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An Eocene paleodoline in the Morcles Nappe of Anzeindaz (Canton of Vaud, Switzerland)

PASCAL LINDER

Key words: Helvetic Realm, Morcles Nappe, Eocene, Siderolithic, Sanetsch Formation, Paleodoline

ABSTRACT

In the helvetic Morcles Nappe of Anzeindaz (Canton of Vaud, Switzerland), Eocene sediments document the successive bypassing of the forebulge and foreland basin of the Alpine orogeny. Cretaceous sediments are cut off by the major erosive unconformity of the so-called "siderolithic" emersion phase. This persistent phase of continental exposure and erosion caused by the presence of the forebulge during the Early to Middle Eocene removed the older sediment record down to the relatively resistant "Mid-Cretaceous" sediments. For the area under consideration, the continental erosion resulted in a peneplain which is perforated at two points by large paleodolines. The study of the sedimentary filling and fossil content of the better preserved one of these paleodolines allows for a reconstruction of the gradual transgression of the foreland basin over the study area. The origin of the paleodoline is interpreted as resulting from a combination of Eocene synorogenic tectonics, providing faults, and the subsequent attack of continental erosion alongside such weak zones.

ZUSAMMENFASSUNG

Eozäne Sedimente in der helvetischen Morcles-Decke von Anzeindaz (Kanton Waadt, Schweiz) dokumentieren die Wanderung der "Forebulge" und des Vorlandbeckens der entstehenden Alpen. Über kreidezeitlichen Sedimenten folgt die sehr bedeutende erosive Diskordanz der "siderolithischen" Emersionsphase. Diese langanhaltende, durch die Anwesenheit der "Forebulge" bedingte Phase kontinentaler Erosion während des frühen bis mittleren Eozäns beseitigte die älteren Sedimente bis hinunter zu den relativ verwitterungsresistenten Sedimenten der "Mittelkreide". Diese Erosionsphase bildete im Untersuchungsgebiet eine "Peneplain" aus, welche allerdings an zwei Stellen von zwei grossen Paläodolinen durchbrochen wird. Das Studium der Sedimentfüllung und des Fossilinhalts der besser erhaltenen dieser beiden Paläodolinen erlaubt eine Rekonstruktion der allmählichen Transgression des Vorlandbeckens über das Untersuchungsgebiet. Die Entstehung dieser Paläodoline wird gedeutet als eine Kombination der eozänen synorogenen Tektonik, welche zu Verwerfungen führte, und der kontinentalen Erosion, welche entlang so gebildeter Schwächezonen angriff.

1. Introduction

A) Topic

In the Early to Middle Eocene, the bypassing of the forebulge and foreland basin of the alpine orogeny through the southern European continental shelf led to the emersion and extensive continental erosion of ancient seafloors, followed by a renewed submersion (Crampton & Allen 1995, Sinclair et al. 1991). Thus, the Eocene erosive unconformity is a major stratigraphic feature that can be observed over large regions throughout the Helvetic Alps, the Jura Mountains and the Swiss Molasse Basin (Burkhard & Sommaruga 1998). In the Helvetic Alps, the region of Anzeindaz (see next paragraph) is particularly suitable to study the effects of long lasting continental erosion. Here, a paleodoline has been discovered nearly a century ago (Lugeon 1919). The topic of this article is to describe this structure and its sedimentary filling, a textbook example of a paleodoline, for the first time. Also, its origin shall be discussed.

B) Geographical and geological setting

The Alp of Anzeindaz lies in the so-called Chablais region of the Swiss Alps and is situated south of the Diablerets Mountains near the border between the cantons of Vaud and Valais. The structure described herein is situated at the mountain range of La Corde (coordinates 578.050/125.375, see Figure 1). A structure similar in form and size is also preserved at the nearby Col des Essets pass (coordinates 578.700/125.075). This structure is less well preserved; therefore, only the first-mentioned structure shall be described here.

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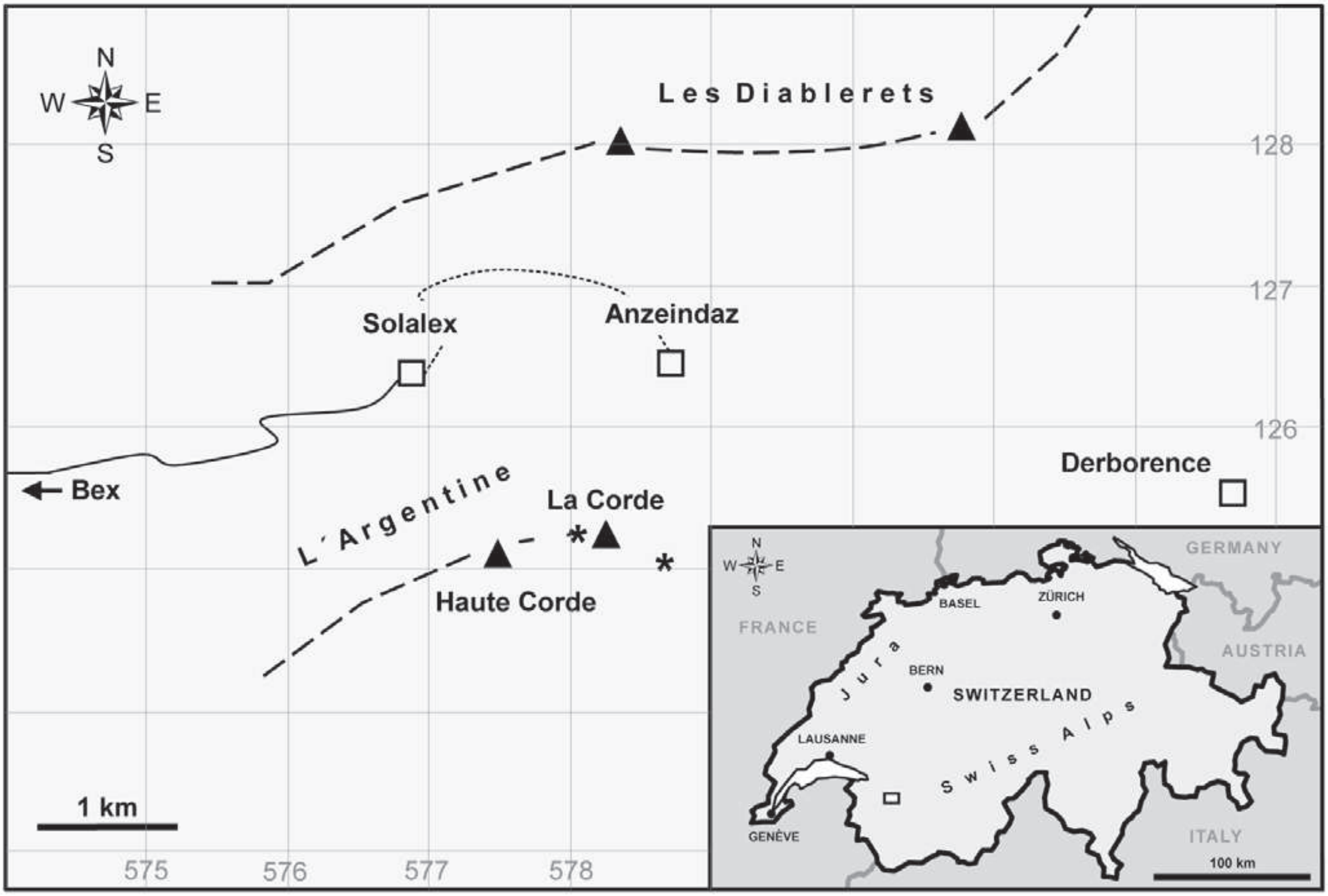


Fig. 1. Geographical situation of the Anzeindaz region. The asterisks mark the paleodolines of La Corde (west) and Col des Essets (east). Squares indicate hamlets, solid and dotted lines mark roads and paths, dashed lines trace mountain ranges, triangles mark individual peaks. Fine lines mark the kilometric topographic grid of Switzerland.

In the Anzeindaz region, the folded frontal zone of the helvetic Morcles Nappe crops out. Its sediments document the evolution of the southern European continental margin during the Mesozoic and parts of the Paleogene: They contain Jurassic and Cretaceous carbonate platform successions; the uppermost of the preserved Cretaceous formations (the Early Cretaceous Schrattenkalk Formation, the "Mid-Cretaceous" Garschella Formation and the Late Cretaceous Seewen Formation) are cut off by the Eocene erosive unconformity. Overlying this unconformity are Eocene and Oligocene transgressive sediments, peaking in Flysch deposits. In the context of this article, the oldest sediments filling the paleodoline are of special interest. They consist of so-called "siderolithic" sedimentary relics related to the Eocene erosion, basal conglomerates and transgressive sediments of the Sanetsch Formation.

C) History

In 1854, Renevier was the first to visit the site of La Corde and to recognize its Eocene sediments. However, he did not notice the special character of the erosive unconformity in this place. Lugeon (1919) first recognized the structure at La Corde as a paleodoline (see also Lugeon 1940). The sedimentary filling of this paleodoline has since been mentioned by several other authors (e.g. Badoux 1973, Badoux et al. 1990, Masson 1980, Masson et al. 1980) but neither of them described the structure in three-dimensions. The Eocene sediments of the Morcles Nappe were described by Rykken (1968), amongst others. The Eocene Sanetsch Formation, which includes most of the sedimentary deposits infilling the structure, was formally described only recently by Menkveld-Gfeller (1993, 1994), based on the work of Herb (e.g. Herb 1988).

2. Description of the paleodoline and its sedimentary filling

A) Eocene erosive unconformity

In the Anzeindaz region, the Eocene erosive unconformity cuts off the relatively erosion-resistant glauconitic and phosphoritic sediments of the Garschella Formation; Scarce relics

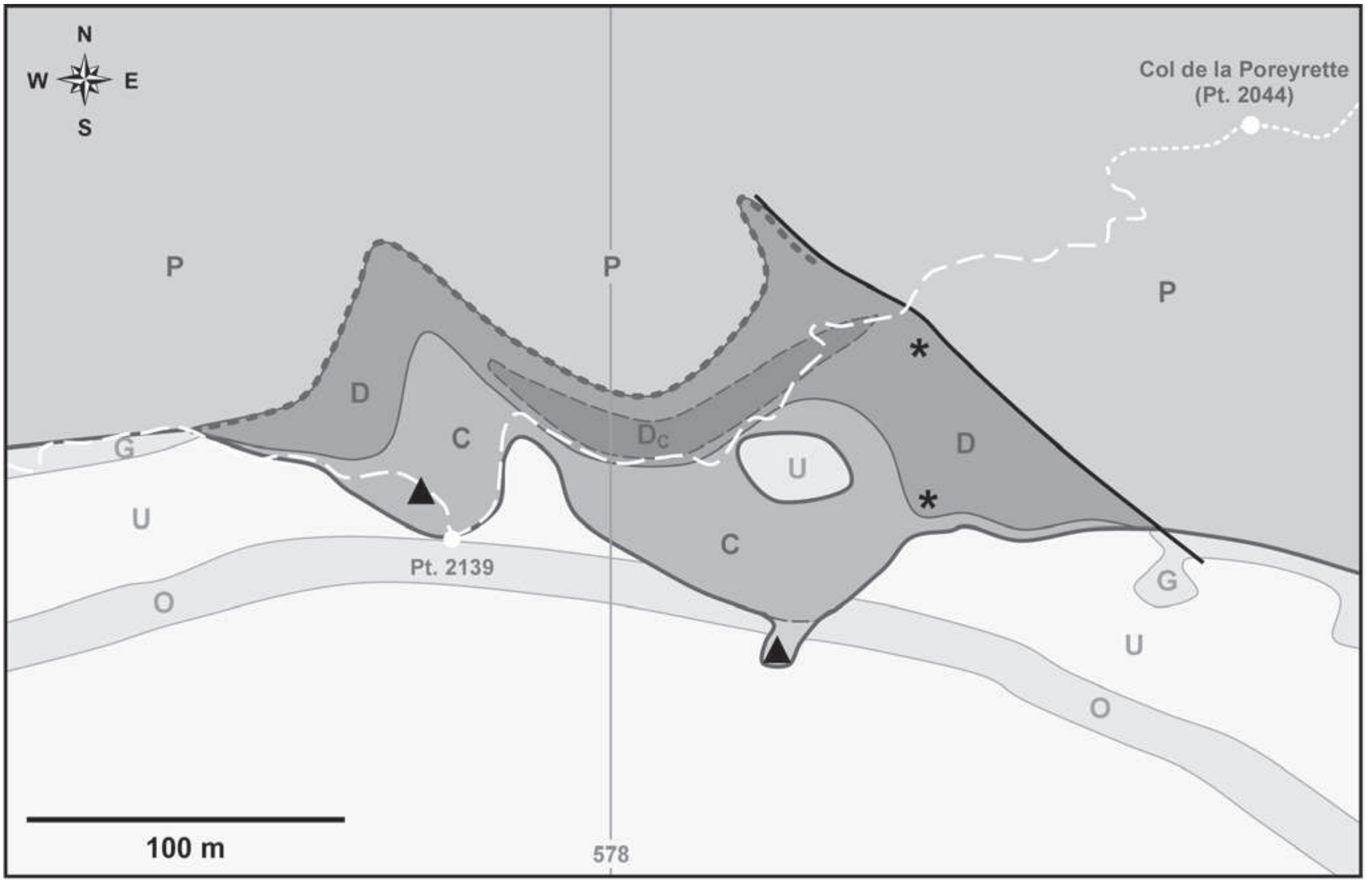


Fig. 2. Map of the paleodoline of La Corde, drawn after aerial photography. Light grey colours: Cretaceous substratum of the structure; Lower Orbitolina Member (O), Upper Schrattenkalk Member (U), Garschella Formation (G). Heavy grey line: eocene erosive unconformity, triangles: siderolithic remnants. The sediments of the Sanetsch formation that are filling the paleodoline are given in darker colours: basal conglomerate (C), Diablerets Member (D), "Cerithium Beds" of the Diablerets Member (D_C). The asterisks mark the oyster (north) and coral (south) reefs. The Tsanfleuron Member forming the lid of the paleodoline is traced by the heavy dotted line. The cover of the structure is formed by the Pierredar Member (P). Note the fault cutting off the structure at its northeastern rim (heavy black line). White lines mark the path from Anzeindaz to the Haute Corde peak.

of overlying Seewen Formation limestone are preserved. Thus, the erosive unconformity marks a peneplain (Masson 1980), a paleosurface with a very gentle profile, which is pierced only by the before-mentioned paleodolines. At these points, the Eocene erosion removed the Garschella Formation and parts of the underlying Schrattenkalk Formation limestones (see figure 6).

This unconformity and its siderolithic relics (see paragraph 2 C) are difficult to date since guide-fossils (e.g. mammal teeth) are rare. In fact, no such fossils could be found in the Anzeindaz region. However, in the Authochtone of the Chablais region a single rodent tooth was found (Weidmann 1984) indicating a probably Bartonian age. After a review of existing studies, Herb (1988) and Menkveld-Gfeller (1993) concluded that the Eocene erosive phase took place in the Mid-Eocene (Lutetian and Bartonian). This corresponds to a duration of continental exposure of about 12 my (Gradstein et al. 2004).

B) The paleodoline: geometry and size

At the notch between the peaks of La Corde and Haute Corde, the sediments of the Garschella Formation have been completely eroded resulting in a bowl-like structure that measures some 300 meters in diameter (see Figures 2, 3 and 6). Due to the outcrop situation, only the northern half of the suspected original structure is still preserved, whereas the southern part has been totally removed by the Quaternary erosion. This allows for a study of a complete vertical section of the structure since it seems to be cut exactly at its deepest point. At this point, the structure reaches its maximum depth of 23 meters with its bottom breaching the Lower Orbitolina Beds of the Schrattenkalk Formation. The northeastern end of the structure is cut off by an alpine normal fault (for discussion see 3 A, last paragraph). This cut-off and the situation of the Quaternary erosional surface lead to a somewhat irregular outcrop situation but the original form of the structure must have been quite regular.

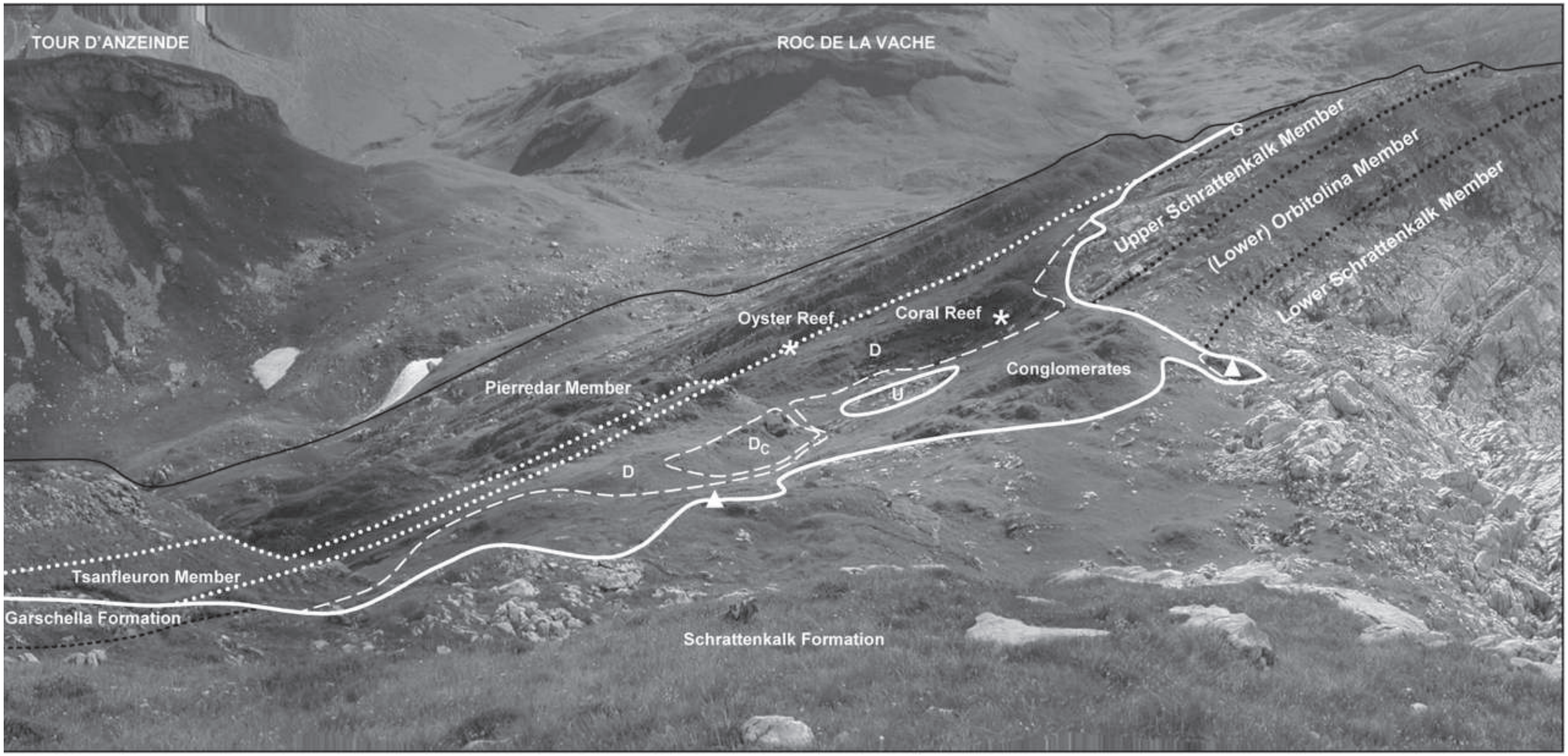


Fig. 3. View of the paleodoline of La Corde seen from the Haute Corde (the picture is oriented approximately NW-SE). The diameter of the structure is about 300 meters; its maximum depth is 23 meters. Abbreviations and simbols as in figure 2. The solid black line marks the silhouette of the Argentine mountain range. In the background, the Tour d'Anzeindaz and Roc de la Vache hills (formed by ultrahelvetic nappes) are visible.

C) Siderolithic sedimentary relics

The historic term “siderolithic” has been used in context with the often iron-rich (=ferralitic, hence the name) sedimentary relics associated with the Eocene erosive unconformity. However, the term was never formally defined and therefore often used in a very broad, vague and sometimes contradicting manner. Following Wieland (1976) one could define siderolithic sedimentary relics as comprising all autochthonously reworked sediments, paleosols, restites and resediments formed during the warm and humid, subtropic phase of Eocene continental erosion. In this sense, siderolithic relics are clearly differentiated from ordinary continental sediments. It is clear from this definition that siderolithic sediments sensu stricto are very rare, but it is equally evident that a depression such as the paleodoline at La Corde is a good place to preserve such relics, and in fact a variety of siderolithic formations can be found here:

At the deepest point of the structure, four meters of grain-by-grain eroded, transported and resedimented sediments of the Garschella Formation can be observed. Sediments reworked in such a kind are common siderolithic features and on first sight easily mistakable for their original sedimentary counterparts (Masson, pers. comm.).

A closer look reveals the redepositional character of these sediments: Firstly, the position of the deposits at the deepest point of the structure, at the stratigraphic level of the Lower Orbitolina Beds is very unusual. Secondly, the sediment consists of a mixture of components from the different lithologies of the Garschella Formation; fine-grained glauconite, sometimes coarse quartz grains and small phosphorite lithoclasts. Furthermore, there are millimetric, chamositic(?) pisoids which represent probably vadose continental formations from the Eocene emersion phase. Finally, and in contrast to the almost structure-less Garschella Formation, the reworked sediments show in some places centimetric irregular beddings, in others millimetric laminations with extension structures (see Figures 4 a and b). Judging from these observations, this deposit is interpreted as the sink hole of the structure.

At the western end of the paleodoline, where its filling overlaps the erosional cut-off of the Garschella Formation, iron oxyhydroxide pisoids similar to those in the bottom of the structure are observed in the corroded surface of the Garschella Formation (see Figure 4 c).

In different places, the erosive surface of the Schrattenkalk limestone at the bottom of the paleodoline shows karstic structures. The karstic infiltrations are filled with reddish, fine-grained clastic sediments that contain some centimetric rusty-eroding nodules. Sometimes the infiltrations are so dense that the surface is reduced to an in situ formed, form-fitting pseudo-conglomeratic fabric.

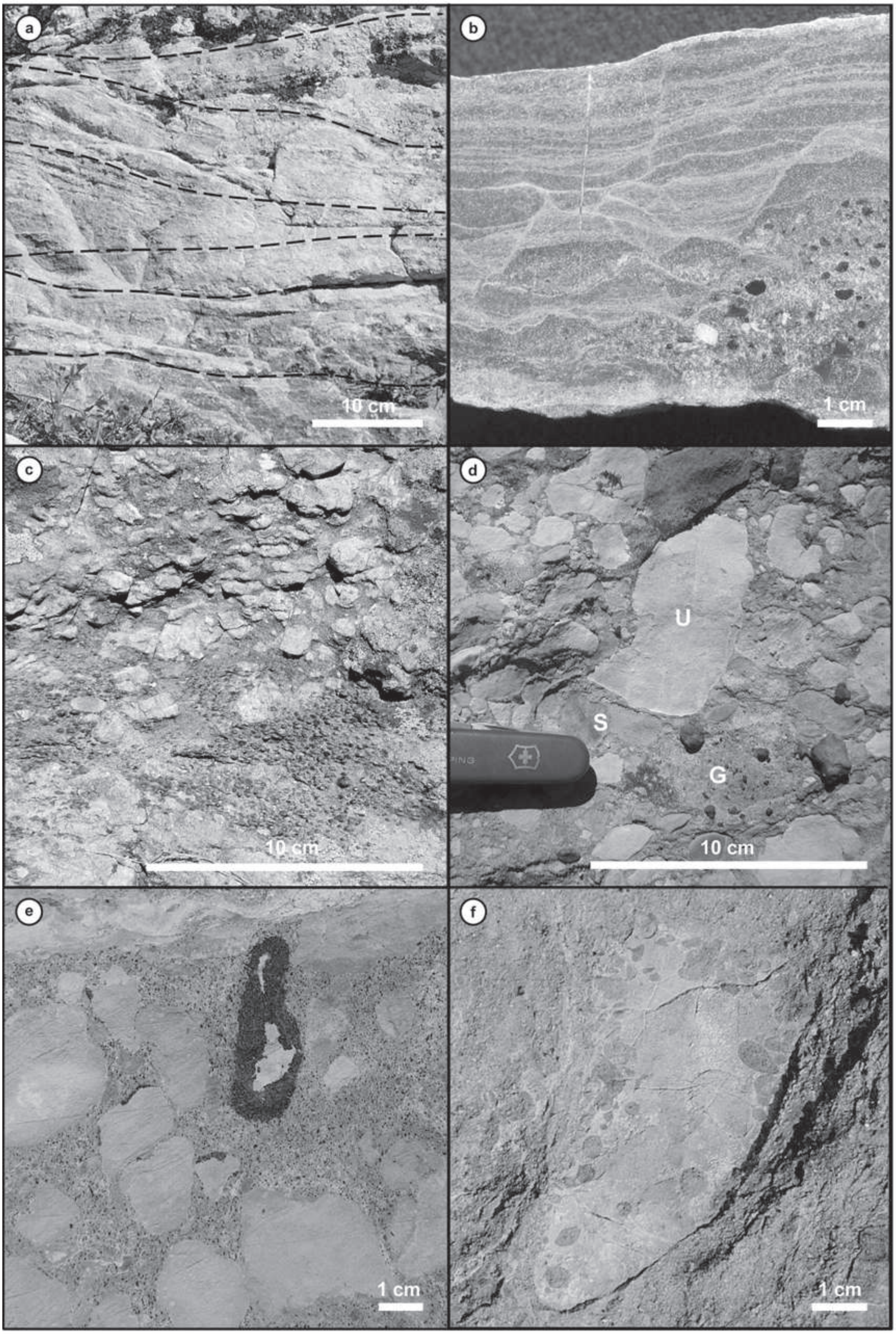
D) Basal conglomerate

At the bottom of the paleodoline, a conglomerate bed has been deposited. These conglomerates are informally known as “Roc Champion Conglomerat” (Lugeon & Argand 1937, Rykken 1968, Herb 1988). This bed wedges out near the rim and reaches its maximum thickness of six to nine meters at the deepest point of the structure. This basal transgressive conglomerate is mediating between the continental siderolithic relics and the marginal marine Diablerets Member: It consists of local pebbles of siderolithic origin, mainly of Schrattenkalk Limestone, as well as of Seewen Limestone and Garschella Formation sediments (Fig. 4d). Some rare pebbles are covered by *Microcodium* carpets (Masson 1980; see also Fig. 4e). The partially siderolithic-derived matrix consists of a ferrous sandstone with abundant *Microcodium* prisms, some centimetric, rusty-eroding nodules and few oysters. These oysters, which are more abundant in the upper part, are documenting wave-induced reworking of the upper part of the conglomerate during the Priabonian onset of transgression. Indeed, Badoux (1973) mentions *Nummulites striatus* (Bruguière, 1792) from the matrix, indicating a Priabonian age of deposition (or of last reworking, respectively). With the age given by Menkveld-Gfeller (1993) for the Diablerets Member of the Sanetsch Formation, the transgression age can be restricted to the early Priabonian. This is in good accordance with the Bartonian age for the original conglomerate formation proposed by Herb (1988).

In the central part of the structure, the amount of pebbles diminishes in the topmost half meter, giving way to a pebbly sandstone. Here, oysters (*Ostrea* sp.), sometimes with *Cliona* sponge borings, and *Lithophaga* borings in the pebbles become frequent (see Figure 4 f). At one point near the northeastern rim, a small oyster reef is observed. It is overgrown onto the surface of the Schrattenkalk Limestone, is 60 centimeters high and has a diameter of 30 meters. Here, the sediment consists almost entirely of oysters (see Figure 4 g).

Until now (Menkveld-Gfeller 1993, 1994) these conglomerates lack a formal attribution but Dr. Menkveld-Gfeller (pers. comm.) agrees that the “Roc Champion Beds” (sensu Rykken 1968) should be assigned entirely to the Diablerets Member of the Sanetsch Formation.

Fig. 4. a) Siderolithic sediment, reworked from the Garschella Formation displaying irregular beddings. b) Ibid; polished section with laminations and soft sediment extension structures. c) Corroded surface of the Garschella Formation with siderolithic pisoids; picture from nearby Ecuelle outcrop. d) Basal conglomerate with pebbles from different lithologies. e) Microcodium carpets and prisms in a conglomerate made of Seewen Limestone pebbles; Ecuelle outcrop. f) Pebble with lithophaga borings.
g) Bed surface of oyster reef. h) shark vertebra from the Diablerets Member; picture from the paleodoline at Col des Essets. i) Coral colony from the coral reef inside the Diablerets Member. j) Typical marly facies of the “Cerithium Beds” (Diablerets Member). k) Bed surface of the Tsanfleuron Member with sea urchin debris. l) Bed surface of the Pierredar Member (“Nummulithic Limestone”) with red algae (Lithothamnium). Abbreviations as in figure 2; S stands for Siderolithic.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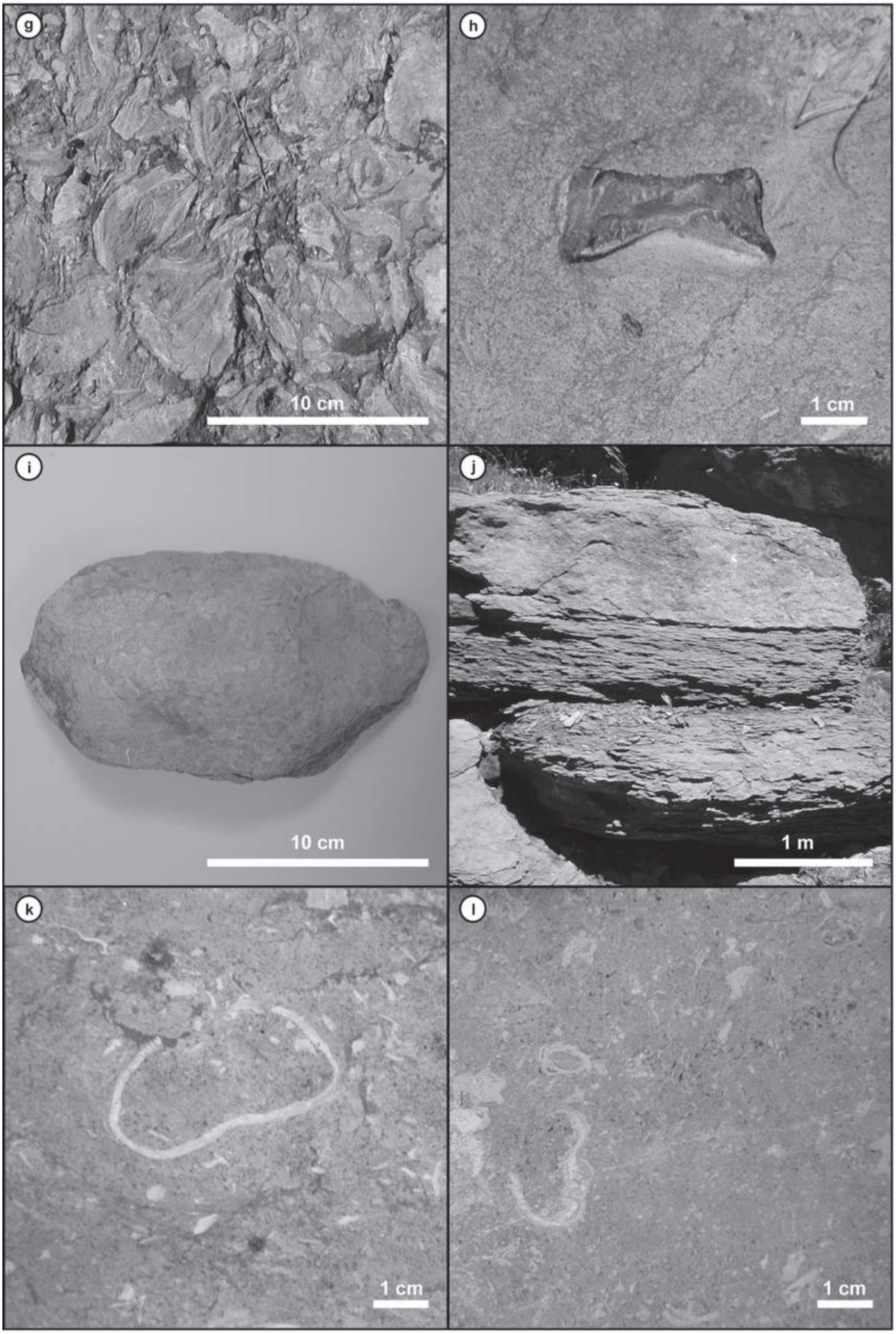
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E) Diablerets Member

On top of the conglomerates, light brown, sandy limestones with abundant centimetric lithoclasts are observed. They wedge out a little bit further to the rim than the conglomerates and measure up to nine meters near the center of the structure. Alveolinid and nummulitid foraminifera, oysters, mussels and gastropods are abundant. Lugeon (1919) mentions *Nummulites striatus* (Bruguière, 1792) from its base. Weidmann et al. (1991) mention tortoise bones as well as fish and shark teeth: *Labrus* sp., *Phyllodus* sp., *Striatolamia macrota* (Agassiz, 1843), *Carcharias hopei* (Agassiz, 1843).

Halfway to the middle of the structure, a small coral reef is observed. It is overgrown onto the basal conglomerate, measures three meters in height and has a diameter of 20 meters at the base. The corals are mostly branched colonies of *Caulastrea*, *Cyathoseris*, *Cladocora* and *Porites* (see Figure 4 i).

Near the center of the paleodoline, a three meter thick, lense-shaped body of dark brown, fossil-rich, sandy marls is embedded in the lower part of the sandy limestones without visible unconformity. It contains large quantities of *Natica (Ampullina) vapincana* D'Orbigny and other gastropods, oysters, other bivalves (some of which still display their original colour patterns), coal and bioturbations. Renevier (1890) gave a list of about 30 species from this site which was revised by Boussac (1912, p. 306 ff.). Although they represent a facies of the Diablerets Member (Sanetsch Formation; Menkveld-Gfeller 1993, 1994) rather than an independent lithostratigraphic unit (Renevier 1854, 1890, Boussac 1912), these sediments are historically known as "*Cerithium*, *Viviparium* or *Natica* Beds" (ibid. and Lugeon & Argand 1937; see Fig. 4j). In contrast to the light-brown facies of the Diablerets Member, which documents shallow but normal marine conditions, the "Cerithium Beds" document a decisively restricted, probably brackish facies (Badoux 1973) comparable to modern mangrove swamps (Masson 1980).

The age given by Menkveld-Gfeller (1993, 1994) for the Diablerets Member is Early Priabonian. This is in accordance with the before-mentioned *Nummulites striatus* (Bruguière, 1792). However, based on the above mentioned fish and shark teeth, Weidmann et al. (1991) rather suggest an Early to Middle Eocene age, but this is in disagreement to the other age estimates mentioned here.

F) Tsanfleuron Member

The lid of the sedimentary filling of the paleodoline is formed by up to three meters of light brown, sandy limestones (Fig. 4k) and a small bed of sandstone with centimetric gravel at the top. It contains alveolinid and nummulinid foraminifera, irregular sea urchins, red algae (*Lithothamnium*) and *Microcodium* prisms. The sandstone bed at the top is rich in bivalves, including oysters. The surface of the Tsanfleuron Member (Sanetsch Formation; Menkveld-Gfeller 1993, 1994) is approximately concordant to the bedding of the Cretaceous substratum. In one thin section, *Nummulites fabianii* (Prever in Fabiani, 1905) could be observed; they indicate a Priabonian age (Linder 2002). This is in accordance with Menkveld-Gfeller (1993), who gives a Middle to Late Priabonian age for the Tsanfleuron Member.

G) Pierredar Member

The Pierredar Member of the Sanetsch Formation (Menkveld-Gfeller 1993, 1994) is an approximate equivalent to the historically known "Nummulithic Limestone". It consists of about 100 meters of grey limestones with abundant nummulitid and other foraminifera, red algae (*Lithothamnium*; Fig. 4l) occasionally preserved with original coloration (Badoux 1973), sea urchins, bivalves, gastropods, corals and bryozoans. The bottom is brownish with reworked sand, centimetric lithoclasts and *Microcodium* prisms. In contrast to the other members of the Sanetsch Formation, the Pierredar Member has been deposited consistently throughout the Anzeindaz region since it forms the cover of the Eocene erosional surface. Menkveld-Gfeller (1993) gives a Middle to Late Priabonian age for the Pierredar Member.

3. Discussion and Interpretation

A) Origin

Earlier researchers (Lugeon 1919, Masson 1980, Masson et al. 1980) have interpreted this structure as a karstic feature, a paleodoline. As this structure is eroded deeply into the Schrattenkalk Limestone, the term paleodoline is of course correct; judging from its size it is undoubtfully a compound doline (uvala). However, the denomination as paleodoline is slightly misleading because it also suggests a (purely) karstic origin for this structure. Though, it is important to state that the origin of this structure is not exclusively erosional. This can be understood by two facts:

Firstly, it is very unusual that in most of the Anzeindaz region the Eocene erosional surface forms an almost perfect peneplain (Masson 1980), which is pierced only at two neighbouring places by these huge structures. In the rest of the region, the paleosurface has a gentle profile of only a few meters with very gentle slopes. This seems to be a contradiction in itself. Secondly, the sediments of the Garschella Formation, although never exceeding a thickness of fifteen meters in the Anzeindaz region, are remarkably competent and largely impervious to water. The mere existence of the above-mentioned peneplain shows that there are no reasons to believe that these sediments were less competent or impervious during Eocene times. Hence, they must have formed an effective barrier against the Eocene erosion, causing it to get stuck. The few small relics of late Cretaceous Seewen Limestone on top of the Garschella Formation that can be found in the region prove, that the Eocene erosion could not have reached the Garschella Formation long before it gave way to the subsequent trans-

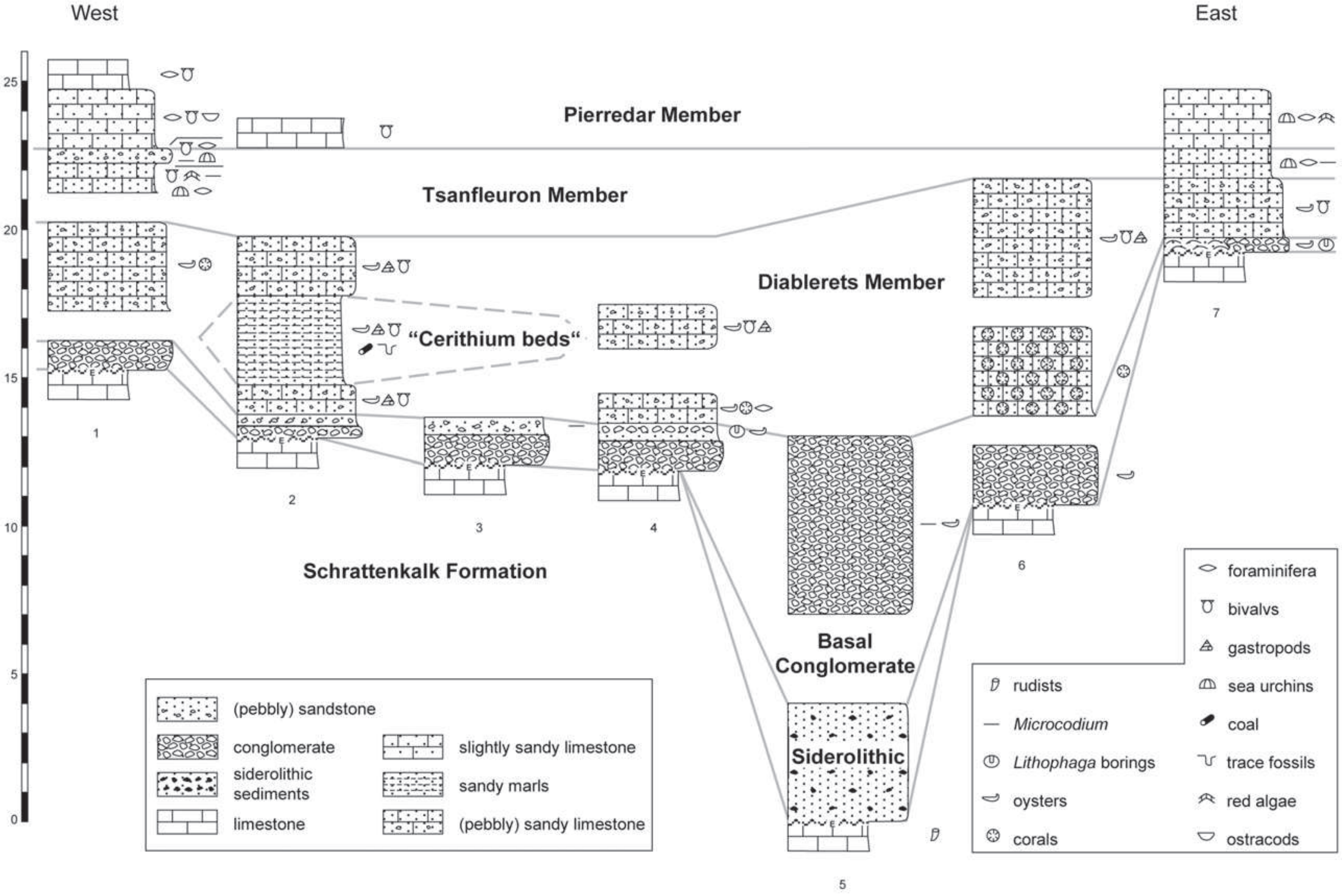

Fig. 5. Sections from the paleodoline of La Corde and their schematic correlation. Note the siderolithic sediments at the base, the lens-shaped "Cerithium Beds" inside the Diablerets Member as well as the coral (section 6) and oyster reefs (section 7).

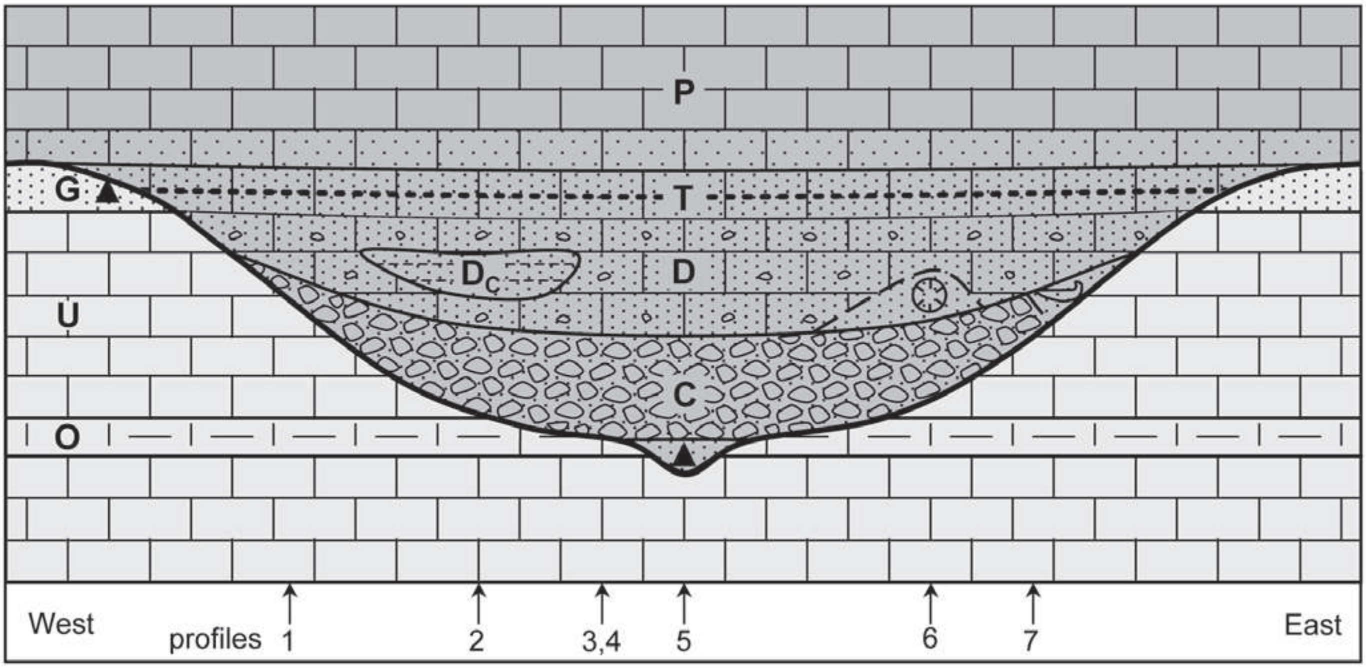

Fig. 6. Simplified, schematic reconstruction of the paleodoline of La Corde in a cross-section, compiled from the profiles 1–7. Abbreviations and simbols as in figures 2 and 5. Note the oyster and coral reefs and the siderolithic relics (triangles) at the bottom and rim of the structure. The sketch is not drawn to scale.

gression. This leaves only little time for the Eocene erosion to break through the Garschella Formation and to form the discussed structures.

The question therefore arises as to how these structures have originated and why they are so localised. It seems to be evident that the origin of the paleodolines cannot be attributed to the Eocene paleokarst alone. Other factors must be considered as well. It must be postulated that there was some kind of sedimentary or tectonic weakness zone in these places beforehand that allowed the Eocene erosion to break through the Garschella Formation much easier than it would have done otherwise.

Earlier studies (Masson 1980, Masson et al. 1980, Linder 2002) postulate a short Aptian phase of emersion and paleokarst of the Schrattenkalk Limestone before the deposition of the Garschella Formation. Probable traces of this earlier paleokarst can be seen throughout the Anzeindaz region and especially at La Corde, 200 meters to the east of the here described structure (ibid.). As the two paleokarsts seem to be superimposed, it is often difficult to tell one from another (Masson 1980). It is therefore possible, though rather unlikely that the paleodoline-like structures were already initiated in Aptian times and then re-excavated and deepened during the Eocene phase of continental erosion.

A much more probable possibility is the existence of a number of alpine faults related to the orogenic flexure of the alpine forebulge (Crampton & Allen 1995, Sinclair et al. 1991) that could have provided the necessary weak zone for the Eocene erosion to attack. Indeed, Eocene synsedimentary faults (some of which are very large) are widely known throughout the Helvetic Realm (Menkveld-Gfeller 1993) as well as in the study area. The before-mentioned normal fault that cuts off the paleodoline of La Corde at its northeastern end (see 2. B) could be such an erosion-facilitating structure. Although there is no evidence for a pre- or synsedimentary activity of this fault and it is the only such fault at this place, alpine faults seem to be the most probable explanation for the origin of these structures.

B) Spatial and temporal reconstruction

From the descriptions of the paleodoline of La Corde and its sediment filling, its mapping and several sections (see figure 5) given herein and in Linder (2002), a reconstruction of the original structure can be established; it is given in figure 6. This allows for a temporal reconstruction of its evolution:

Lutetian to Bartonian: During the warm and humid, subtropical phase of continental exposure in the Early to Middle Eocene, synorogenic faulting most probably provided the weak zones alongside which the intense continental erosion could attack, eventually forming a paleodoline on a otherwise peneplained landscape. The sink-hole at its deepest point drained the eroded fine sediment fraction from the Garschella Formation. The bottom of the structure was already filled with the autochthonous rubble generated during its formation. Above this initial filling, land plants grew, forming a ferralitic paleosol with frequent *Microcodium* carpets.

With the onset of the Eocene transgression at the turn from the Bartonian to the Priabonian, the area was now the intertidal zone of a beach. Here, paleosols were washed out, local gravels were reworked and the bottom of the structure was further filled with local rubble forming its transgressive base lag. On the surface of the Schrattenkalk Limestone at the rim of the structure, a small oyster reef grew. The top of the conglomerate was colonized by oysters and endolithic organisms such as *Lithophaga* bivalves and *Cliona* sponges.

In the Early Priabonian, with the continuing transgression over the surface of the mostly flat landscape, the paleodoline became a calm pool within a wide stretch of a shallow lagoonal, subtropical sea. On top of the conglomerates, a small coral reef began to grow. In the pool, sandy limestone was deposited. A little while later on, and further to the west in the structure, the baffling effect of a stranded tree trunk may have temporarily generated a small muddy shallow or island with mangrove-like vegetation that harboured masses of gastropods, bivalves and other benthic animals. Thus, the situation during this stage can be compared to the recent environment at the coast of Florida.

In the Middle to Late Priabonian, with a continuing transgression, the pool was completely filled up. With the installation of open marine conditions and the deposition of the Pierredar Limestone over the completely filled structure, the early history of Eocene transgression was concluded.

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