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MICROMORPHOLOGICAL CHANGES IN PRIDOLIAN LOCHKOVIAN CONODONTS FROM THE LOWGRADE METAMORPHOSED NAUX LIMESTONE (ARDENNES, FRANCE)

by

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ABSTRACT

The Pridolian/Lochkovian conodonts from the Naux Limestone (Ardennes, France) have CAI values of 5.0-5.5 and show various low-grade metamorphic features. If the early Carboniferous is considered as the time of maximum burial, these CAI values indicate burial temperatures of 305-350°C. The degree of recrystallization of the conodonts is demonstrated by a series of SEM photographs. Besides recrystallization and pitting, numerous specimens are cracked and deformed.
Likely the metamorphism is the result of sedimentary burial. The thickness of Devonian and Lower Carboniferous strata, exposed in the surroundings of Naux, may indicate a possible overburden for the Naux Limestone of some 7300 m.

KEY WORDS

Conodont alteration, Pridolian/Lochkovian, Naux (Ardennes)

1. INTRODUCTION

The conodont faunas from Naux are quite unique in the Silurian-Devonian stratigraphy of the Ardennes, and as a consequence they have been of the interest to several palaeontologists for many years, among them Bender (1967), Bultynck (1982) and Borremans & Bultynck (1986).
The conodonts belong to the *woschmidti* Zone, and thus indicate an uppermost Pridolian - lower Lochkovian age.
The specimens studied in this paper (plates 1-4) are from the collections of Borremans & Bultynck (1986), which are deposited in the Instituut voor Aardwetenschappen of the Catholic University of Leuven.

1.1. LOCATION AND GEOLOGICAL SETTING

Naux is located immediately south of the Caledonian Rocroi Massif in the Neufchâteau Synclinorium (fig. 1), where Palaeozoic rocks are altered by regional low-grade metamorphism.
The metamorphism can be illustrated by illite crystallinity data and mineral assemblages of magnetite, ilmenite, chloritoides and chiastolite in the Cambrian basement of the Rocroi Massif as well as in the Devonian cover (Beugnies *et al.* 1981). In the southern part of the Rocroi Massif and in the adjacent areas of the Neufchâteau Synclinorium, including the Naux area, illite crystallinity indicates the highest metamorphism, which is considered to be epi-metamorphic by Dandois (1981). This area coincides well with the occurence of magnetite (Beugnies *et al.* 1981).

1.2. LITHOLOGY OF THE NAUX LIMESTONE

The Naux Limestone consists of greyish-blue detrital, partly recrystallized wackestones and packstones, which are rich in crinoid debris. Locally the limestone

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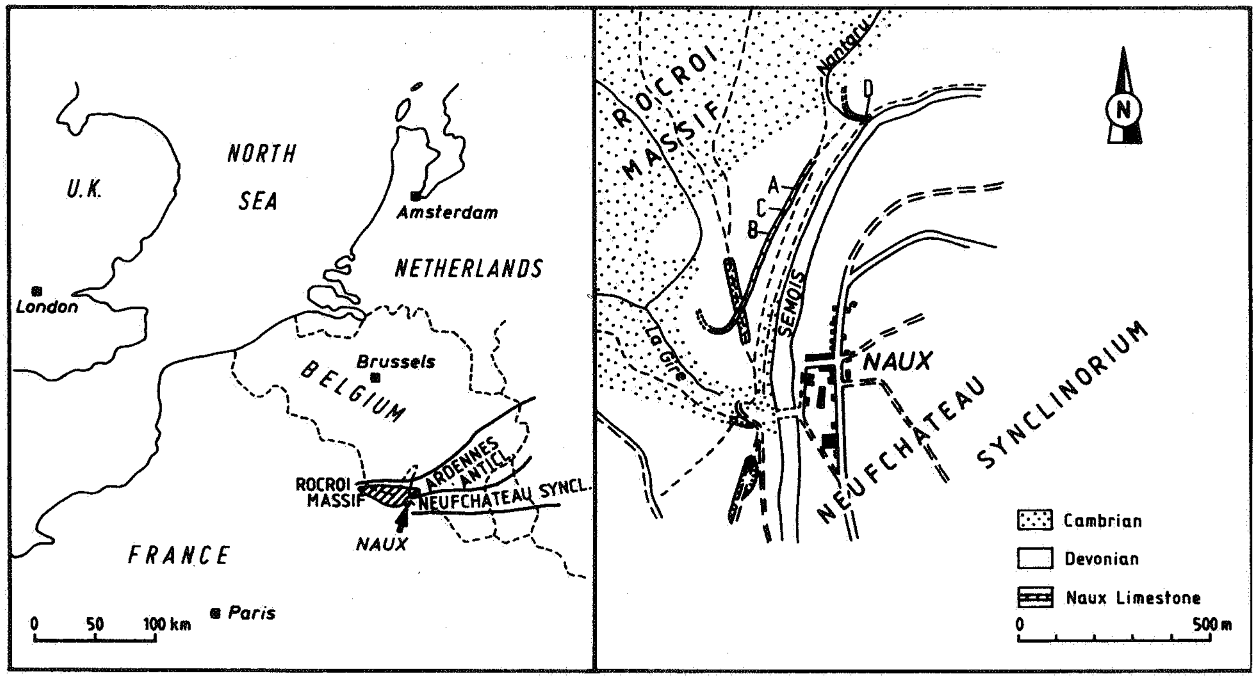

Figure 1. Location map of the Naux outcrops (after Borremans & Bultynck, 1986).

becomes very shaley and in these parts a slaty cleavage is developed. The total thickness of the limestone series in the Naux outcrops is some 3.0 m (Borremans & Bultynck, 1986). Numerous stylolites recognized in thin sections, mark the importance of pressure solution. This is probably the reason why quartz grains are grown together with the calcite rhombs. Other minerals in the limestones include detrital as well as new-formed muscovite, pyrite and iron oxides (Borremans & Bultynck, 1986).

2. CONODONTS FROM REGIONALLY METAMORPHOSED ROCKS

2.1. CONODONT ALTERATION DURING METAMORPHISM

Conodonts from regionally metamorphosed rocks can be recognized from hydrothermally altered and contact-metamorphosed conodonts by their uniform CAI value within a sample, which generally ranges between CAI 5.0 and 5.5. The corresponding temperatures of 300-440°C (Rejebian *et al.* 1987) refer to chlorite-grade metamorphism.

Usually conodonts from regionally metamorphosed rocks have suffered from recrystallization, corrosion, deformation and annealing of other minerals than apatite. Because most of the conodonts are fractured and broken in small fragments during recrystallization of the host-rock, identification may be complicated. As a result juvenile specimens and ramiform elements, with CAI values above 5.0 are less common in these conodont samples (Königshof, 1992). Yet, conodonts are usually the only stratigraphic control in metamorphosed carbonate rocks despite their poor preservation.

2.2. RECRYSTALLIZATION

Beside a few exceptions in Germany (Buggisch, 1986 and Fuchs, 1989), recrystallization of conodonts is only known from metamorphosed terranes. Although the recrystallization increases with the degree of metamorphism, it does not allow to define the epi-anchizone transition precisely. In the epizone CAI values of 6.0 and 7.0 are more common than CAI values of 5.0, the latter shown to be more characteristic in the anchizone (Kovacs & Arkai, 1986).

2.3. DEFORMATION AND FRACTURING

Depending on the local pressure conditions, conodonts in the anchi- and epizone may be deformed as well (Borremans & Bultynck, 1986 plate 1-fig.22 ; Elbert *et al.* 1988 fig. 6 ; Harris *et al.* 1983 plate 1 ; Königshof, 1992 plate 3 and 8 ; Kovacs & Arkai, 1986 plate 13.5 ; Kozur & Mock, 1973 p.5 ; Kozur & Mostler, 1991 plate 1). On the SEM photographs the deformation may be analyzed as a series of minute displacements along cracks. Very often these cracks are parallel shear planes following the cleavage or oriented texture of the host-rock, which relates them to tectonic stress. Differential reaction to heat by the host-rock components may produce fracturing in conodonts as well, especially in delicate forms, since the thermal expansion of the conodont francolite is different from that of calcite or quartz from the surrounding sediment (Burnett, 1988).

3. MICROMORPHOLOGICAL ALTERATION OF THE CONODONTS FROM NAUX

3.1. GENERAL PRESERVATION

The conodont faunas from Naux are poorly preserved and not abundant as demonstrated in Table 1 (from Borremans & Bultynck, 1986). The relative abundance of conodonts ranges from nihil to 11 per kg and apart from A9, B10, C7 and C8, the samples yield less than 5 specimens per kg. Table 1 shows also clearly the relative importance of the more robust Pa-elements from Ozarkodina remscheidensis remscheidensis in comparison to the other elements, especially to the more delicate S-forms. This is probably the result of intense fracturing of the more fragile and juvenile specimens during recrystallization of the Naux limestone.

The CAI values of 5.0-5.5 correspond to the black to dark greyish colour of the conodonts. These CAIs are uniform within a sample, as well as from sample to sample. They indicate palaeotemperatures of 305-350°C, when a burial time of 70 Ma is assumed (after Rejebian *et al.* 1987).

To study the micromorphological alteration and the degree of recrystallization in detail, the Naux conodonts were examined by means of a Scanning Electron Microscope. Besides, SEM observations are necessary to distinguish recrystallized surfaces from corrosion effects (see also Kovacs & Arkai, 1986). The conodonts studied in this paper show all kind of micromorphological changes and metamorphic features, which are discussed below.

3.2. RECRYSTALLIZATION (plates 1-2)

Recrystallization is the most striking of the micromorphological changes of the studied conodont specimens. First of all, both ramiform and platform elements show an agressive growth of granules upon their surfaces (plate 1, figs 1-3). Granules are small subangular structures of similar size. Since these granules are more common at Naux than the larger, blocky crystals (plate 1, fig. 4) and the surface aligned crystals, they may be an early stage of recrystallization, as suggested by Burnett (1988). In case of the studied conodonts, granules can grow together but do not form dense structures. As a result the recrystallized framework is porous and granular (plate 1, figs 1, 3). Since some of the granules are less rounded, they may be a transition towards the blocky crystals. On the conodont denticles blocky crystals may show some alignment with the teeth-axis (plate 1, fig. 2). The latter may be recrystallized as single apatite crystals with hexagonal cross-sections, as shown in the paper by Borremans & Bultynck (1986, plate 1-fig.25) and on plate 2 of this paper. Depending on local temperature and pressure conditions and the supply of dissolved phosphate, these recrystallized teeth are grown together partly (plate 1, figs 7-8) or completely (plate 1, fig. 10), forming narrow ridges. On the top surfaces of these teeth, scaly structures are more common than the subangular granules (plate 2, fig. 7).

Occasionally tabular apatite crystals are formed on Pa- and S-elements of Ozarkodina remscheidensis remscheidensis (plate 2, figs. 1-2). Similar crystals were recognized on Silurian conodonts from Austria by Schönlaub *et al.* (1976, plates 1 and 3).

3.3. DEFORMATION AND FRACTURING (plate 3, figs 1-4 ; plate 4)

Structural deformation of conodonts occurs preferentially at delicate specimens (e.g. S- and Pb-elements), or at the weaker zones of the more robust Pa-elements. Often the deformed Pa-elements of Ozarkodina remscheidensis remscheidensis show kinks following their longitudinal axis (e.g. plate 4, fig. 9). As shown on plate 4 (figs 1, 3 and 8), the weaker

Sample	Ao	A1	A2	A3	A4	A5	A6	A8	A9	B6	B10	C7	C8	C10	D
Sample Weight (kg) (dissolved)	17.90	3.75	2.30	0.90	0.70	0.10	2.70	2.15	2.20	0.95	11.50	1.80	1.70	2.30	2.0
C. woschmidti															
I	12	6	-	-	-	-	5	-	-	-	5	-	-	2	1
S2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O. rem. remscheidensis															
Pa	30	12	2	-	2	-	3	8	20	-	99	10	8	8	1
Pb	7	-	-	-	-	-	-	-	2	-	9	2	-	-	-
Sc	2	-	-	-	-	-	-	-	2	-	2	-	3	1	-
Sb	2	-	-	-	-	-	-	-	-	-	1	-	-	-	-
Sa	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
M	1	-	-	-	-	-	1	-	-	-	1	-	-	-	-
Ozarkodina n. sp. G															
Pa	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oulodus cf. aclys															
Pb	2	-	-	-	-	-	-	-	-	-	2	-	-	-	-
Sa	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sb	3	-	1	-	-	-	1	-	-	-	2	-	-	-	-
Sc	3	-	-	-	-	-	-	-	-	-	2	-	-	-	-
Drepanodus type b	2	1	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 1. Conodont distribution in the Naux Limestone (from Borremans & Bultynck, 1986).

points during stretching are in between the conodont nodes. Deformation of the Naux conodonts appears to be ductile and a step-like shift along parallel cracks, as shown by Königshof (1992), was not recognized in this study.
Currently, more research is done on the deformation of these conodonts and a paper with M. Sintubin is in progress on the possible applications of deformed conodonts, such as the Naux faunas in structural geology.
Intense fracturing of delicate and ramiform conodont elements, common in regionally metamorphosed terranes, characterizes the Naux faunas as well. Most of the cracks in the more robuste elements are observed in the conodont teeth and it seems that the first are oriented preferably perpendicular to the teeth axis (plate 3, figs 1-2). Minor cracks may lead to wider fissures depending on the local temperature and pressure conditions.

3.4. CORROSION EFFECTS (plate 3, figs 7-8)

Corrosion and etch pitting of specimens (cf. Burnett, 1988 fig.18 ; Kozur & Mostler, 1991 plates 3 and 6) is another important feature. Some of the larger corrosion pits are as large as 60 ìm (plate 3, fig. 7), while others are smaller than 1 ìm (plate 3, fig. 8). Pitting may occur anywhere on the conodont surface and in any direction. However, if denticles are corroded, small pits start to develop preferentially along minute cracks perpendicular to the longitudinal axis of the teeth so that wider fissures can be formed (plate 3, figs 1, 4). Even recrystallized surfaces may be etched during a later stage of alteration ; generally these are corroded layer by layer (plate 2, figs 1, 3). As a result, inner surfaces may remain well preserved while outer surfaces are already intensely corroded. Corrosion effects as well as recrystallization of the conodont surface may be related to pressure solution.

3.5. APATITE PSEUDOMORPHS AND DEPOSITION OF OTHER MINERALS (plate 3)

S.E.Microprobe analyses have shown Ca and P as main components in dolomite-like «saddle shaped» rhomboedrons (plate 3, fig. 9) and in the crystal twins, pictured in plate 3, fig. 10. This may indicate apatite pseudomorphism after minerals such as dolomite.
Annealing of minerals that were formed during diagenesis and metamorphism is observed as well. These minerals include phyllosilicates (as shown by the K-Mg-Al-Si-composition), crystals rich in Si-Al-P-Ca (plate 3, fig. 11) and pyrite. In some cases annealing of detrital quartz grains from the surrounding sediment complicates conodont determination.

4. BURIAL HISTORY OF THE NAUX LIMESTONE

The regional metamorphism in the Rocroi Massif and adjacent areas, which is well documented by many investigators, is believed to be the result of prekinematical burial (Beugnies, 1963 ; Dandois, 1981). Piqué *et al.* (1984) showed that the development of the cleavage is contemporaneous with the metamorphism.
The metamorphism of the Cambrian rocks of the northern Rocroi Massif, which is thus considered to indicate maximum burial, is dated early Viséan (Piqué *et al.* 1984). This can prove a Tournaisian timing for the maximum burial of the Cambrian rocks in the southern Rocroi Massif and the Siluro-Devonian strata in the Neufchâteau Synclinorium. If the early Carboniferous is considered as the time of unloading for the Naux Limestone, a maximum burial time of 70 Ma and burial temperatures of 305-350 °C are inferred for the CAI values of 5.0-5.5 (after Rejebian *et al.* 1987).
According to the unpublished isopach maps of Adams, the thickness of the sedimentary pile, deposited on the Naux Limestone during the Devonian period and the Tournaisian stage accounts for some 7300 m. This thickness can explain the relatively high burial temperatures. Both burial depth and temperatures include an average geothermal gradient ranging between 39-45°C/km, which is somewhat higher than the actual 20-30°C/km in this area (Atlas of subsurface temperatures in the European Community, 1980). However, in the north-African and European Variscan foredeep basins and fold belts such high gradients are not uncommon (see Belka, 1990, 1991 ; Buntebarth *et al.* 1981 ; Burnett *et al.* 1993 ; Königshof, 1992 ; Muchez *et al.* 1991 ; among others). The high gradients may be related to crustal thinning and to the existence of a major mantle plume below a triple junction in central and western Europe (Zwart & Dornsiepen, 1978).

According to Tsien (1974) sedimentation in the Rocroi region was reduced or absent in the Eifelian, before the area was flooded during the Givetian transgression. Indeed, the occurence of the barrier reef limestone of Couvin, north of the Rocroi Massif, may indicate that the Rocroi area was emergent during Eifelian times.
However, one or more growth faults may have separated the Rocroi Massif in the north from the southerly Neufchâteau Basin, where subsidence was much more important. As a result thick Devonian sequences could be deposited in the Naux area, whereas sedimentation was reduced (or absent?) in the Rocroi region.

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PLATE 1

Recrystallization of conodont surfaces

Figure 1. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux 8A, x 990.

Figure 2. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 680

Figure 3. *Ozarkodina remscheidensis remscheidensis*, S-el., Naux A9, x 2080

Figure 4. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A9, x 940

Figure 5. *Caudicriodus woschmidti woschmidti*, I-el., Naux A1, x 750.

Figure 6. *Caudicriodus woschmidti woschmidti*, I-el., Naux A6, x 480.

Figure 7. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 230.

Figure 8. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 780, detail of Pl. 1/Fig. 7.

Figure 9. *Ozarkodina remscheidensis remscheidensis*, S-el., Naux B10, x 285.

Figure 10. Unidentified conodont specimen, S-el., Naux A9, x 130.

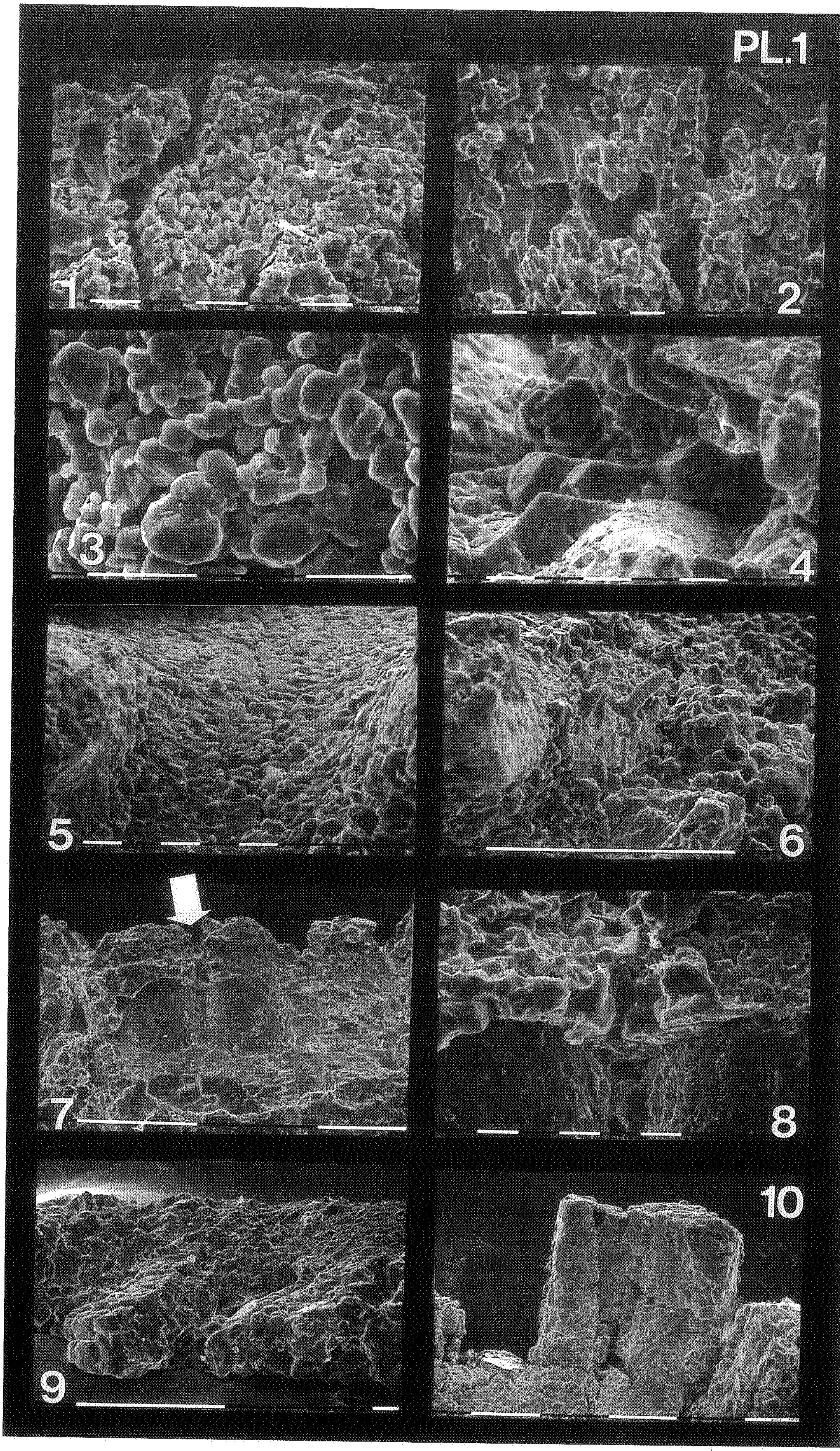
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PLATE 2

Recrystallization of conodont surfaces and denticles

Figure 1. Apatite crystals on *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A6, x 1600.

Figure 2. Apatite crystals on *Ozarkodina remscheidensis remscheidensis*, S-el., Naux B10, x 2950.

Recrystallization of conodont denticles

Figure 3. *Ozarkodina remscheidensis remscheidensis*, Sc-el., Naux A9, x 97.

Figure 4. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A8, x 101.

Figure 5. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A8, x 163.

Figure 6. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A6, x 193.

Figure 7. *Ozarkodina remscheidensis remscheidensis*, Sc-el., Naux A9, x 150, same conodont specimen of Pl. 2/ Fig. 1.

Figure 8. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A0, x 300.

Figure 9. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A8, x 183, same specimen of Pl. 1/Fig. 1.

Figure 10. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 385

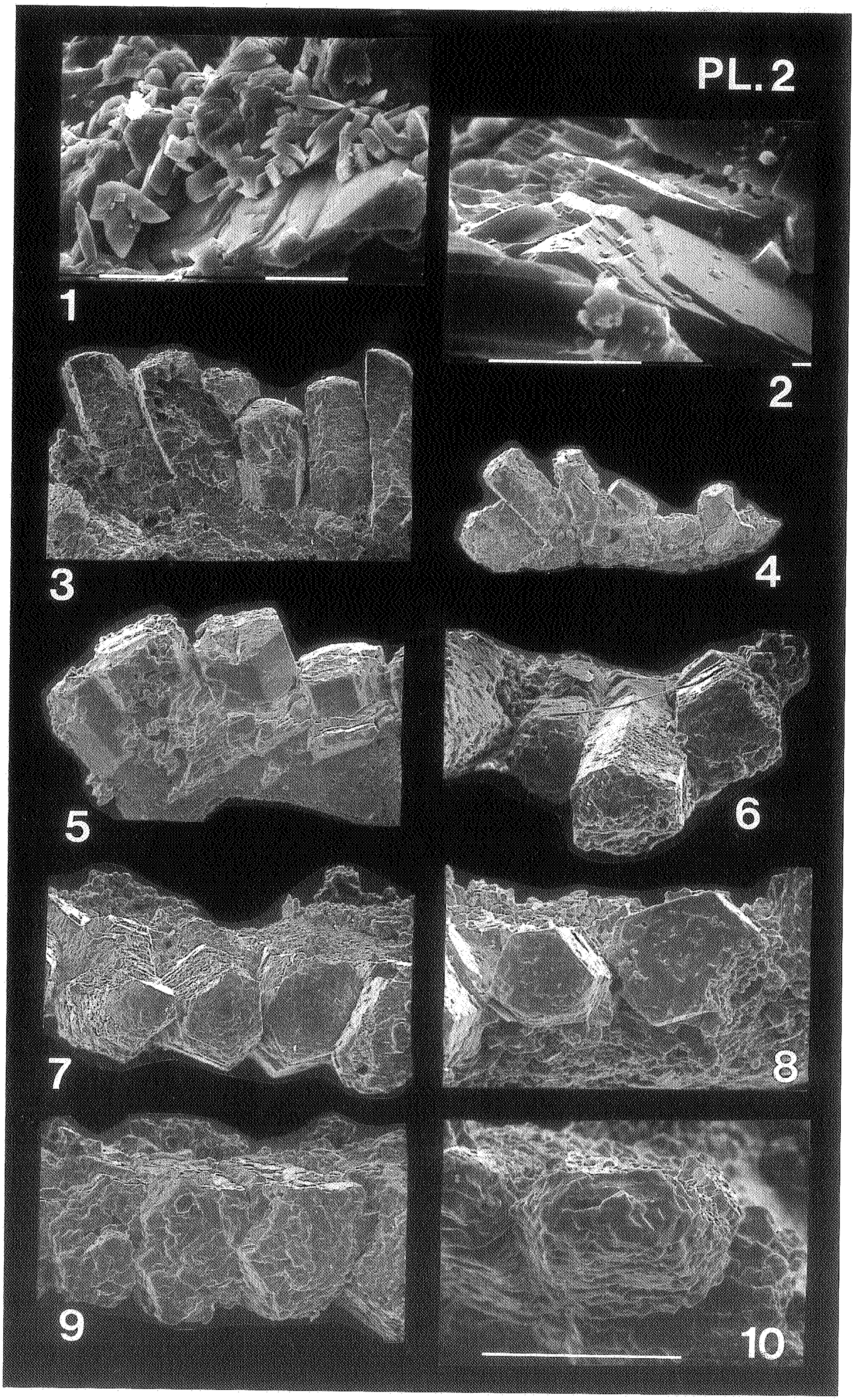
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PLATE 3

Fracturing and corrosion of conodonts

Figure 1. *Oulodus* cf. *O. aclys*, S-el., Naux A0, x 220.

Figure 2. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 750.

Figure 3. *Ozarkodina remscheidensis remscheidensis*, Pb-el., Naux B10, x 150.

Figure 4. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 178, same specimen of Pl. 1/Fig. 2.

Figure 5. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A1, x 90.

Figure 6. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 370.

Figure 7. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 750, detail of Pl. 3/Fig. 5.

Figure 8. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 2390, detail of Pl. 3/Fig. 5.

Apatite pseudomorphs and annealing of other minerals

Figure 9. Apatite pseudomorphs after dolomite on *Oulodus* cf. *O. aclys*, S-el., Naux A0, x 500.

Figure 10. Apatite pseudomorphs ? on *Caudicriodus woschmidti woschmidti*, I-el., Naux A6, x 6000, detail Pl. 1, Fig. 6.

Figure 11. Annealed crystal with Si-Al-Ca-P-composition on unidentified conodont specimen, S-el., Naux A9, x 2100.

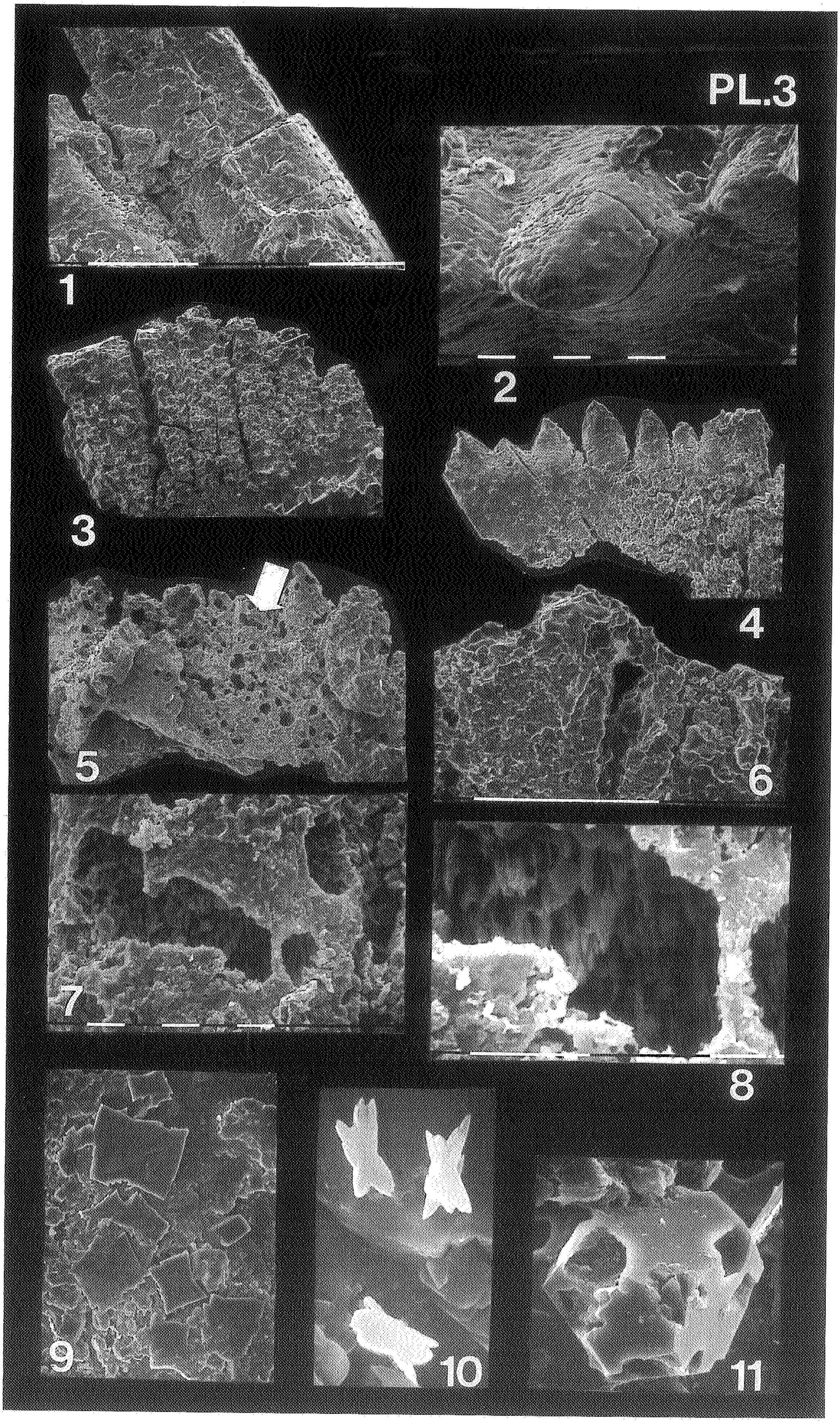
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PLATE 4

Deformation of conodonts

Figure 1. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 66, same specimen of Pl. 2/Fig. 6.

Figure 2. *Ozarkodina remscheidensis remscheidensis*, S-el., Naux B10, x 72.

Figure 3. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 55.

Figure 4. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 93.

Figure 5. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A1, x 55.

Figure 6. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 50.

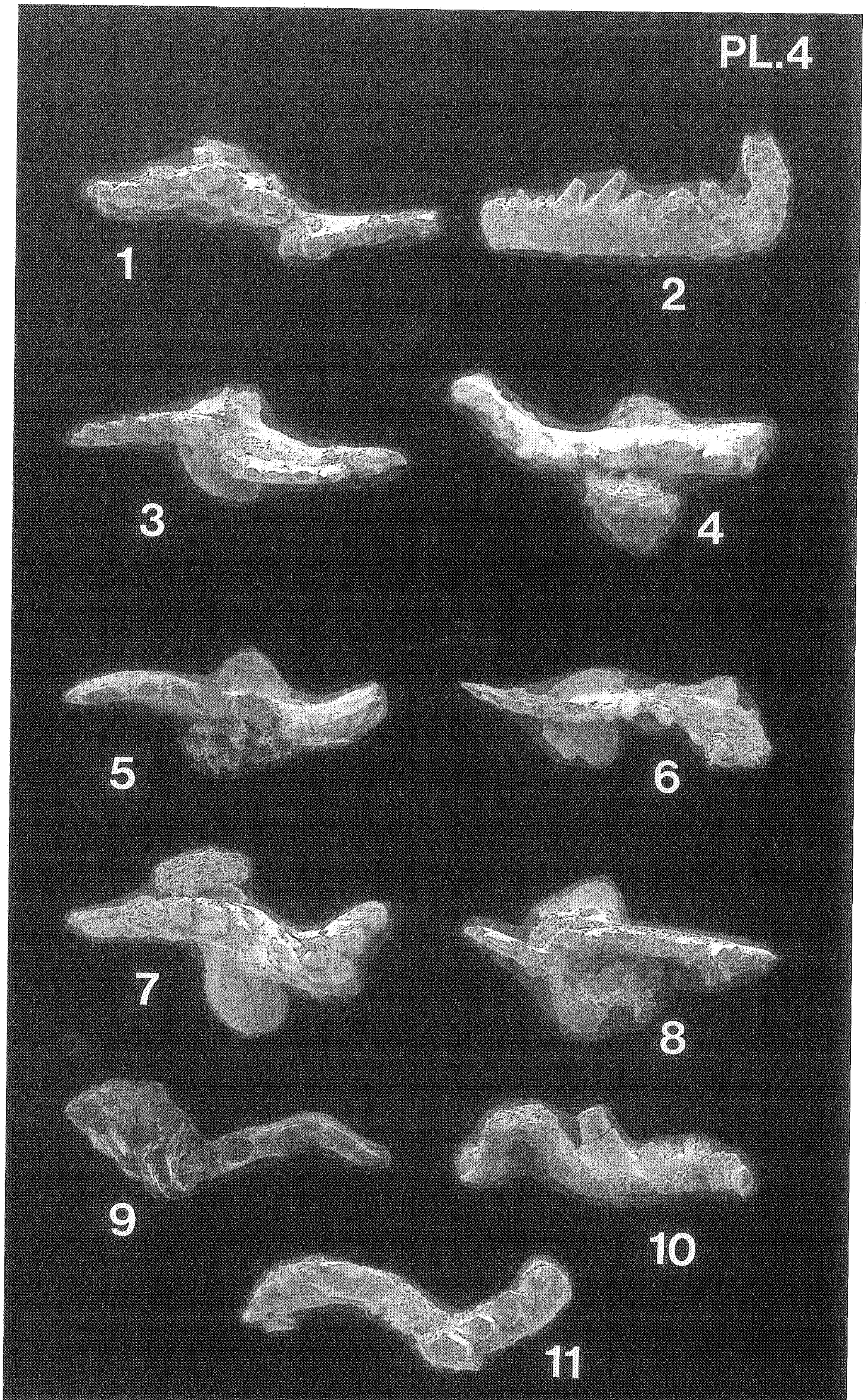
Figure 7. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A9, x 57.

Figure 8. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 76.

Figure 9. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux B10, x 72.

Figure 10. *Ozarkodina remscheidensis remscheidensis*, S-el., Naux B10, x 75.

Figure 11. *Ozarkodina remscheidensis remscheidensis*, Pa-el., Naux A0, x 72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