits of the Middle–Late Priabonian on the NE-Jura Mountains.

Assemblage zone SPN-EC 2

(= Tuberculata Superzone and Vectensis Zone, small mammal zones MP 19–20). With *Harrisichara tuberculata* (very common), *Nitellopsis (Tectochara)* gr. *latispira-wonnacotti* (locally very common), *Nitellopsis (Tectochara)* gr. *aemula-latispira* (very common), *Stephanochara vectensis*, *Rhabdochara* gr. *stockmansi–major*, *Sphaerochara* gr. *headonensis-parvula* and *Tolypella pumila*. The taxa *H. tuberculata*, *N. (T.)* gr. *aemula-latispira* and *Rh.* gr. *stockmansi-major* were already known from the Swiss Plateau, the Jura Mountains and the Alps (Weidmann et al. 1991; Berger 1992, 1999; Berger et al. 2005b; Weidmann et al. 2014), but *St. vectensis*, *N. (T.)* gr. *latispira-wonnacotti*, *Sph.* gr. *headonensis-parvula* and *T. pumila* are for the first time recorded in Switzerland and complement the regional Paleogene charophyte biostratigraphy (Fig. 9).

Stephanochara vectensis from the Terre jaune of the Swiss Jura Mountains is characterized by ellipsoid to ovoid gyrogonites of small size (Fig. 11.22–37), with a short basal funnel and a pentagonal star-shaped basal pore (Fig. 11.30). The spiral cells are smooth and generally slightly convex or flat, rarely concave, with 7–10 convolutions and simple sutures. The apex can be rounded with small prominent apical nodules (Fig. 11.22/29) or slightly flattened and smooth (Fig. 11.31–32), rarely pointed (Fig. 11.37). At Châtillon, some 20 kg of Terre jaune have yielded an abundant assemblage of *Stephanochara*. Within

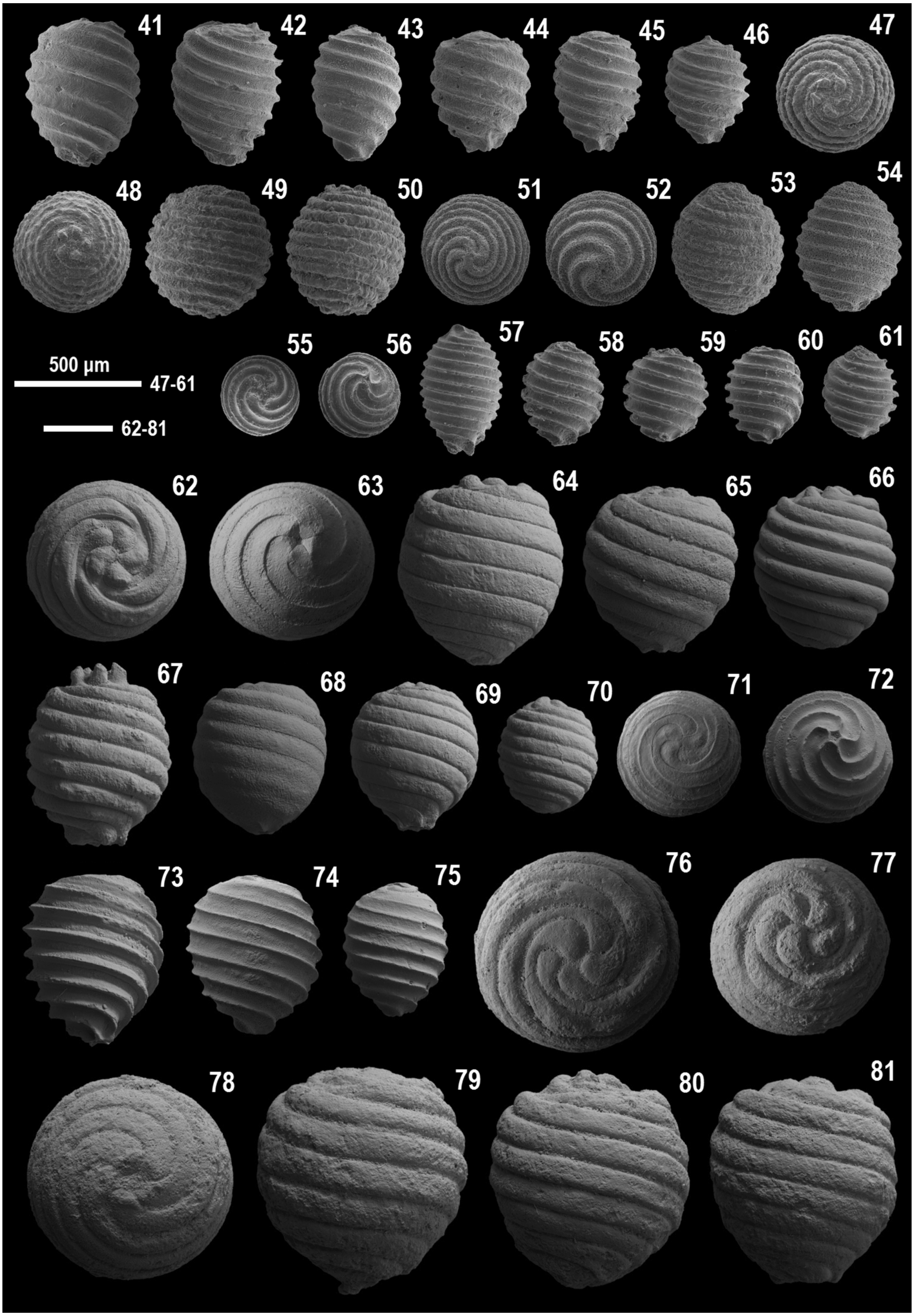


Fig. 11 continued

this material, the larger specimens clearly fit to *Stephanochara vectensis* (Fig. 11.22–26/29) according to reference specimens of this species published by Riveline (1984, 1986) and Sanjuan and Martín-Closas (2015). Numerous smaller specimens (Fig. 11.27–28/30–37) can be otherwise referred to *Stephanochara lychnothamnoides* (Feist and Ringeade 1977) or to *Hornichara blayaci* (Feist et al. 2005), as already noticed by Berger (1992, p. 214, Pl. X, figs. 5, 6) in samples from other localities of the Terre jaune. These various *Stephanochara* morphotypes from the Terre jaune form a typical polymorphous assemblage, strongly representative of the variability observed among many other taxa of charophytes, and, therefore, can be unified under the *vectensis* species. Many gyrogonites of *St. vectensis* from the Terre jaune show numerous predatory perforations (Fig. 11.25/27–29/34–37) bored by the taenioglossate radula of Hydrobiidae gastropods. Such perforations are also recorded in gyrogonites of *Nitellopsis (Tectochara)* gr. *aemula-latispira* and *Stephanochara pinguis* (Fig. 11.7/10–11) from the Early Oligocene of the Jura Mountains.

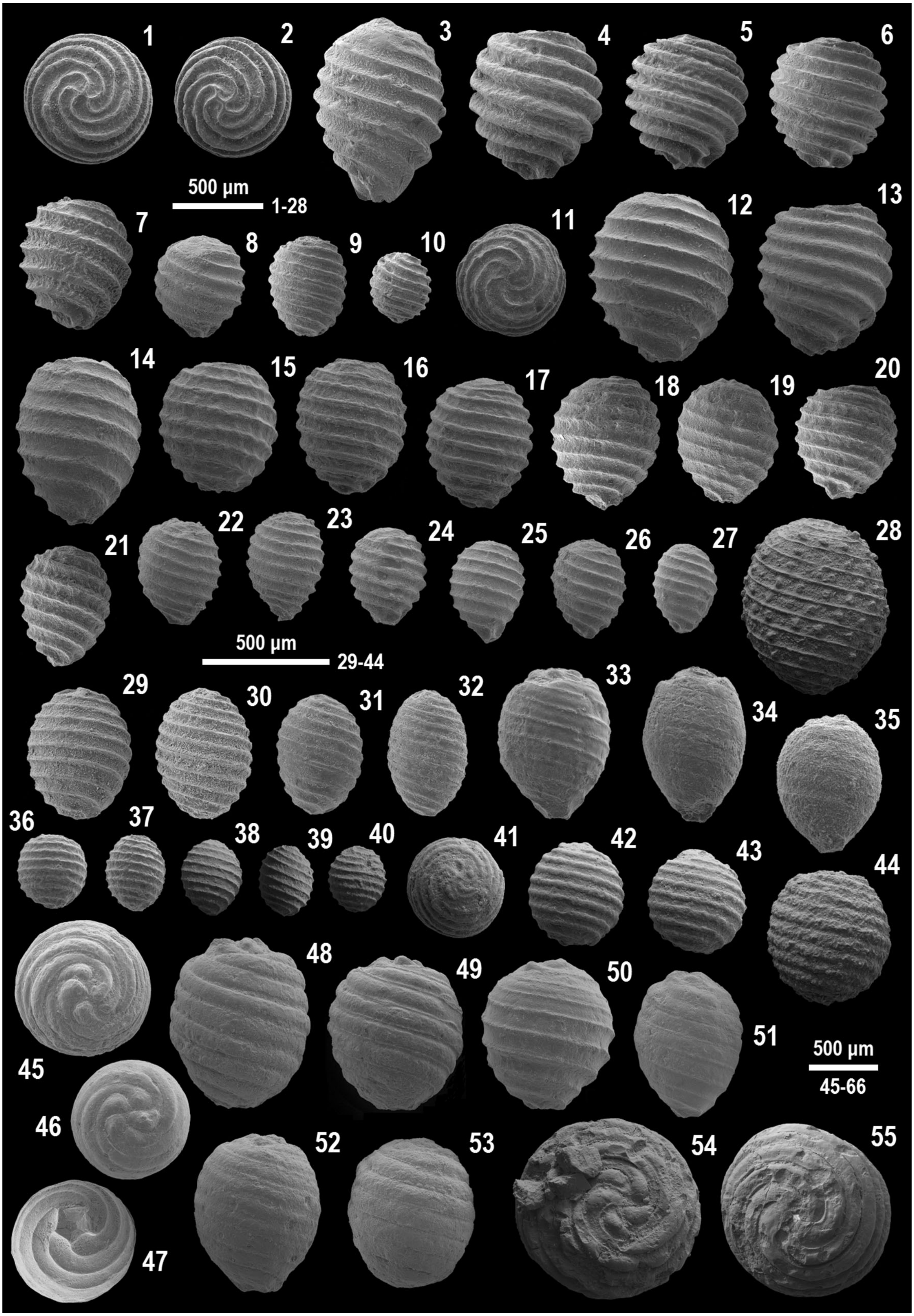
Typical gyrogonites of ***Nitellopsis (Tectochara)* gr. *latispira-wonnacotti*** characterize the Oberdorf Süsswasserkalk (Fig. 11.76–81). These gyrogonites or related morphotypes close to *N. (T.) latispira* are subglobose and very large, with smooth and very broad spiral cells generally convex or rarely concave, usually with eight convolutions and a truncated apex with large protruding apical nodules (Fig. 11.62/76–77). The base of the gyrogonites is rounded with occasionally a wide and very short truncated funnel (Fig. 11.64–65/81) and a large pentagonal pore (Fig. 11.63/78). In the reference site of the Isle of Wight (Southern England), typical specimens of *N. (T.)* gr. *latispira-wonnacotti* characterize the Bembridge Marls Member of the Bouldnor Formation and the underlying Bembridge Limestone Formation (Feist-Castel 1977a; Riveline 1984, 1986) in an interval defined by the uppermost Eocene small mammal zones MP 19–20 (Sille et al. 2004). The species *N. (T.) wonnacotti* was also reported from the Middle–Late Priabonian of the Paris Basin (Riveline 1984, 1986) and the Untere Pechelbronn Schichten of the Upper Rhin Graben (Schwarz & Griessemer 1994). In other Eocene deposits of the Jura Mountains (Diegten Süsswasserkalk, Terre jaune, Conglomérat de Porrentruy), mixed assemblages of ***N. (T.)* gr. *aemula-latispira*** show a gradual transition with intermediate morphotypes between the species *latispira-wonnacotti* (Fig. 11.62–65) and *aemula-latispira* [Figs. 10.36–40 and 11.66–75; Mojon *in* Weidmann et al. 2014, Pl. II, figs. 7–10/17–18 from the "marnes argileuses et calcaire lacustre d'Orbe" (Weidmann 1984)]. The morphotypes *aemula* (Fig. 11.66–75) are characterized by spheroidal-rounded to ovoid-elongated gyrogonites of medium to large size, with apical nodules more or less well developed (Fig. 11.67/71). The spiral cells are wide, smooth and convex to concave, with 7–10 convolutions. The base of the gyrogonites is elongated and forms a truncated funnel (Fig. 11.67/69/73) with a small pentagonal pore (Fig. 11.72). *N. (T.) aemula* is very close to *N. (T.)* gr. *meriani* and was considered initially as a species of this group (Grambast 1972). As already reported by Berger (1992, p. 226–227), the Late Eocene *N. (T.) latispira-wonnacotti-aemula* species group must not be confused with the Paleocene-Early Eocene *Nitellopsis (Campaniella) helicteres*. The name "*Chara helicteres*" used for the material collected by J.-B. Greppin in the Terre jaune of the Delémont Basin (Heer 1856, 1859; Rollier 1910) must be, therefore, rectified.

Tolypella pumila (= *Tolypella* sp. *in* Gander 2013) is an Upper Priabonian-Early Rupelian species from the Vectensis and Pinguis Zones (MP 20–21) in the Paris Basin and Pechelbronn-Schichten of the Rhine Graben (Breuer and Feist 1986; Schwarz and Griessemer 1994, 1992; Schwarz 1997). The ovoid-rounded to ellipsoid-elongated gyrogonites of *T. pumila* from the Terre jaune are very small with 8–11 strongly concave convolutions (Fig. 11.55–61) and close to those of *Chara nannocarpa* Schwarz 1985 from the Late Oligocene–Early Miocene of the Rhine Graben (Schwarz 1997).

Sphaerochara* gr. *headonensis-parvula from the Terre jaune and basal Conglomérat de Porrentrruy of the Jura Mountains has very small subglobose-spherical to ovoid gyrogonites. The convex or concave spiral cells are smooth or adorned with fine irregular granules and 8–11 convolutions. The only major difference is the strong calcification of *headonensis* morphotypes (Fig. 11.47–50) forming convex convolutions with granules and small well-developed apical nodules. The *parvula* morphotypes (Fig. 11.51–54) are less calcified, with rather concave convolutions and without apical nodules. These two varieties form mixed assemblages in the studied deposits and are so resembling that placement in a common *headonensis-parvula* group or even in a single species seems plausible. Surprisingly, there are apparently no well-preserved specimens of ***Gyrogona*** in the assemblage zone OC 1 of the Swiss Molasse: only a single poorly preserved gyrogonite of doubtful affiliation was found in the Terre jaune (Gander 2013, Anhang, fig. 6).

Assemblage zone SPN-OC 1

(= Tuberculata Superzone and Pinguis Zone, small mammal zone MP 21). With *Harrisichara* gr. *lineata-tuberculata*, *Stephanochara pinguis*, *Nitellopsis (Tectochara)* gr. *aemula-latispira*, *Rhabdochara* gr. *stockmansi-major* and *Sphaerochara* gr. *headonensis-parvula* (rare).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◀**Fig. 12** Charophytes from the Late Eocene (SPN-EC 1-2, reworked) and Early Oligocene (SPN-OC 2–3) of the NW-Swiss Plateau border and Folded Jura. 1/3–4/12–14/67–72: ***Rhabdochara* gr. *praelangeri-major*** (69: ornate morphotype close to *Rhabdochara* gr. *langeri*). 2/5–11/15–27/65: ***Rhabdochara* gr. *stockmansi-major***. 28: ***Harrisichara tuberculata***. 29–32: ***Chara tornata***. 33–35: ***Stephanochara* aff. *martinii***. 36–40: ***Chara minutissima***. 41–44/95–99: ***Sphaerochara* gr. *hirmeri*** (95 and 98: same specimen). 45–53: ***Nitellopsis (Tectochara)* gr. *meriani***. 54–59: ***Gyrogona wrighti-medicaginula***. 60–63: ***Gyrogona wrighti***. 64: ***Psilochara* cf. *conspicua casselensis***. 66: ***Psilochara* gr. *bitruncata-conspicua***. 73–94: ***Chara* gr. *praemicrocera-microcera*** (morphotypes *praemicrocera*: 73–86; morphotypes *microcera*: 87–94). **FCP-2014/2**: Early Rupelian/OC 2 (1–10/29–32). **HRT-2013/POM/1**: Late Rupelian/OC 2 (11–27/33/36–37/45–53), **HRT-2013/POM/2**: Early Chattian/OC 3 (67–99). **Del1-S1-1990** (85–92 m): reworked Late Priabonian/EC 2 (28) and Rupelian/OC 2 (44). **LRS03-2009/MW/1** (102–118 m): Rupelian/OC 2 (34–35). **LGR007/81** (38–40) **/84** (41–43), **POI007/2808** (54) **/2503** (55) **/2293** (56) **/2775** (57) **/1953** (63–64) **/1357** (65) **/2405** (66) and **/2942** (59), **POI010/482** (58), **PRC004/246** (60/62) **/255** (61): Late Rupelian/OC 2 (38–43) with reworked Middle–Late Priabonian/EC 1 (54–64/66). **Lateral views** (3–10/12–40/42–44/48–53/56–60/63–66/68–94/97–99), **apical views** (1–2/11/41/45–46/54/61/67/95–96), **basal views** (47/55/62)

Stephanochara pinguis from the basal Conglomérat de Porrentrruy has ovoid-ellipsoid gyrogonites of medium size (Fig. 11.7–15), with a short and truncated basal funnel, a wide pentagonal and star-shaped basal pore (Fig. 11.10), mostly flat or slightly concave, rarely slightly convex smooth spiral cells (Fig. 11.7), 8–10 convolutions and simple sutures, an apex forming a slightly convex and smooth apical cap, sometimes with small irregularly developed apical nodules (Fig. 11.7–9). In the reference site of the Isle of Wight (Southern England), *St. pinguis* characterizes the Hamstead Member (Lower Hamstead Beds) of the Bouldnor Formation (Feist-Castel 1977a; Riveline 1984, 1986) dated by the lowermost Oligocene small mammal zone MP 21 (Sille et al. 2004).

Harrisichara* gr. *lineata-tuberculata include gyrogonites of middle to big size, sometimes ornamented by very big tubercles. The aspect of *H. lineata* with a median line and thickenings along the spiral cells is very similar to the basic ornamentation of small gyrogonites of *H. vasiformis* and bigger ones of *H. tuberculata*. By their common features, these three species are closely related together and, therefore, the criteria of size and ornamentation argue for a representative species group. The material collected at Fessevillers in the basal part of the Conglomérat de Porrentruy includes broad and ellipsoidal gyrogonites of highly variable size and ornamentation with flat apex and narrow operculum of five short flattened or tuberculated cells, truncated basal funnel forming a short stalk, medium to large size of 800–1300 µm long and 700–1100 µm wide. The five spiral cells of the gyrogonites are concave with 7–9 convolutions and individually show a typical thin median line along the sinistral coiling. This median line is often thickened and merged into unequal swelling ridges and nodes (Fig. 11.2–3) or, more rarely, very big isolated tubercles irregularly distributed (Fig. 11.1). *H. lineata* is currently known from Middle Bartonian to Early Rupelian of Western Europe; small specimens without tubercles are reported from the Lymnäenmergel and Untere Pechelbronn Schichten of the Upper Rhine Graben (Schwarz & Griessemer 1994, Schwarz 1997) and similar other ones with sometimes small tubercles were found in the Late Eocene–Early Oligocene of NE-Spain (Sanjuan and Martín-Closas 2014).

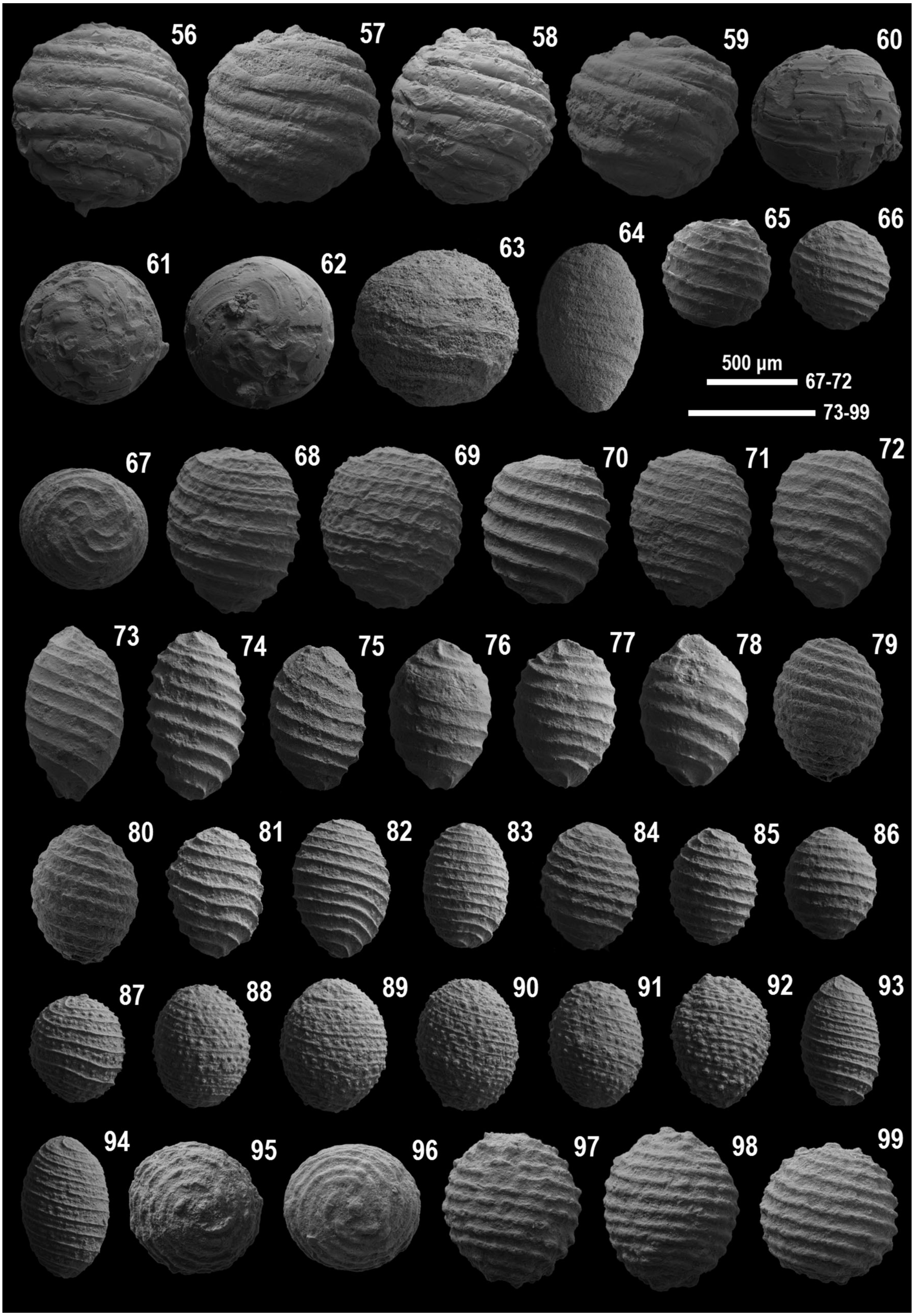
Assemblage zone SPN-OC 2

(= Major Zone, small mammal zones MP 22–24). With *Rhabdochara* gr. *stockmansi-major* (very common) and *Rhabdochara* gr. *praelangeri-major*, *Nitellopsis (Tectochara)* gr. *meriani*, *Stephanochara* aff. *martinii* (rare), *Sphaerochara* gr. *hirmeri*, *Chara tornata* (occasional in the USM, known mainly from the Ungeri Zone/MP 27–28) and *Chara minutissima* (occasional in the USM and OSM, Berger 1992).

In the Gruyère area (Alpine foothills, Prealps), the Hauteville-Le Ruz section is well-known (Homewood 1978; Weidmann 1982; cf. Engesser et al. 1984, p. 36) with two regressive dark clayey sequences in the deltaic top of the Subalpine UMM (sandstones and clays of the Vaulruz Formation). The first one of about 2 m thick (yet unreported and unpublished) includes basal lignite beds (40 cm) and an upper emersive layer (lignite and grey marls, 15 cm) with lacustrine or brackish microfossils as gastropods (Planorbidae, Hydrobiidae), bivalves (Unionidae) and ostracods (*Moenocypris olmensis*, *Hemicyprideis parvula*). The second one is the most interesting and includes a thin lacustrine beige limestone (Fig. 13a) with lignite and typical freshwater Rupelian microfossils as charophytes of the SPN-OC 2 Zone (*Rh.* gr. *stockmansi-major*, *Rh.* gr. *praelangeri-major*, *N. (T.)* gr. *meriani*) and ostracods (*Moenocypris olmensis*).

Chara tornata is known from the Early Oligocene to Early Miocene (MP 20–MN 3) of the Rhine Graben (Schwarz 1997), as well as from the Late Oligocene and Middle Miocene of the NE-Swiss Molasse Basin (Aarwanger Molasse of Wolfwil-Kennisbännli, Ungeri Zone/MP 27, Mädler 1955; Becker 2003, p. 80–81; Mauensee, "Ginsburgi" Zone/MN 4b, Jost et al. 2006). The ellipsoid-elongated gyrogonites from the Conglomérat de Porrentruy are small-sized, with slightly concave spiral cells and 8–12 convolutions (Fig. 12.29–32).

Stephanochara* aff. *martinii is represented by rare specimens of the Rouges-Terres (Fig. 12.33) and La Rippe borehole at the foot of the Vaud Jura Mountains



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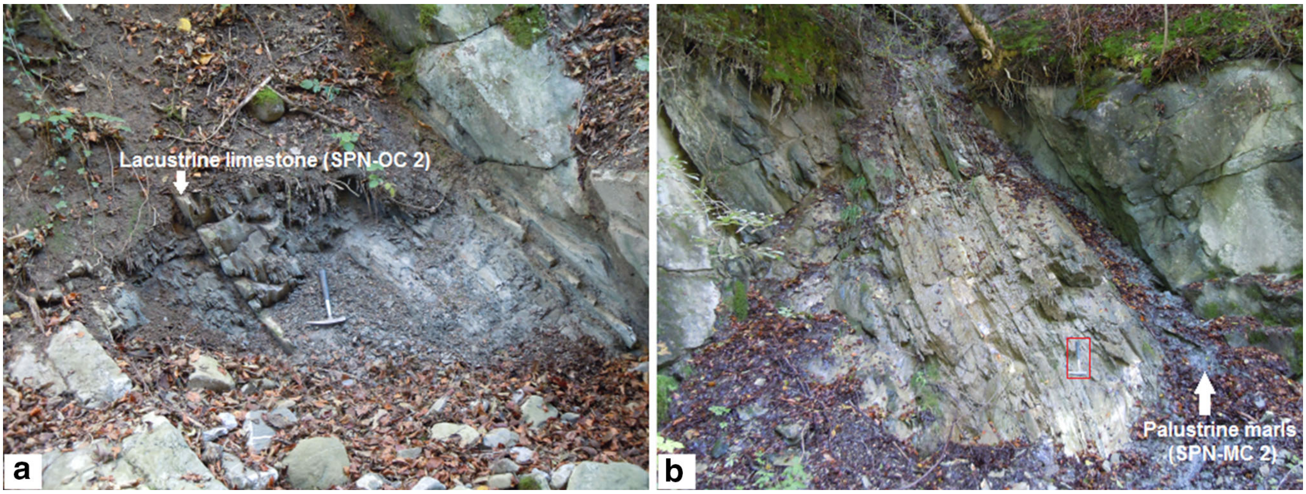


Fig. 13 Deltaic regressive sequences with charophytes in the Subalpine Marine Molasse of Switzerland. **a** Hauteville–Le Ruz section (Gruyère), emersive sequence with lacustrine limestone of the SPN-OC 2 Zone (Middle–Late Rupelian) in the upper part of the UMM (Grès de Vaulruz, Vaulruz Formation). **b** Hasle-Entle section (Entlebuch), emersive sequence with palustrine marls of the SPN-MC 2 Zone (Late Aquitanian) in the lower part of the OMM I (Luzern Formation). The hammer (red frame in **b**) is 31.5 cm long. Photos by P.-O. Mojon (2017)

(Fig. 12.34–35), which is only the second locality with this species in the USM of the Swiss Molasse Basin. Typical specimens of *Stephanochara martinii* are larger and occur in somewhat younger strata; they are associated with *Chara* gr. *praemicrocera-microcera* in the Oligocene of the Bavarian Molasse Basin (Reichenbacher and Schwarz 1997).

Assemblage zone SPN-OC 3

(= Microcera Zone, small mammal zones MP 24–26). Paucispecific assemblage with *Chara* gr. *praemicrocera-microcera* (rare), *Rhabdochara* gr. *praelangeri-major* (very common), *Nitellopsis (Tectochara)* gr. *meriani* and *Sphaerochara* gr. *hirmeri*.

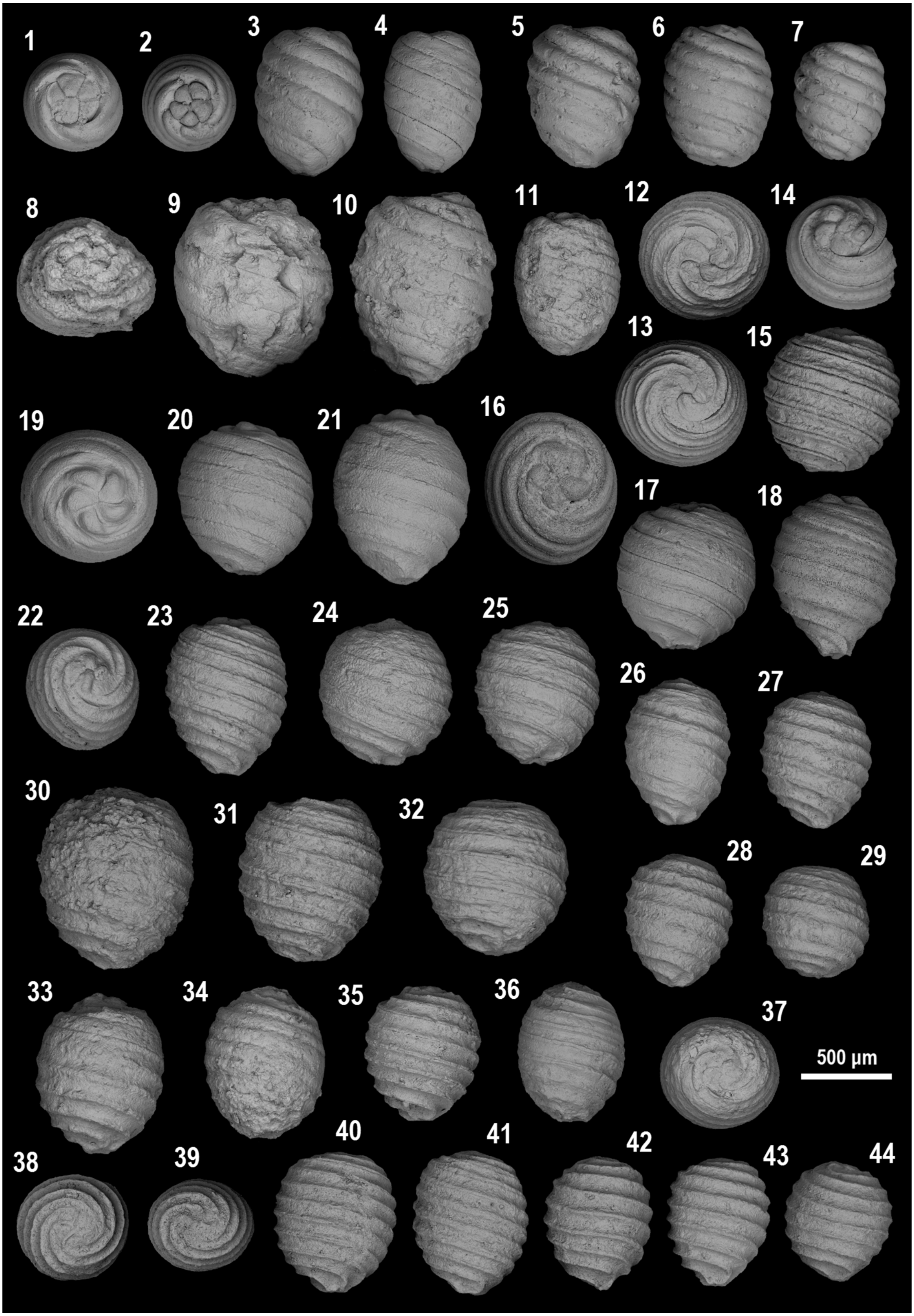
Chara praemicrocera and ***Chara microcera*** are well-known taxa from the Oligocene of the Bavarian Molasse Basin (Reichenbacher and Schwarz 1997) and the Rhine Graben (Schwarz and Griessemer 1992; Schwarz 1997). In the Swiss Molasse Basin, the gyrogonites of *Chara* gr. *praemicrocera-microcera* (Fig. 12.73–94) are very similar (size, polymorphism and ornamentation) to those of *Chara* gr. *molassica-notata* (Fig. 15.50–57; Mojon *in* Weidmann et al. 2014, Pl. IV, figs. 11–46). Compared to *C. notata* (Fig. 15.54–55/57; Mojon *in* Weidmann et al. 2014, Pl. IV, figs. 11–13/21–32/38–39/43–46) with small tubercles disposed in single rows along the spiral cells, the ornamentation of *C. microcera* is similar but less regular, much finer and denser (Fig. 12.87–94). The morphotypes of *C. praemicrocera* (Fig. 12.73–86) differ clearly from the Miocene specimens of *C. molassica* with strongly concave and generally significantly thinner convolutions (Fig. 15.50–53/56). This distinction is less obvious for Late Oligocene specimens of *C. molassica*. *C. praemicrocera* has, however, frequently very small scattered tubercles (Fig. 12.81–83) and is a little less massive and smaller than *C. molassica* (Mojon *in* Weidmann et al. 2014, Pl. IV, figs. 19–20/33–37/40–42).

Assemblage zone SPN-OC 4

(= Ungeri Zone, small mammal zones MP 27–28). Paucispecific assemblage with *Stephanochara* gr. *ungeri* (elongated morphotypes very common), *Rhabdochara* gr. *praelangeri-major*, *Rhabdochara* gr. *langeri*, *Nitellopsis (Tectochara)* gr. *meriani*, *Hornichara* gr. *lagenalis* and *Sphaerochara* gr. *hirmeri*. In the Niederroedern Formation of the Upper Rhine Graben, the range of *H.* gr. *lagenalis* includes the Microcera Zone (Pirkenseer et al. 2013). The assemblage zone SPN-OC 4 is well known in the Molasse of Vaud Plateau (Weidmann et al. 2014).

Assemblage zone SPN-OC 5

(= Notata Zone, small mammal zones MP 28–30). With *Chara* gr. *molassica-notata* (very common), *Stephanochara* gr. *oodea-praeberdotensis* (see below "Assemblage zone SPN-MC 1" and "Assemblage zone SPN-MC 2"), *Stephanochara* gr. *ungeri* (large-sized and wider morphotypes, very common), *Rhabdochara* gr. *praelangeri-major*, *Rhabdochara* gr. *langeri*, *Nitellopsis (Tectochara)* gr. *meriani*, *Nitellopsis (Tectochara) ginsburgi* (rare), *Hornichara* gr. *lagenalis* and *Sphaerochara* gr. *hirmeri*. The occurrence of *St.* gr. *oodea-praeberdotensis*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◀**Fig. 14** Charophytes from the Early Miocene of the Swiss Molasse Basin (Early-Late Aquitanian, SPN-MC 1–2). 1–11: ***Rantzieniella nitida***, **MCX008/16** (1–4, SPN-MC 1), **LG-2014/DK/1** (5–7, SPN-MC 1), **CB-2017/POM/1** (8–11, SPN-MC 2, MN 2b, damaged specimens partially reworked in the base of the OMM). 12–21: ***Stephanochara* gr. *oodea-praeberdotensis***, **TIL004/48** (12–15, morphotypes *praeberdotensis*, SPN-MC 1), **MCX008/16** [16–18, morphotypes *oodea* (16–17) and *pseudoodea* (18), SPN-MC 1], **Mèbre-1997/POM/1** [19–21, morphotypes *oodea* (19–20) and *pseudoodea* (21), SPN-MC 2, MN 1–2a]. 22–37: ***Stephanochara berdotensis***, **MR-2017/POM/1** (22–29, SPN-MC 2, MN 2a–b), **CB-2017/POM/1** (30–37, SPN-MC 2, MN 2b). 38–44: ***Lychnothamnus rhabdocharoides***, **CR-2017/POM/1** (SPN-MC 2, MN 2b). **Lateral views** (3–7/9–11/15/17–18/20–21/23–36/40–44), **apical views** (1–2/8/12–14/16/19/22/37–39)

and *N. (T.) ginsburgi* in the upper part of small mammal zone MP 28 is linked to a warming episode with an increasing aridity named "Microbunodon Event", according to a renewal of the large herbivorous mammal fauna (Weidmann et al. 2014; Mennecart 2015). The assemblage zone SPN-OC 5 is well known in the Swiss Plateau and Subalpine Molasse (Berger 1998; Weidmann et al. 2014).

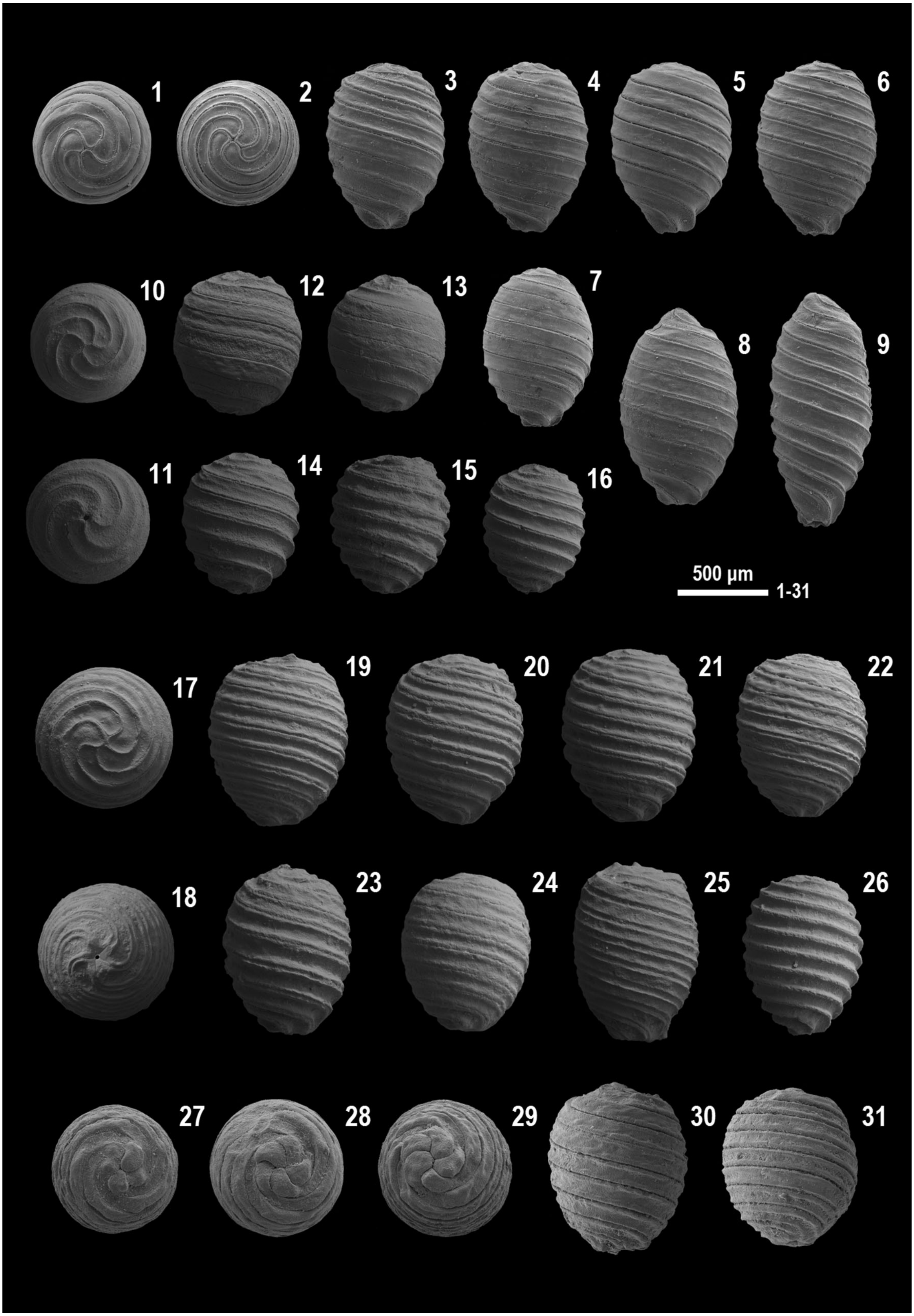
Assemblage zone SPN-MC 1

(= Nitida Zone, small mammal zone MN 1). With *Rantzieniella nitida* (rare, Fig. 14.1–7), *Stephanochara* gr. *oodea-praeberdotensis* (very common, Fig. 14.12–21), *Stephanochara* gr. *ungeri* (large and rounded morphotypes), *Chara* gr. *molassica-notata* (morphotypes *notata* very common), *Nitellopsis (Tectochara)* gr. *meriani*, *Nitellopsis (Tectochara) ginsburgi* (rare), *Rhabdochara* gr. *langeri* and *Sphaerochara* gr. *hirmeri*. Difficult to characterize, the typical assemblage zone SPN-MC 1 with *R. nitida* is at present recognized in eight localities of the Swiss Molasse [Plateau: La Morges (Kissling 1974), Nant d'Avanchet (Charollais et al. 2007), Boudry (Weidmann et al. 2014), Bevaix and Marin-Epagnier (this study); Jura: Métairies de Chaux, Courfaivre and Laupersdorf (this study)]. The occurrence of *R. nitida* (Raskyellaceae) can be related to a rise of temperature and humidity in the beginning of Aquitanian, after a Late Chattian warming period of aridity (MP 28–30, Picot et al. 1999; Picot 2002; Becker et al. 2002; Becker 2003).

Assemblage zone SPN-MC 2

(= Berdotensis Zone, small mammal zones MN 2a–b). With *Stephanochara berdotensis*, *Stephanochara* gr. *oodea-praeberdotensis*, *Rantzieniella nitida* (very rare), *Lychnothamnus rhabdocharoides*, *Chara* gr. *molassica-notata*, *Nitellopsis (Tectochara)* gr. *meriani* and *Sphaerochara* gr. *hirmeri*. In the Bavarian Molasse Basin, *N. (T.) ginsburgi* is present in the Berdotensis Zone (gyrogonites adorned with typical swellings on the ridges of the protruding spiral cells, cf. Fig. 15.32–36 with material from the OSM-J of Le Locle) and was reported to *N. (T.)* gr. *meriani* (spp. *meriani*, *globula* and *huangi*, Schwarz & Reichenbacher 1989, Pl. 2, figs. 1–3). In France, *R. nitida* is reported from the mammal biozones MN 1 (Paulhiac) and MN 2b (Laugnac) of Aquitaine (Feist and Ringeade 1977) and from sediments just below the Faluns de Touraine of Early Burdigalian (MN 3) in the Paris Basin (Riveline 1984, 1986). The assemblage zone SPN-MC 2 occurs in the Molasse grise de Lausanne of the central Swiss Plateau (Berger 1983, 1985; Engesser et al. 1993) and in the basal Luzern Formation or deltaic OMM I of Eastern Switzerland (Benkert 1984; Schlunegger et al. 2016; this study, Fig. 13b). About 240 m above the base of the Luzern Formation and in the top of a major regressive sequence of floodplain, an emersive palustrine layer of dark brown and grey marls has provided charophytes of the Berdotensis Zone (*Stephanochara berdotensis*, *Sphaerochara* gr. *hirmeri*, *Chara* gr. *molassica-notata*). The gyrogonites of *St. berdotensis* from Hasle-Entle are similar to those from Marnand (Fig. 14.22–29) and close to those of *Lychnothamnus rhabdocharoides* (Fig. 14.38–44) collected in the upper Berdotensis Zone (small mammal zone MN 2b). This regressive sequence is the most important in the OMM I and the non-marine marly layer with Late Aquitanian charophytes can be interpreted as the transgressive surface of the Early Burdigalian, well-dated in higher regressive sequences by small mammal zone MN 3b (Schlunegger et al. 2016). The interval MN 1–2a of the Swiss Molasse is mainly characterized by large *St.* gr. *oodea-praeberdotensis* (Fig. 14.19–21) and the interval MN 2a–b by transitional *St. berdotensis* assemblages derived from *St.* gr. *oodea-praeberdotensis* (Fig. 14.22–29, Berger 1983), typical *L. rhabdocharoides* (see below) and large *St. berdotensis* (Fig. 14.30–32; Berger 1983, Pl. 2, figs. 6, 7; Mennecart et al. 2016, fig. 7.11) occur only in the upper part (with large *R. nitida*, Fig. 14.8–11) shortly before the OMM transgression.

Stephanochara* gr. *oodea-praeberdotensis is a species group including mixed assemblages of gyrogonites with morphotypes *oodea*, *pseudoodea* and *praeberdotensis* from small mammal zones MP 28 to MN 1–2a. The typical morphotypes *oodea* are large and rounded, with big apical nodules and slightly concave to convex convolutions separated by generally simple sutures (Fig. 14.16–17/19–20). The morphotypes *pseudoodea* are very similar, but distinctly elongated (Fig. 14.18/21). Both characterize particularly the palustrine black marls around the limit MN 1–2a in the Molasse grise de Lausanne (localities of Bois-Genoud and La Mèbre, Mumenthaler et al. 1981; Berger 1983; Engesser et al. 1993). The morphotypes *praeberdotensis* are characterized by concave convolutions with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◀**Fig. 15** Charophytes from the Middle Miocene of the NW-Swiss Folded Jura (Serravallian, SPN-MC 3 for sample LCF-CS3, SPN-MC 4 for all the other samples). 1–9: ***Lychnothamnus barbatus*, LL-PC2**. 10–16: ***Lychnothamnus antiquus*, LL-CG10**. 17–31: ***Lychnothamnus duplicicarinatus*, LL-CE24** (17–26), **LL-TDS13** 0.9–1.3 m (27–28/31) and 16.2–16.6 m (29–30). 32–36: ***Nitellopsis (Tectochara) ginsburgi*, LL-CG10**. 37–43: ***Nitellopsis (Tectochara) etrusca***; 44–49: ***Nitellopsis (Tectochara)* gr. *meriani*** (intermediate morphotypes with *N. (T.) etrusca*), **LL-CG10** (37/41–42/46), **LL-CG20** (38–40/43–45/47–49). 50–57: ***Chara* gr. *molassica-notata*** (morphotypes *molassica*: 50–53/56; morphotypes *notata*: 54–55/57), **LL-HC12** (50–52), **LL-CG33** (54), **LCF-CS3** 5–5.1 m (53/55) and **LL-JJHS** (56/57). **Lateral views** (3–9/12–16/19–26/30–31/33–36/39–43/45–57), **apical views** (1–2/10/17/27–29/32/37–38/44), **basal views** (11/18)

double sutures; they are generally rounded and smaller than the morphotypes *oodea* and *pseudoodea*, apical nodules can be developed or not (Fig. 14.12–15). According to our opinion, the differences of morphology and size result from variable conditions of growth or calcification for related gyrogonites and are not significant to consider the morphotypes *oodea*, *pseudoodea* and *praeberdotensis* as separate taxa.

Stephanochara berdotensis includes ovoid to rounded or elongated gyrogonites of very variable size generally characterized by strongly concave convolutions and double sutures (Fig. 14.22–37), small apical nodules can be present (Fig. 14.22/33) or not (Fig. 14.37). Some small elongated specimens with slightly convex or concave convolutions are very close to *Stephanochara* gr. *ungeri* (Fig. 14.26/34/36) and were attributed formerly to *St.* aff. *rochettiana* (Berger 1983, Pl. 2, fig. 5). In such cases, a careful examination and comparison is essential to differentiate surely isolated atypical specimens of *St. berdotensis* assemblages from those of *St.* gr. *oodea-praeberdotensis* and *St.* gr. *ungeri*.

Lychnothamnus rhabdocharoides (Berger 1983) Mojon, nov. comb. (= *Stephanochara rhabdocharoides* Berger 1983, p. 20–21, Pl. 1, figs. 9–12) has ovoid to ellpsoid gyrogonites of medium size (650–800 µm long, 490–750 µm wide) with short basal funnel, flattened apex without nodules and 8–10 strongly concave convolutions separated by generally simple (rarely double) sutures (Fig. 14.38–44). In the Swiss Molasse Basin, this taxon derived from *St. berdotensis* occurs in MN 2b, the species owns all the primary features of the genus *Lychnothamnus* (cf. "Update of the genera *Rhabdochara*, *Stephanochara* and *Lychnothamnus*") and is represented by very abundant homogeneous assemblages of gyrogonites (MN 2b–3).

Assemblage zone SPN-MC 3

(= "Ginsburgi" Zone, small mammal zones MN 3–middle MN 6). With *Nitellopsis (Tectochara) ginsburgi* (common), *Nitellopsis (Tectochara)* gr. *meriani*, *Lychnothamnus rhabdocharoides*, *Chara tornata*, *Chara* gr. *molassica-notata* and *Sphaerochara* gr. *hirmeri*. In the northern Swiss Plateau, *N. (T.) ginsburgi* is known since MP 28 (Weidmann et al. 2014) and *L. rhabdocharoides* is common from the top USM (Late Aquitanian/MN 2b, sections of Cheyres, Burg and Vully) to the basal OMM (Early Burdigalian/MN 3, sections of Vully and Jaïssberg). In the southern Jura Mountains near Tramelan and Sorvilier (Pré Golat hill, vallée de Tavannes), Becker (2003) mentioned briefly *N. (T.) ginsburgi*, *N. (T.)* gr. *meriani*, *C.* gr. *molassica-notata*, *Lychnothamnus* and *Sphaerochara* spp. from a section attributed to basal OSM-J (MN 5–6).

In Eastern Switzerland, lacustrine and palustrine layers of the OMM II (St-Gallen Formation, MN 4) and OSM (MN 5–8) yielded also some interesting charophytes as *N. (T.) ginsburgi*, *N. (T.)* gr. *meriani*, *L. rhabdocharoides*, *Lychnothamnus antiquus*, *C. tornata* and *C.* gr. *molassica-notata* (Matter 1964; Reichenbacher et al. 2005; Jost et al. 2006, 2015; Schlunegger et al. 2016; this study). *Lychnothamnus antiquus* occurs in upper MN 6 (Mariahaldetobel and Brandtobel, cf. Table 1 and Fig. 9), probably towards the end of the short period of aridity (MN 4–7) reported by Becker (2003).

Assemblage zone SPN-MC 4

(= Etrusca Zone, small mammal zones upper MN 6—MN 9). With *Nitellopsis (Tectochara) ginsburgi* (common), *Nitellopsis (Tectochara) etrusca* (typical very large morphotypes), *Nitellopsis (Tectochara)* gr. *meriani*, *Lychnothamnus antiquus*, *Lychnothamnus duplicicarinatus*, *Lychnothamnus barbatus* and *Chara* gr. *molassica-notata*. In Tramelan, the age of the OSM-J can be precisely determined until MN 7 + 8 with teeth of small mammals (Aufranc et al. 2016a) and typical specimens of *L. antiquus* and *L. duplicicarinatus*, quite similar to those of the basal Etrusca Zone from La Chaux-de-Fonds - Le Locle syncline (samples from Cridor boreholes, Combe Girard and Les Varodes). For the currently covered outcrops of the Nebelberg Süsswasserkalk (MN 9), Becker (2003) mentioned briefly *Nitellopsis (Tectochara)* and *Lychnothamnus* spp., with *Chara* gr. *notata* and *Chara* sp. In the Swiss Molasse, the assemblage of charophytes from MN 9 is represented by very little material and should be characterized more precisely.

Lychnothamnus antiquus (Soulié-Märsche 1989) Mojon, nov. comb. (= *L. barbatus* var. *antiquus* Soulié-Märsche 1989, p. 155–156, Pl. XXXVII, figs. 1–9) has spheroidal-rounded to oval gyrogonites of medium size (Fig. 15.10–16), with a wide and slightly convex or flattened apex without apical nodules (Fig. 15.10). The spiral

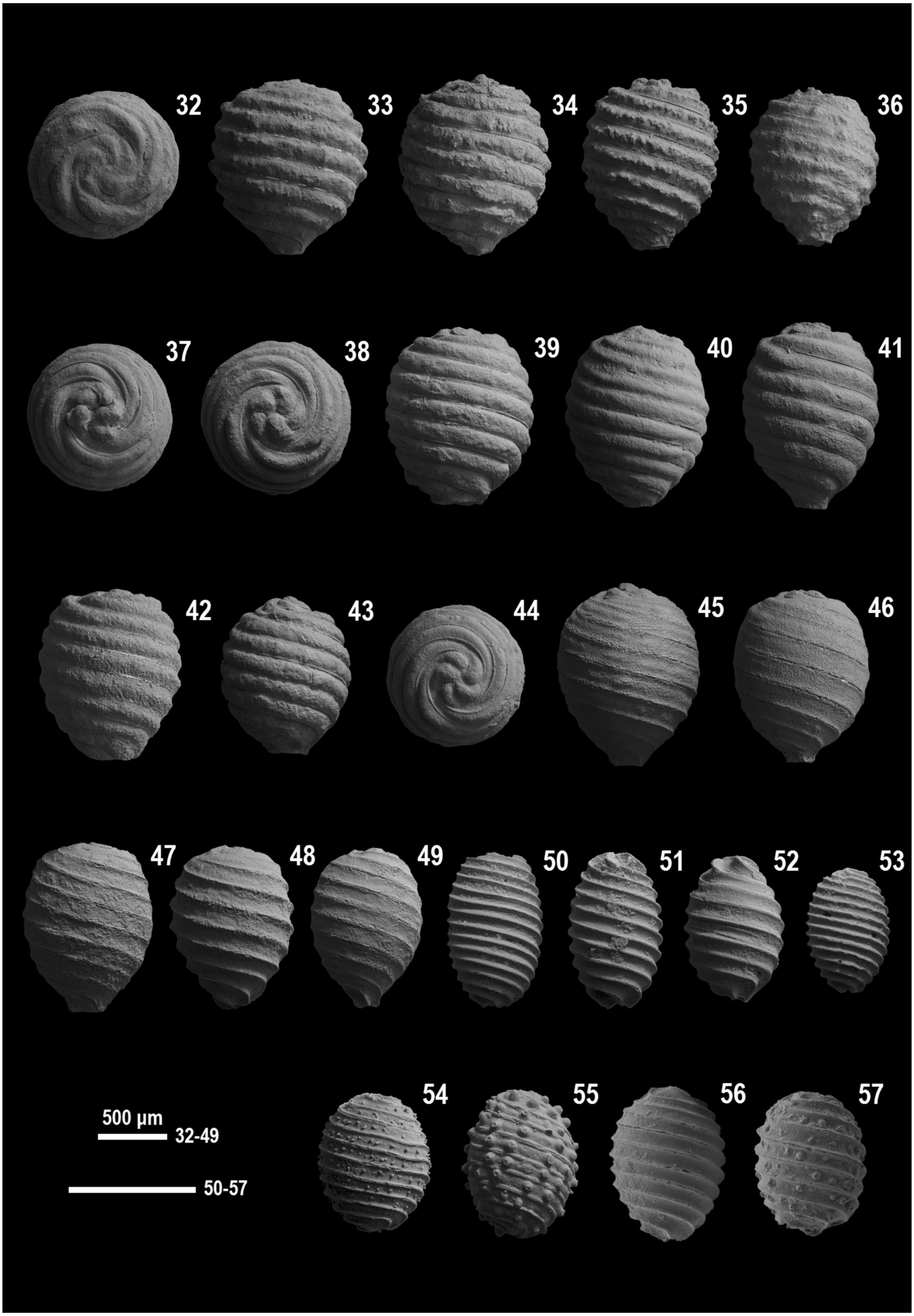

Fig. 15 continued

cells are broad and smooth, flat or concave, with 7–8 convolutions and double flat sutures (Fig. 15.13) or generally double often protruding sutures (Fig. 15.12/14–16). The base is rounded with basal funnel absent or poorly developed and small pore (Fig. 15.11). *L. antiquus* is well known in the Middle Miocene of SW-France (Soulié-Märsche 1989) at Sansan and La Grenatière (MN 6). In the Swiss Molasse, *L. antiquus* occurs in upper MN 6 as a derived species from *L. rhabdocharoides*. In the Late Miocene of Portugal (MN 10, Etrusca Zone, Telles Antunes et al. 1992), *L. antiquus* is associated with *N. (T.) etrusca*, *N. (T.) ginsburgi*, *C.* gr. *molassica-notata* and *Sphaerochara* sp. In Asia, *L. breviovatus* is a synonym for *L. antiquus* (Lu & Luo 1990: Tarim Basin, China, Middle Miocene (not Middle Oligocene as initially indicated)–Pliocene; Bhatia 1999, 2003: Middle-Upper Siwalik Group of India and Nepal, Late Miocene–Pliocene). The gyrogonites of the Middle Miocene assemblages of *L. antiquus* are consistently rounder and smaller than those of *L. barbatus*; these taxa are, therefore, considered as separate species.

Lychnothamnus duplicicarinatus has oval gyrogonites of medium size (Fig. 15.17–31), with a usually flat apex (Fig. 15.17) that may rarely feature flattened and well-developed apical nodules (Fig. 15.27–29). The spiral cells are smooth and concave with 8–10 convolutions, their surface is sometimes uneven and partly slightly bumpy (feature equivalent to thickened rods of *Rhabdochara*, Fig. 15.21). The base of the gyrogonites is elongated and truncated, forming a short funnel with a small star-shaped and pentagonal pore (Fig. 15.18). The bulging and irregular (slightly wavy) sutures of the convolutions form typical double and strongly protruding ridges; some smaller specimens show simple sutures (Fig. 15.26). According to Soulié-Märsche (1978), this species is frequent in the Swiss OSM of Anwil (Baselland) dated by late Middle Miocene small mammals (MN 8, Engesser 1972). In the Swiss Molasse, *L. duplicicarinatus* occurs in MN 7 + 8 as a derived species of *L. antiquus* (primitive morphotypes with a smaller size and simple sutures, Fig. 15.26), the species is also well known in the Late Miocene (MN 8–11) of Austria (Papp 1951) and Portugal (Soulié-Märsche 1978).

Lychnothamnus barbatus has oval-elongated gyrogonites of medium size (Fig. 15.1–9) with wide and generally flattened apex lacking apical nodules (Fig. 15.1, 2). A short basal funnel is well developed. The spiral cells are smooth, broad and slightly concave to flat with 8–10 convolutions and a slightly prominent double suture. In extreme cases of polymorphism, gyrogonites may feature a pointed apex and an elongated to very oblong shape (Fig. 15.8, 9), the latter most likely corresponding to a teratological specimen. This species occurs in the Middle Miocene of the Swiss Jura Mountains (MN 7 + 8) and is well known from the Late Miocene to the Present (Soulié-Märsche 1989; Soulié-Märsche & Martin-Closas 2003). *L. barbatus* may also show local assemblages of gyrogonites with double and protruding sutures (*L. barbatus* var. *bicarinatus* from Late Pliocene–Pleistocene of Greece, Soulié-Märsche 1979); these gyrogonites are very similar to those of *L. duplicicarinatus* but nevertheless significantly smaller. In this regard, Soulié-Märsche (1989, *in* Telles Antunes et al. 1992) considered *L. duplicicarinatus* and *L. antiquus* simply as ecological varieties of *L. barbatus*, arguing the local influence by environmental factors on growth and calcification of gyrogonites. However, *L. antiquus* first occurs in the early Middle Miocene (upper MN 6), whereas *L. duplicicarinatus* and *L. barbatus* are a little younger (MN 7 + 8). Accordingly, *L. duplicicarinatus*, *L. antiquus* and *L. barbatus* constitute morphologically and temporally separated fossil and extant assemblages, thus representing distinct species.

The related taxa ***Nitellopsis (Tectochara) etrusca*** (Fig. 15.37–43) and ***Nitellopsis (Tectochara)* gr. *meriani*** (Fig. 15.44–49) feature large rounded and heavily calcified gyrogonites, they co-exist until the end of the Late Miocene [Gentili et al. 1998 (p. 677): Turolian sequence MN 11–13 of Bacinello with *N. (T.) etrusca* according to Tongiorgi 1956; Soulié-Märsche et al. 2002 (p. 1704): Tortonian–Messinian deposits MN 9–13 of Morocco with *N. (T.)* gr. *meriani*]. *N. (T.) etrusca* forms very large ovoid-globular gyrogonites, with generally 8–10 convolutions and protruding apical nodules surrounded by strongly narrowed spiral cells (Fig. 15.37–38). The gyrogonites related to the *meriani* group are usually smaller with less convolutions (7–8) and the apical nodules as well as the terminal narrowing of the spiral cells are less developed (Fig. 15.44). The mixed assemblages of gyrogonites from the OSM-J of La Chaux-de-Fonds–Le Locle syncline show typically evolved specimens of *N. (T.) etrusca*, while others are still very close to *N. (T.)* gr. *meriani*.

The charophyte biozonation of the Swiss Molasse ends in the early Late Miocene (small mammal zone MN 9), Pliocene deposits include only very altered and rare karst fillings in the Jura Mountains (MN 15, Bolliger et al. 1993). From the Late Miocene to Early Quaternary, new cosmopolitan taxa occur in Eurasia (Fig. 9, stratigraphic ranges in black for taxa or ranges not represented in Switzerland) with *Nitellopsis (Tectochara) majoriformis* (Kovar-Eder et al. 2002) from Late Miocene (MN 9–11, Harzhauser & Binder 2004) and *Nitellopsis (Nitellopsis) megarensis* from Pliocene–Early Pleistocene (Soulié-Märsche 1979, Bhatia et al. 1998). The current species *Nitellopsis (Nitellopsis) obtusa* was spread by migratory birds since the end of the last Ice Age. The fossil charophytes from the Quaternary deposits of Switzerland are still poorly known, *N. (N.)*

obtusa was recently found (2016) in the Early Pleistocene near the Swiss border (Tiefere Deckenschotter vom Hungerbol *in* Graf 2009, cf. Höhere Deckenschotter dated to MN 17 *in* Bolliger et al. 1996, = MNQ 17 *in* Guérin 2007). The Late Glacial and Holocene of the Jura Mountains recently yielded also some varieties of *Chara globularis* (e.g. *C. globularis* var. *rousseaui*) and *Nitella* spp. (Mojon et al. 2015). The current charophyte microflora of Switzerland includes many species of *Chara*, *Nitella* and *Tolypella*, as well as *N. (N.) obtusa* (Auderset Joye and Schwarzer 2012).

Update of the genera *Rhabdochara*, *Stephanochara* and *Lychnothamnus*

The genera *Rhabdochara*, *Stephanochara* and *Lychnothamnus* are closely related and have common features (Figs. 11, 12, 14 and 15, concave spiral cells, periapical depression, apical nodules, double and protruding sutures). For this reason, *Rhabdochara* and *Stephanochara* are sometimes considered as synonymous with *Lychnothamnus* (Soulié-Märsche 1989; Sanjuan and Martín-Closas 2015) or, as an intermediate point of view, as sub-genera of *Lychnothamnus* (Berger *in* Pirkenseer et al. 2013). The genus *Stephanochara* is frequently characterized by convex convolutions and apical nodules or pointed apical cells with a periapical depression. The gyrogonites of *Rhabdochara* are typically characterized by strongly concave spiral cells with thickened oblique rods, but flat convolutions and apical nodules by massive calcification can be seldom observed (Soulié-Märsche 1989, Pl. XXXVIII, figs. 1–12). Apical nodules are also rarely developed in some assemblages of Recent *L. barbatus* (Soulié-Märsche 1989, p. 154–155, Pl. XXXV, fig. 6) and *L. duplicicarinatus* from the OSM-J (Fig. 15.27–29). However, the apical nodules of *Lychnothamnus* differ significantly by their flattened and bumpy shape from those rounded-globular and smooth of *Stephanochara* or *Rhabdochara*. These genera give likewise very important biostratigraphic informations. *Rhabdochara* disappears in the Early Aquitanian (Nitida Zone, Berger *in* Charollais et al. 2007), *Stephanochara* vanishes at the end of the Aquitanian (Berdotensis Zone), then *Lychnothamnus* occurs in the Late Aquitanian (MN 2b) and continues until the Present. According to the differences and significant criteria summed up here, an unequivocal distinction is thus maintained for *Rhabdochara*, *Stephanochara* and *Lychnothamnus* in accordance with the charophyte classification of the *Treatise on Invertebrate Palaeontology* (Feist et al. 2005) as basic taxonomic reference.

Early Oligocene UMM and gompholites of the central Jura

The Early Rupelian UMM of Montmollin (Figs. 4e and 7a–d) is a very short marine ingression of the Perialpine Sea (western Paratethys) in the Jura area, a little older than the Late Rupelian connection (NP 23–24) between Upper Rhine Graben (URG) and western Paratethys (UMM of Eastern Switzerland) with marine sediments and microfossils partially reworked from the developing Alpine chain (Büchi 1983; Berger 1995, p. 666; Reichenbacher et al. 1996, p. 68 and 87–88, layer 10 of TOR 4 borehole; Berger et al. 2005a; Pirkenseer 2007; Pirkenseer et al. 2011). Similarly, this prior UMM is also characterized by reworked elements (nannoflora) from marine shallow sediments of the central Jura (Hauterivian to Albian–Cenomanian) and deeper flysch deposits of the Alpine realm (Late Campanian–Early Maastrichtian and Paleocene–Eocene); its occurrence is coherent with a marine connection between URG and western Paratethys postulated at NP 22 by Martini (1990).

According to an early phase of deformation and fracturing of the Jura area highlighted by the tectonic model of Valley et al. (2004), the UMM of Montmollin can be attributed to a deposition in the low parts of tilted blocks, conjointly with subaerial deposits like non-marine gompholites on Mesozoic substratum in the northern and central Jura. In the Conglomérat de Porrentruy of Ajoie, scarce marine fossils are present and attest a first early Rupelian ingression into the URG. In the Neuchâtel mountains, conglomerates and breccias with partially rounded and angular pebbles, entirely devoid of marine fossils or marine indicators (pebbles perforated by pholads and encrusted by barnacles, red algae or other marine organisms), constitute presumed Early Oligocene non-marine gompholites (not dated) below the Burdigalian OMM along the Vallée des Ponts (Pasquier et al. 2013; Weidmann and Pasquier 2014; this study, Table 2a, Fig. 16a–d). Oligocene paleoreliefs are attested in the Jura Mountains area by other similar gompholites (Aubert 1958, 1975; Berger et al. 1987; Fourneaux et al. 1990; Nicod 1990; Charollais et al. 2007). In the Vallée de Joux (Vaud NW-Folded Jura), the Conglomérat du lac Ter is another example of Late Priabonian–Early Oligocene gompholite below USM deposits dated by charophytes and small mammals (Weidmann 2008). The initial formation of paleoreliefs with lacustrine basins in the Jura area during the Late Eocene and Early Oligocene is interpreted as an extensive fracturing by flexure of the lithosphere due to the northward migration of the foreland bulge, before the

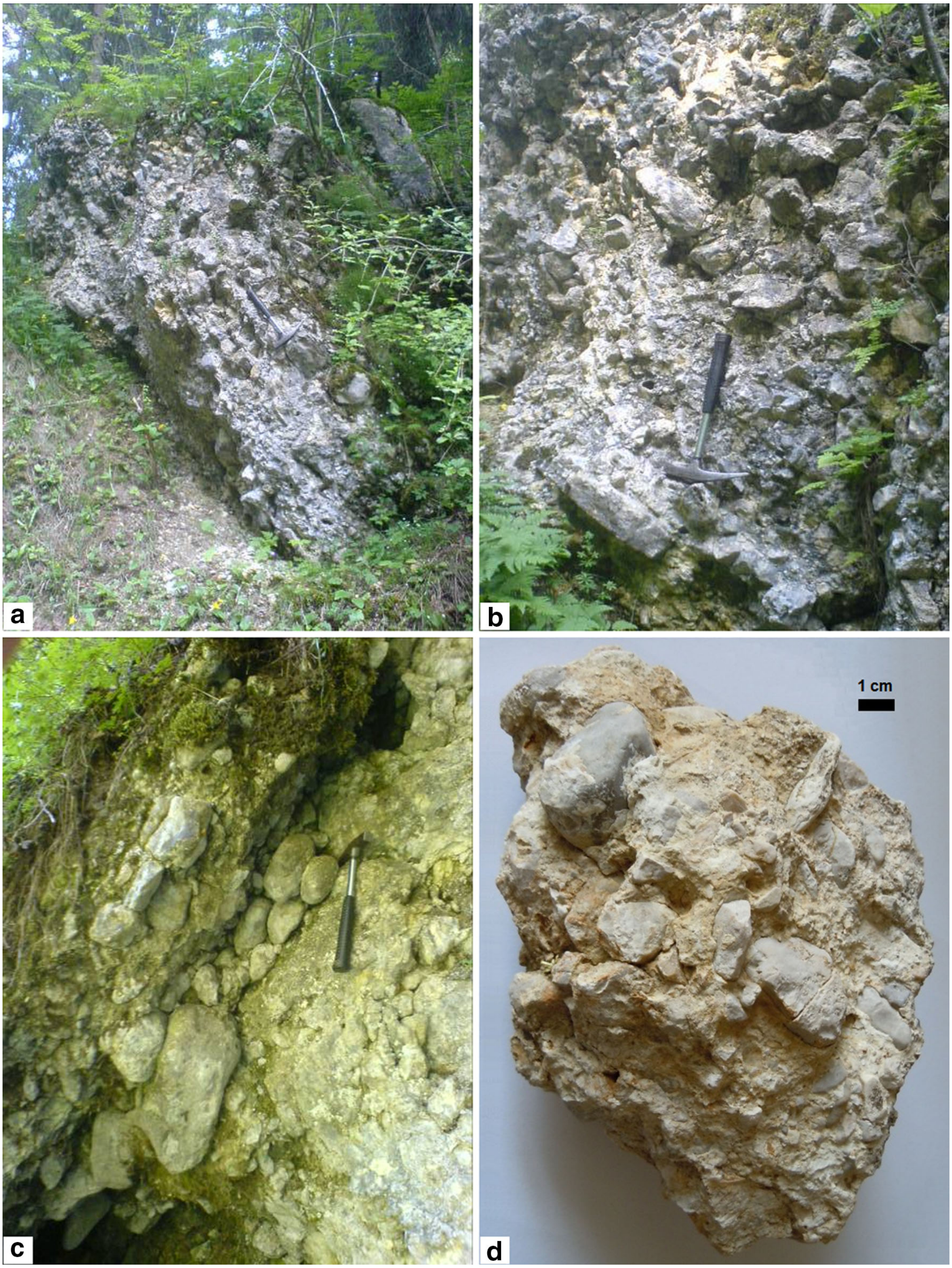

Fig. 16 Early Oligocene gompholites of the Vallée des Ponts (fossil sinkholes of Voisinage, near Ponts-de-Martel). **a**, **b** Western doline (coord. 2545.380/1204.600). **c**, **d** Eastern doline (coord. 2545.540/1204.760, **d** detailed view of the gompholite). Coordinates from the map of Switzerland 1:25'000. The hammer is 31.5 cm long. Photos by P.-O. Mojon (2008)

Late Miocene compression folding the Jura Mountains (Valley et al. 2004).

The UMM of Montmollin proves that the Perialpine Sea reached the central Jura area likely through an Early Rupelian framework of tilted fault blocks, a structure in accordance with partial deposits of the USM nearby (Rochefort syncline, Weidmann 1986) or their complete gap in the Vallée des Ponts (Kälin et al. 2001, p. 84), presumably by non deposition or erosion before the OMM transgression in the Neuchâtel High-Jura area (synclines of La Brévine, La Sagne–Les Ponts, La Chaux-de-Fonds–Le Locle). This example of Early Rupelian UMM is currently unique in the central Jura.

Conclusions

The diachronous deposits between the Siderolithic and the Lower Freshwater Molasse of the northern Swiss Plateau and Jura Mountains (Fig. 1, Tables 1 and 2a, b) range from the Late Eocene (Diegten Süsswasserkalk, Oberdorf Süsswasserkalk, lower Terre jaune, Calcaire d'eau douce d'Orbe) to the Early Oligocene (Marnes rouges and Calcaire d'eau douce de Trois-Rods, upper Terre jaune, Conglomérat de Porrentruy and "Molasse alsacienne"), according to new biostratigraphic data based on charophytes from Middle–Late Priabonian (Vasiformis–Tuberculata Zone, Tuberculata Superzone/Vectensis Zone), Rupelian (Tuberculata Superzone/Pinguis Zone, Major Zone) and Early Chattian (Microcera Zone). In the northern Swiss Jura, the non-marine premolassic Paleogene is notably influenced by the tectonic activity of the Upper Rhine Graben and includes major stratigraphical subdivisions with names of groups defined in the URG (Table 2b), as Haguenau Group (Diegten Süsswasserkalk, Oberdorf Süsswasserkalk), Pechelbronn Group (Terre jaune, Conglomérat de Porrentruy) and Stockstadt Group (Série grise, "Molasse alsacienne"). This stratigraphical terminology complements and changes the classical nomenclature for the Paleogene and Neogene of the Swiss Jura Mountains (USM-J, UMM-J, OMM-J, OSM-J) previously published by the Schweizerisches Komitee für Stratigraphie und Landesgeologie (2014). New lithostratigraphic data on Terre jaune are also reported with the log of Del 1 borehole providing a detailed and complete overview.

These results are completed in the central Jura by Early Chattian small mammals relating to biozone MP 25–26a (*Eomys* nov. sp. 2 from the Calcaire d'eau douce de Trois-Rods) and Lower Marine Molasse/UMM well-dated to NP 21 (lowermost Rupelian) by a rich nannoflora. This Early Rupelian UMM corresponds to a first marine ingression of the Perialpine Sea (western Paratethys) in the Jura area, clearly prior to a previously assumed Late Rupelian connection with the Upper Rhine Graben at NP 23–24 (Berger 1995; Berger et al. 2005a). According to an early phase of deformation and fracturing of the Jura area (Valley et al. 2004), this early UMM was likely deposited along a framework of tilted fault blocks, conjointly with Late Eocene–Early Oligocene non-marine breccias and conglomerates as Conglomérat de Daubrée and Conglomérat de Porrentruy in the northern Jura, gompholites de Martel-Dernier et du Voisinage (Vallée des Ponts) and Conglomérat du lac Ter (Vallée de Joux) in the central Jura.

In the northern Jura, typical Early Miocene charophytes of the Nitida Zone (Early Aquitanian) as the rare index-species *Rantzieniella nitida* are reported for the first time from the Calcaires delémontiens of the USM-J. In the Upper Freshwater Molasse (OSM-J) from Middle Miocene to early Late Miocene (Langhian–Serravallian and lowermost Tortonian, middle MN 5–MN 9), the charophyte microflora highlights the basal *Nitellopsis (Tectochara) etrusca* Zone (upper MN 6–MN 7 + 8). Observations about the charophytes collected attest that *Stephanochara*, *Rhabdochara* and *Lychnothamnus* constitute separate taxonomic genera and groups of species, in accordance with the *Treatise of Invertebrate Palaeontology* (Feist et al. 2005) and, therefore, are not synonyms as previously reported (Soulié-Märsche 1989; Sanjuan and Martín-Closas 2015).

In the Paleogene and Neogene of Switerland (SPN), 11 assemblage zones of Eocene–Oligocene and Miocene charophytes (SPN-EC 1–2, SPN-OC 1–5 and SPN-MC 1–4) complement the classical biozonations of charophytes and small mammals from Late Eocene (MP 18–20) to Oligocene (MP 21–30) and Miocene (MN 1–9). These data provide a new concept for more reliable correlations of biostratigraphic timescales and taxa distribution in the European Cenozoic basins, notably for the Upper Rhine Graben and the Molasse basins of Eastern Switzerland and Bavaria.

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