

ALTITUDINAL ZONATION OF MOUNTAINOUS DIATOM FLORA IN BOLIVIA: APPLICATION TO THE STUDY OF THE QUATERNARY

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A methodology is proposed to determine temperature variations during the past by studying altitudinal assemblages in the living diatom flora. A local zonation is established, according to the distribution of diatom assemblages in a series of lakes located at different altitudes within the same valley. Changes in the altitudinal position of these assemblages in the core enable one to evaluate temperature variations during the Holocene.

Introduction

The Ichu Kkota glacial valley ($16^{\circ}15$ Lat. $69^{\circ}30$ Long.) is located at the foot of numerous glaciers reaching an altitude of 5500 meters (Fig. 1). In connection with the last deglaciations, four lakes were formed behind the corresponding moraines ranging in age from approximately 15 000 to late Holocene [4]. They are located at 4310 m, 4450 m, 4690 m, and 4900 m respectively (Fig. 2). The catchment area is composed of Paleozoic rocks and Quaternary moraines; the feed waters are essentially glacial run-off and meteoric water [2].

Chemical analysis indicate a very low concentration of dissolved salts (Table I). The ortograde distribution of dissolved oxygen, the low biomass and the hypolimnion/epilimnion ratio greater than 20 allow one to classify them as typical oligotrophic lakes. From the upper lake to the lower, the thermal difference of the water is 10°C . [1].

The Living Diatom Assemblages

The diatom flora analysis is made on the basis of recent sediment samples (when possible duplicated by an *Isoetes* sample taken in the same place), collected from the littoral zone, 10-20 cm under the water level. Two sediment samples come from slope moors located at an altitude of 4850 and 4200 meters where the aquatic vegetation is essentially composed of *Isoetes* and *Sciaromum*. About 122 taxons have been identified, the most abundant genera are: in the lakes, *Achnanthes*, *Cyclotella*, *Cymbella*, *Fragilaria*, and *Nitzschia*; in the slope moor, *Melosira*, *Pinnularia*, and *Surirella*. The samples, especially those from the slope moor, contain many diatoms. In the upper lake, where there is no aquatic vegetation, the diatom flora is very poor.

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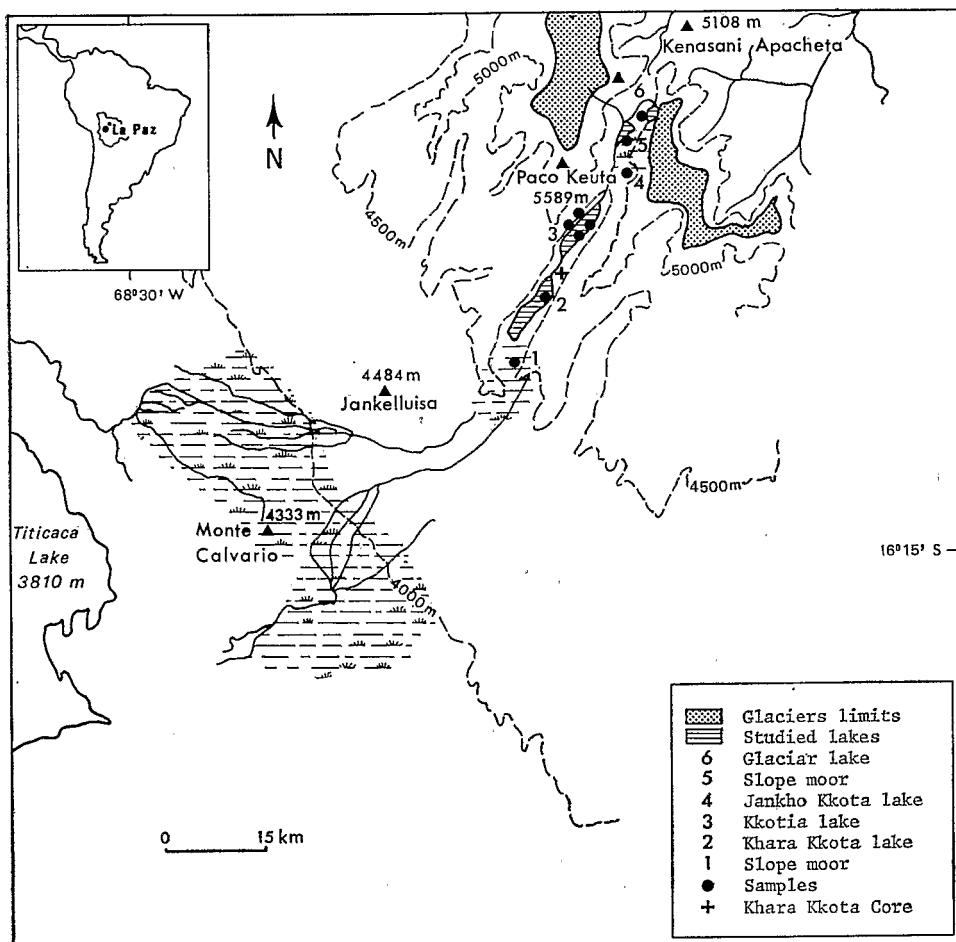


Fig. 1. Geographic location

Figure 3 shows quantitative frequency variations of diatom species according to site location and altitude.

As seen on this figure, a number of species (56) are strictly restricted to certain lakes. All the species found in the same lakes are considered as diatom assemblage characteristic of the corresponding altitude. From the four lakes and two peat bogs studied, we have named six assemblages A, B, C, D, E, F (Fig. 4).

The other species (66) have a large altitudinal distribution. They have been classified into different assemblages, a, b, c, d, e, f, each one being defined by a specific upper limit. The actual altitudinal distribution of these assemblages and the list of the corresponding species are represented in Fig. 5.

Table I
Water chemical composition of the Ichu Kkota lakes

	Jancko Kkota	Khotia	Khara Kkota
Temperature (°C)	5,80	7,80	9,20
pH (unity pH)	6.83	7.03	7.12
Conductivity (μmhos)	27	42	52
Alcalinity (mg/l)	0.10	0.16	0.20
SO_4 (mg/l)	8.64	12.96	14.40
Cl (mg/l)	0.00	0.00	0.00
Na^+ (mg/l)	1.04	1.84	2.07
K^+ (mg/l)	0.39	0.39	0.78
Ca^{++} (mg/l)	3.04	4.46	5.47
Mg^{++} (mg/l)	0.73	0.97	1.09
SiO_4H_4 (mg/l)	4.10	4.30	3.40
Total dissolved salts	18.04	25.08	27.41
Nitrates ($\mu\text{g/l}$)	115	65	40
Phosphates ($\mu\text{g/l}$)	21.4	2.2	<0.1

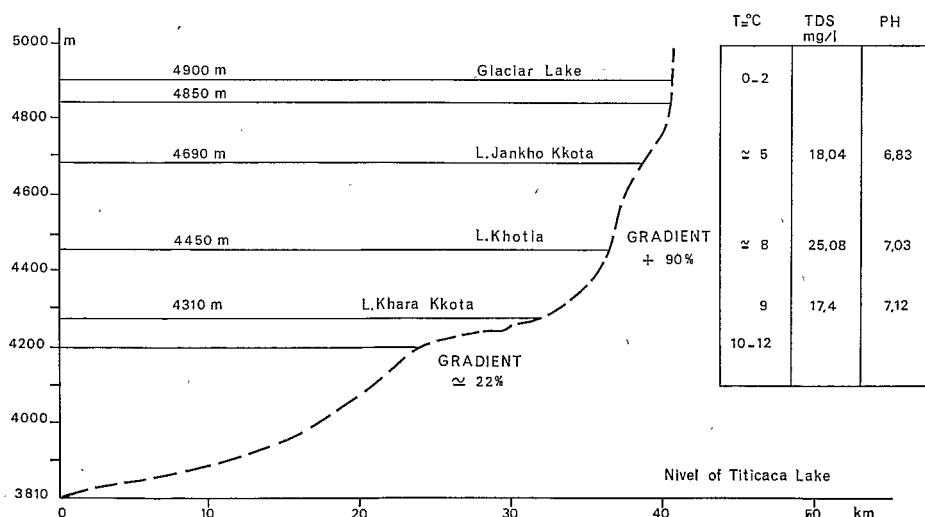


Fig. 2. Profile of the valley

The Fossil Diatom Assemblages

A nine meter core was taken in the valley previously studied for living diatoms (cf. Part One) near Khara Kkota lake at 4310 meters altitude From the base to the top:

930—610 cm:	Clay
	930—920 No diatoms
	890—610 Very rich in diatoms. <i>Cocconeis</i> and <i>Epithemia</i> are dominant.
580—325 cm:	Clay with plant remains ¹
	Abundant diatoms. <i>Fragilaria</i> , <i>Cocconais</i> , <i>Cyclotella</i> are dominant.
290—225 cm:	Peat
	Abundant diatoms. <i>Fragilaria</i> , <i>Cocconeis</i> are dominant.
175 cm:	Sand
	Few diatoms. <i>Fragilaria pinnata</i> dominant.
150 cm:	Peat
	No diatoms. Radiocarbon data: 3120 ± 150 years Bp. (J. C. FONTES, personal communication).
140—40 cm:	Clay
	140—100 Very abundant diatoms. <i>Diatoma</i> and <i>Melosira</i> are dominant.
	85—40 Few diatoms. <i>Melosira</i> and <i>Achnanthes</i> are dominant.
25—15:	Clayey and some fragments of frustulae.

The quaternary diatom flora presented in alphabetical arrangement in Table II can be classified into three groups:

The first one is characterized by some of the species found in assemblages A, B, C, D, E, F (see the list of the species in legend of Fig. 6). In this figure, are shown the quantitative frequency variations of each assemblage along the core. Assemblage D is preferentially developed in the middle part of the core (490 to 150 cm). Assemblage B is well developed in the upper part (140 to 40 cm). In the lower part of the core the assemblages are poorly represented.

The second group is characterized by some of the species found in assemblages a, b, c, d, e, f (see the list of the species in legend of Fig. 7). This figure shows the quantitative frequency variations of these assemblages along the core. Assemblage "d" is well developed from 790 to 290 cm and from 240 to 175 cm. Assemblage "c" is abundant from 140 to 85 cm.

The third group is composed by species which do not presently live in the lakes. As in the two other groups, it includes cosmopolitan and psychrophilic species. The quantitative variations of these last species is very interesting to study, (Fig. 8 No. 7), see Part Three.

What is the significance of the variations seen in Figs 6 and 7? In the middle part of the core where assemblage "D" is preferentially abundant; diatom assemblages of the lake were at that time similar to those found in the 4450 meters lake today. In the top part of the core dated 3120 ± 150 years BP, assemblage "B" becomes well developed showing conditions similar to those found in the 4850 m lake.

Interpretation

In order to understand the meaning of these changes, we have characterized each level by the percentage value of the most developed assemblage (Fig. 8 No. 4). With respect to the position of the core at 4310 m and considering that temperature falls $0.8^{\circ}\text{C}/100$ meters, we have deduced temperature fluctuations for each level (Fig. 8 No. 6). For example, in samples 40 and 85, assemblage "B" is well developed, "B" represents the actual diatom assemblage at 4850 m. Considering that the core is at 4310 m, the position of assemblage "B" descends 540 m in altitude, from 4850 to 4310 m. This should represent temperature drop of 4°C . In the levels 100, 275, 500 and 530 and in the lower part of the core, no assemblages (A, B, C, etc) is well developed, but the assemblages a, b, c, etc. can be important, in these cases temperature fluctuations cannot be evaluated with precision.

The above analysis is based on a direct comparison between the living and the fossil diatom flora not considering their ecological requirements. On the other hand, if we plot the percentage of psychrophilic diatoms (according to global ecological information), we get a curve (Fig. 8 No. 7) which is very similar to the previous curves of B and D assemblages in Fig. 6.

Discussion

This striking picture seems to be a result of the exceptional conditions of the studied lakes situation. As a matter of fact, it is rather rare to find an environment in which one can advance an hypothesis about the preeminent role of altitude (or others factors which are directly associated with it) on the diatom flora. One can nevertheless admit that the factors which habitually play a determinant role (chemical factors, pH, depth) can here be neglected.

On the other hand, by the position of the core and the absence of tectonic phenomena one may think that the observed variations in the sedimentary column, registered the same phenomena as those determined today. For this reason, it was possible to confront directly present and past data and to obtain such a good correlation. This study will soon be clarified by a second series of samples, and by a study in a neighbouring valley, the Ovejhuyo valley, in which vegetational belts defined in the aquatic flora are identical as those from Ichu Kkota valley. The pollen analyses are under proceeding to complete these results.

Acknowledgements

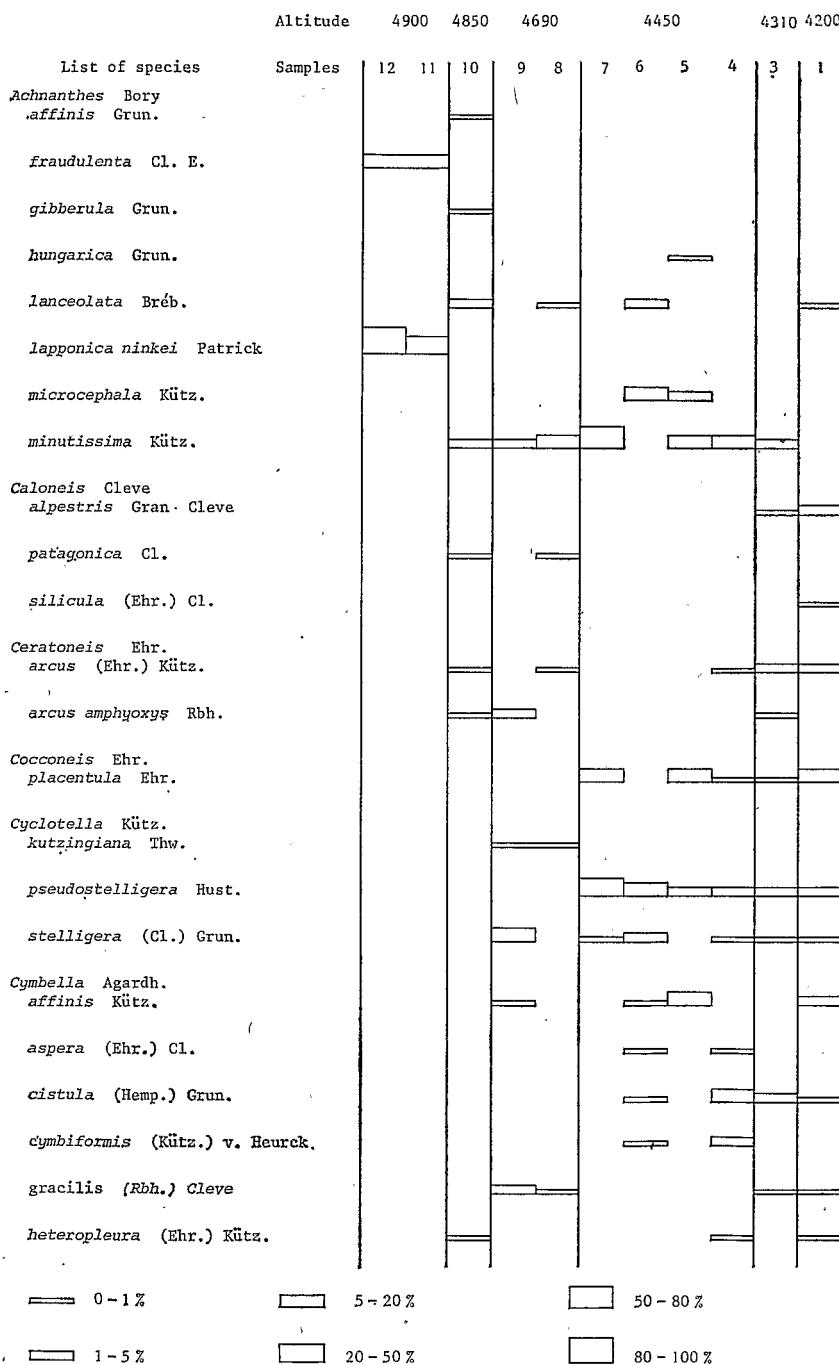
This study is supported by La Paz University and Orstom France which have undertaken a multidisciplinary approach in the Ichu Kkota Valley, a part of the glacial system of the Bolivian Andes Mountains.

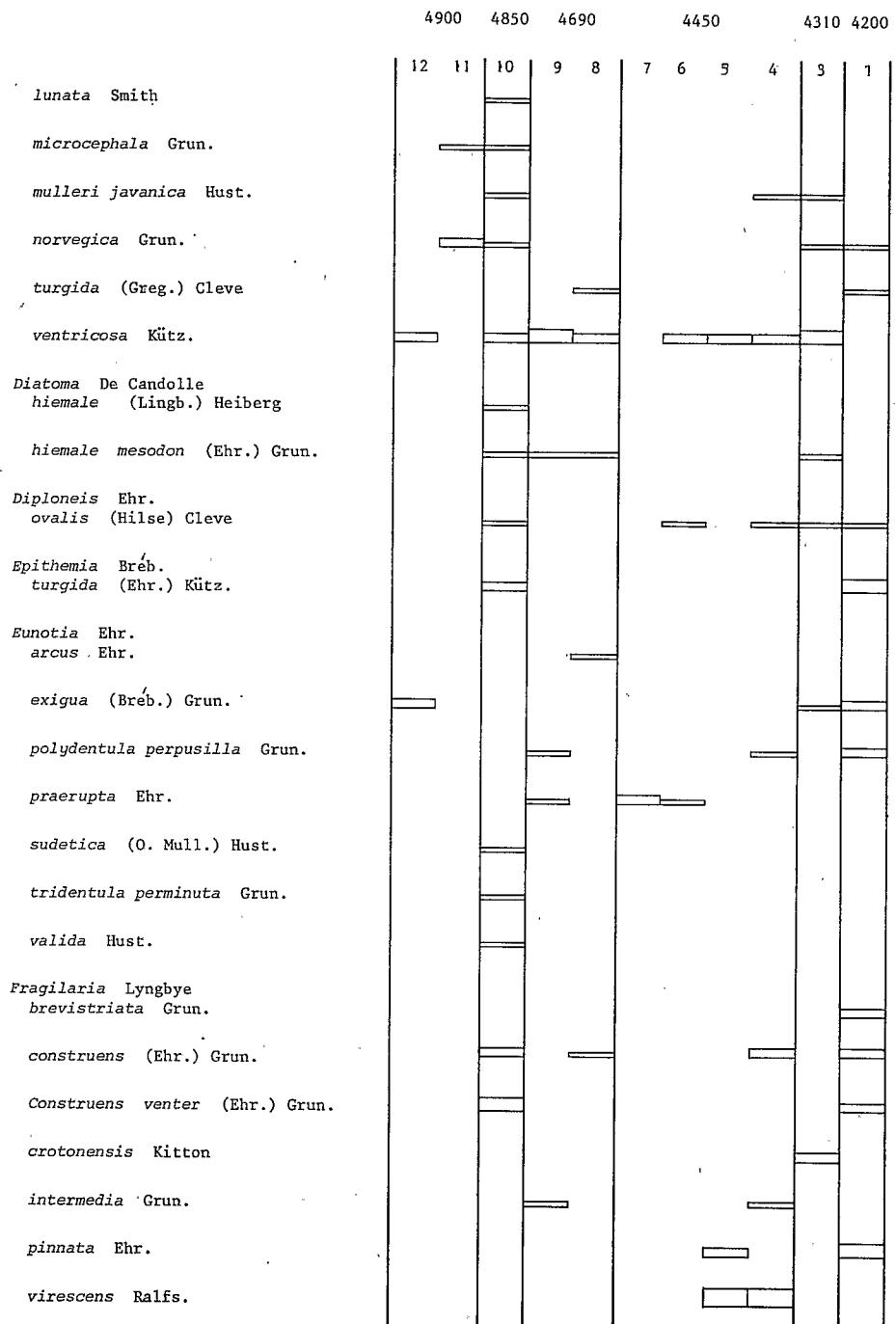
Appreciation is expressed to Dr. M. SERVANT, Dr. L. A. RODRIGO, D. COLLOT, C. ARCE, X. LAZZARO for stratigraphy, sedimentology, botany, and chemical analysis supports.

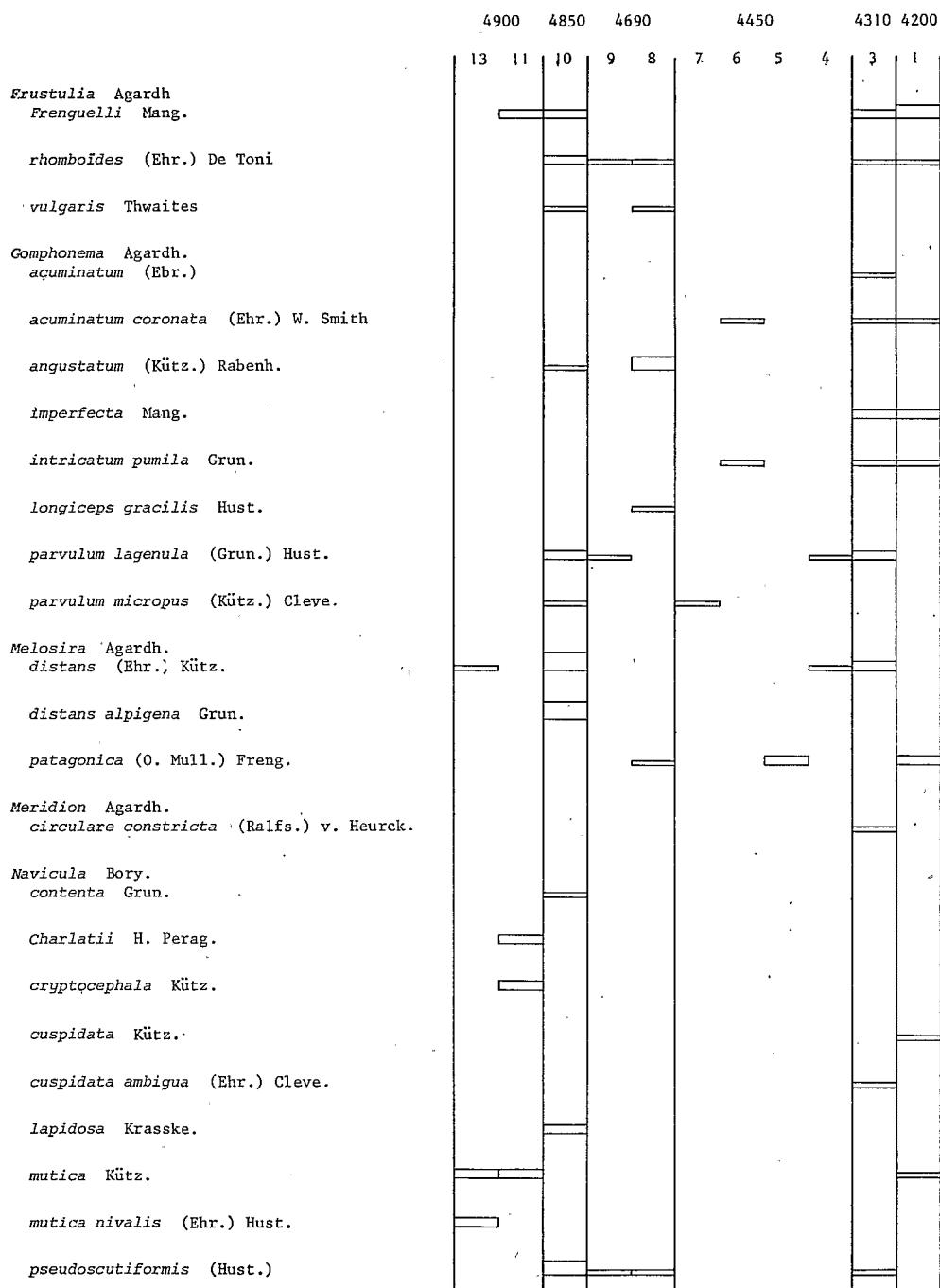
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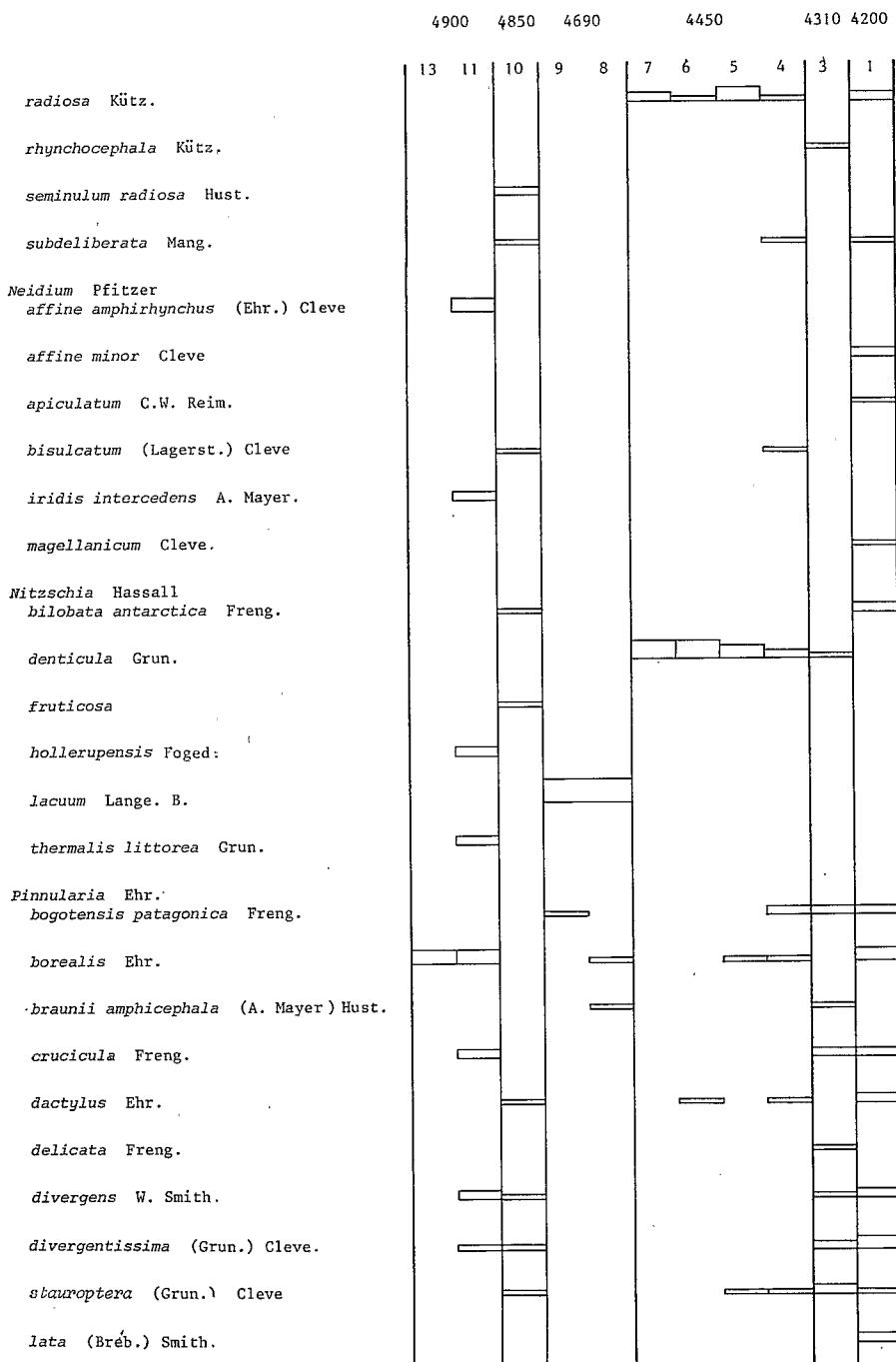
1. COLLOT, D.: Vegetation acuatica del valle de Ichu Kkota comparacion con el valle de Ovej-huyo. Insti. Geodin. y Limn. Convenio UMSA — ORSTOM. La Paz, Bolivia, 23—27, 1979.
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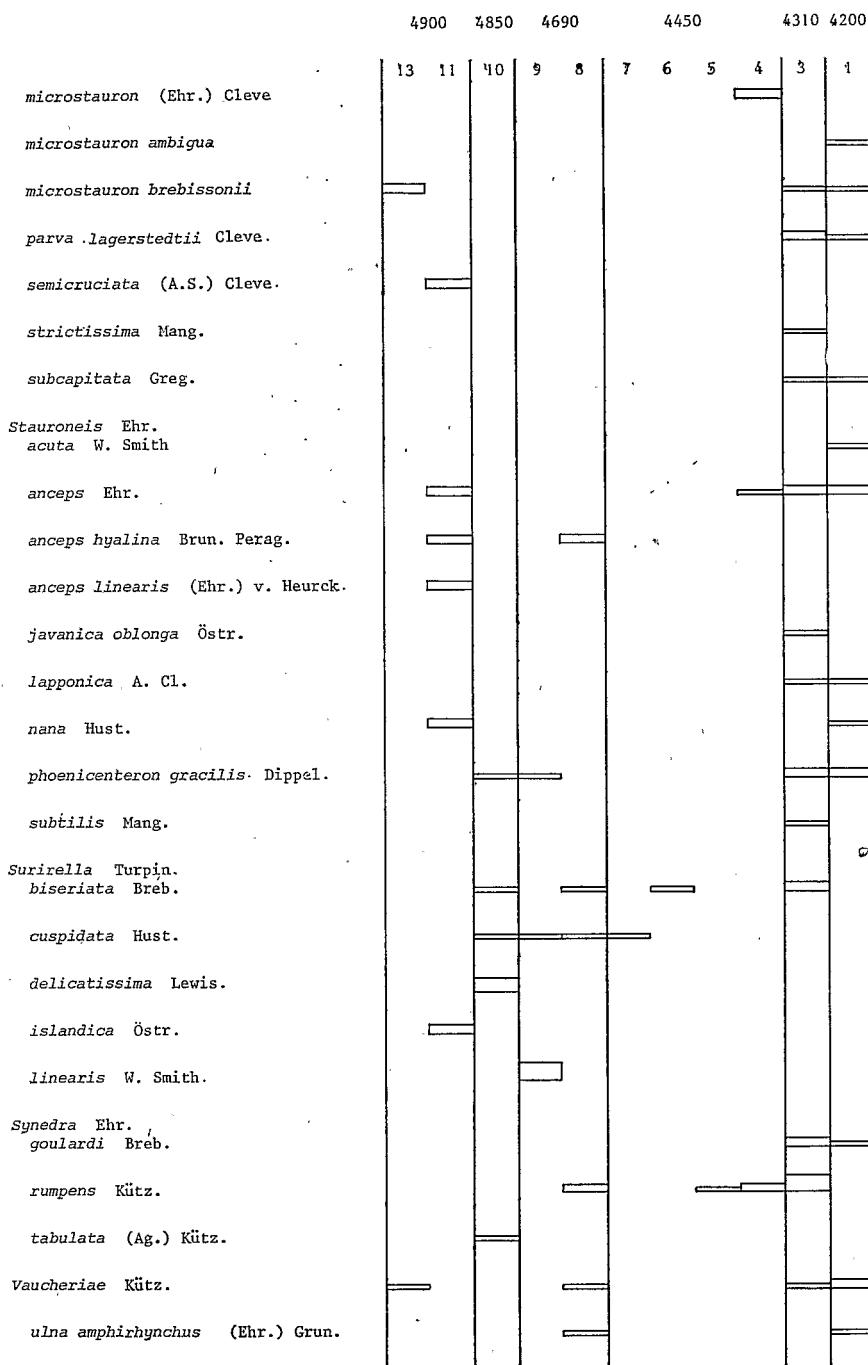
Fig. 3. List of living diatoms











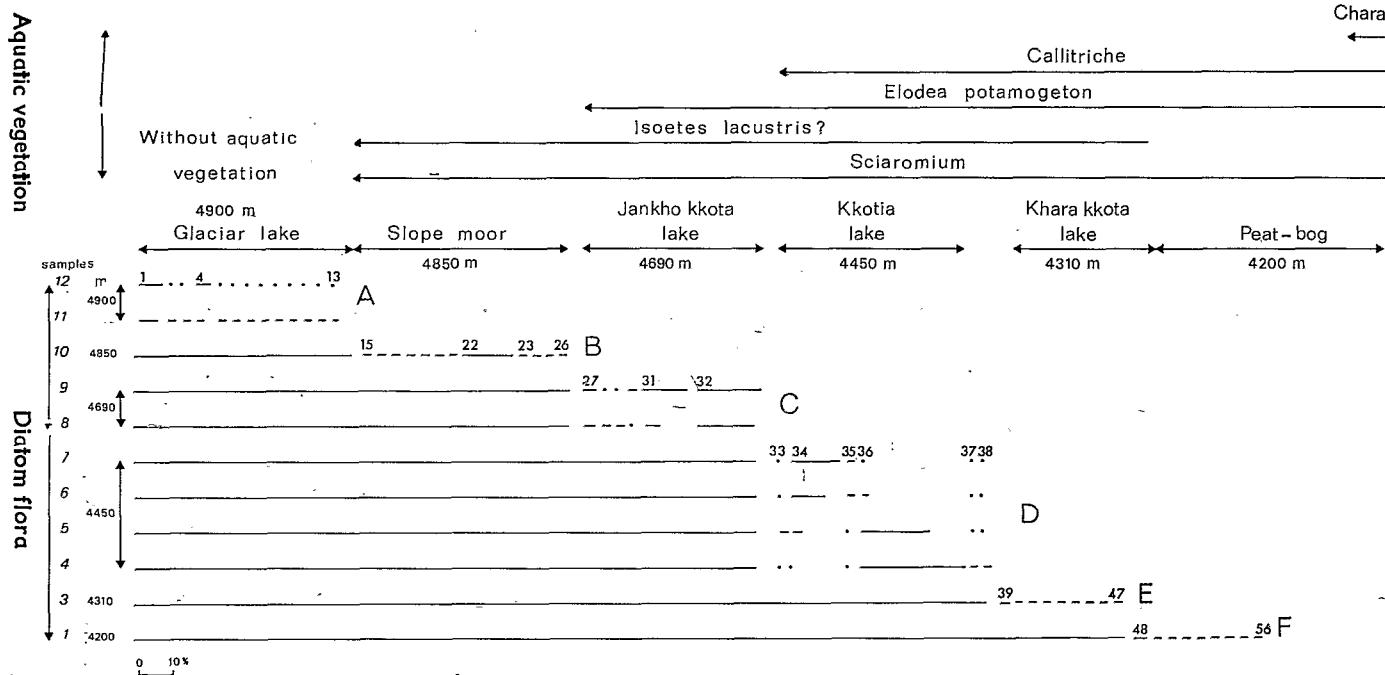


Fig. 4. Altitudinal position of assemblages in Sichu Kkota valley

- Association A: list of the diatoms only found at 4900 meters altitude
- Samples 12: Ice
Superficial sediments of the
11: superficial sediments of the gla-
cier lake
1. *Achnanthes fraudulenta*
 2. *Achnanthes lapponica ninkei*
 3. *Navicula charlatii*
 4. *Navicula cryptocephala*
 5. *Navicula lapidosa*
 6. *Navicula mutica nivalis*
 7. *Neidium affine amphirhynchus*
 8. *Neidium iridis intercedens*
 9. *Nitzschia hollerupensis*
 10. *Nitzschia thermalis litorae*
 11. *Pinnularia semicruciata*
 12. *Stauroneis anceps linearis*
 13. *Surirella islandica*
- Association B: list of the diatoms only found at 4850 meters altitude
- Samples 10: Slope moor, superficial sediment
15. *Achnanthes affinis*
 16. *Achnanthes gibberula*
 17. *Cymbella lunata*
 18. *Diatoma hiemale*
 19. *Eunotia sudetica*
 20. *Eunotia tridentula perminuta*
 21. *Eunotia valida*
 22. *Melosira distans alpigena*
 23. *Navicula contenta*
 24. *Navicula seminulum radiosa*
 25. *Nitzschia fruticosa*
 26. *Synedra tabulata*
- Association C: list of the diatoms only found at 4690 meters altitude
- Samples 9: Superficial sediments of Jankho-
KKota lake
8: On Isoetes
27. *Cyclotella kuetzingiana*
 28. *Eunotia arcus*
 29. *Comphonema longiceps gracilis*
 31. *Surirella linearis*
 32. *Nitzschia lanceolata*
- Association D: list of the diatoms only found at 4450 meters altitude
- Samples 7.5: Superficial sediments KKota
lake
6.4: On Isoetes
33. *Achnanthes hungarica*
 34. *Achnanthes microcephala*
 34. *Cymbella aspera*
 36. *Fragilaria virescens*
 37. *Pinnularia microstauron*
 38. *Cymbella cymbiformis*
- Association E: list of the diatoms only found 4310 meters altitude
- Samples 3: Superficial sediments Khara
KKota lake
2: On Isoetes
39. *Fragilaria crotonensis*
 40. *Comphonema acuminatum*
 41. *Meridion circulare constricta*
 42. *Navicula cuspidata ambigua*
 43. *Navicula rhynchocephala*
 44. *Pinnularia delicata*
 45. *Pinnularia strictissima*
 46. *Stauroneis javanica oblonga*
 47. *Stauroneis subtilis*
- Association F: list of the diatoms only found at 4200 meters altitude
- Samples 1: Superficial sediments peat bog
Khara KKota
48. *Caloneis silicula*
 49. *Fragilaria brevistriata*
 50. *Navicula cuspidata*
 51. *Neidium affine minor*
 52. *Neidium apiculatum*
 53. *Neidium magellanicum*
 54. *Pinnularia lata*
 55. *Pinnularia microstauron ambigua*
 56. *Stauroneis acuta*

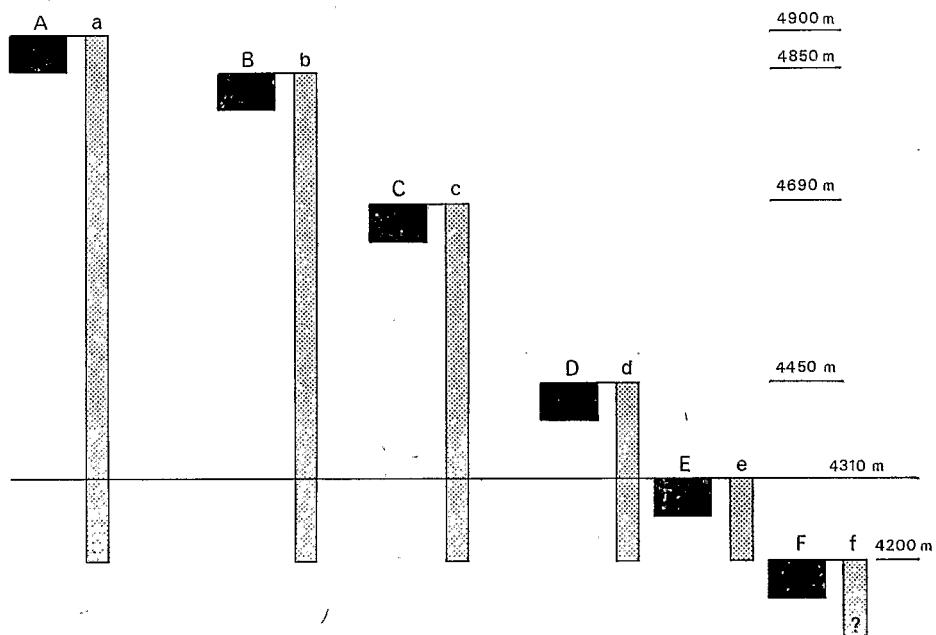


Fig. 5. Actual position of the different assemblages
Restricted species at one altitude

A (4900 m) — B (4850 m) — C (4690 m) — D (4450 m) — E (4310 m) — F (4200 m)
Non restricted species

Upper limit at 4900 meters

Association a

Cymbella microcephala, *Cymbella norvegica*, *Eunotia exigua*, *Frustulia frenguelli*, *Pinnularia borealis*, *Pinnularia microstauron brebissonii*, *Pinnularia divergens*, *Stauroneis anceps*, *Synedra vaucheriae*.

Upper limit at 4850 meters

Association b

Achnanthes lanceolata, *Caloneis patagonica*, *Ceratoneis arcus*, *Ceratoneis arcus amphioxis*, *Cymbella heteropleura*, *Diploneis ovalis*, *Fragilaria construens*, *Frustulia rhomboides*, *Frustulia vulgaris*, *Navicula subdeliberata*, *Navicula pseudoscutiformis*, *Surirella biseriata*.

Upper limit at 4690 meters

Association c

Cyclotella stelligera, *Cymbella affinis*, *Cymbella turgida*, *Eunotia polydentula*, *Eunotia praerupta bidens*, *Diatoma hiemale mesodon*, *Melosira patagonica*, *Pinnularia bogotensis*, *Synedra rumpens*.

Upper limit at 4460 meters

Association d

Cocconeis placentula, *Cymbella cistula*, *Cymbella cymbiformis*, *Cyclotella pseudostelligera*, *Fragilaria pinnata*, *Gomphonema intricatum*, *Navicula radiososa*.

Upper limit at 4310 meters

Association e

Pinnularia subcapitata, *Synedra goulardi*.

Upper limit at 4200 meters

f = F.

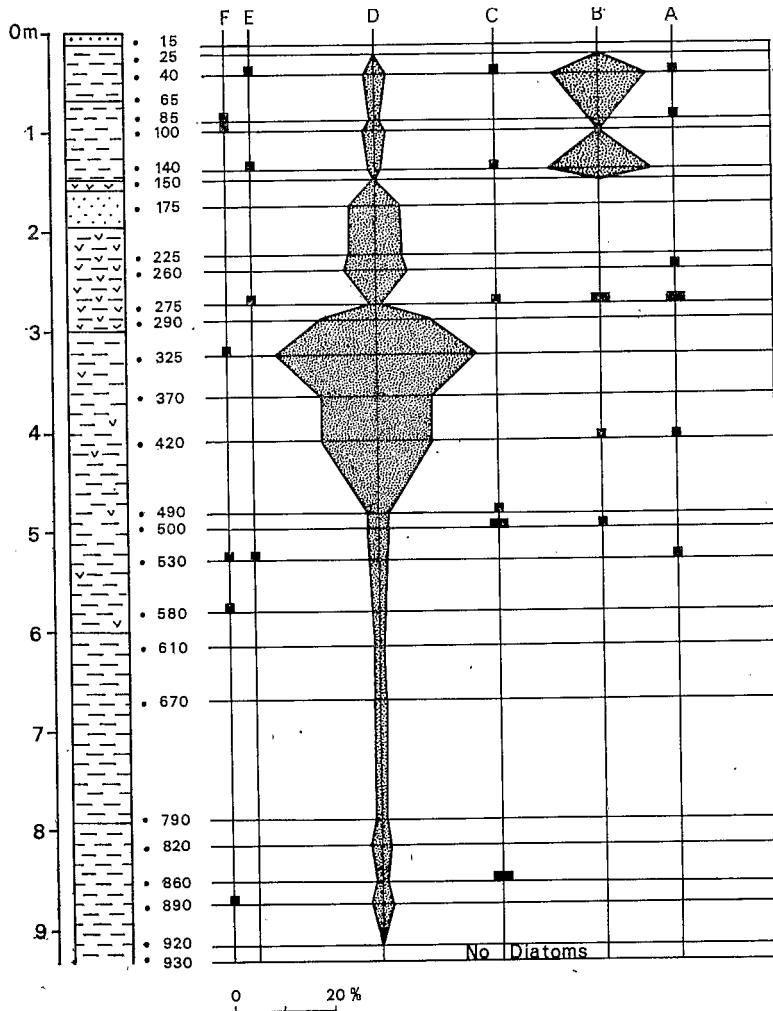


Fig. 6. Frequencies of restricted species assemblages along the core

Quantitative variation of A

- Achnanthes fraudulenta*
- Achnanthes lapponica*
- Navicula charlatii*
- Navicula cryptocephala*
- Navicula lapidosa* 275 (0.6) 240 (0.4)
- Navicula mutica nivalis*
- Pinnularia semicruciate*
- Neidium affine amphirhynchus* 40 (1.6)
- Neidium iridis intercedens*
- Nitzschia hollerupensis* 420 (0.5)
- Nitzschia thermalis littorea*
- Surirella islandica* 275 (0.6) 890 (0.7)

Quantitative variation of B

Achnanthes affinis
Achnanthes gibberula
Cymbella lunata 140 (0.8) 275 (0.6) 420 (1) 500 (2) 860 (3.5)
Eunotia valida
Navicula contenta
Navicula seminulum radiosus
Nitzschia fruticosa
Melosira distans alpigena 40 (18) 85 (8) 140 (21) 275 (4.4)
Synedra tabulata
Eunotia tridentula permixta

Quantitative variation of C

Cyclotella kuetzingiana
Eunotia arcus 40 (0.4)
Gomphonema longiceps gracilis 275 (0.6) 500 (2) 480 (1)
Surirella linearis
Nitzschia lacuum 225 (1) 325 (0.3) 890 (0.4)

Quantitative variation of D

Achnanthes microcephala 670 (0.4) 820 (0.7) 860 (0.4) 890 (0.8)
Achnanthes hungarica 40 (0.8) 240 (1) 275 (1.2) 325 (0.3) 420 (0.5) 580 (1) 610 (0.5) 670 (0.4)
 790 (0.4) 860 (0.4)
Cymbella aspera 140 (0.8) 275 (0.6) 420 (1) 500 (1) 530 (1.7) 670 (0.4) 820 (4.4) 860 (0.4) 890 (0.8)
Cymbella cymbiformis 240 (2.4) 290 (3.4) 325 (1.8) 420 (1.7) 500 (4) 580 (1.6) 890 (0.8)
Fragilaria virescens 40 (1.2) 100 (2.2) 175 (10.2) 225 (14.5) 240 (11.8) 275 (1.2) 290 (25)
 325 (38.3) 370 (18.5) 420 (20.8) 480 (6.3) 500 (5.1) 530 (1.7) 670 (0.9) 890 (0.4)
Pinnularia microstauron 140 (0.8) 820 (0.7)

Quantitative variation of E

Fragilaria cotonensis
Gomphonema acuminatum
Meridion circulare constricta 40 (0.4) 275 (0.6)
Navicula cuspidata ambigua
Navicula rhynchocephala 670 (0.9)
Pinnularia strictissima
Stauroneis javanica oblonga
Stauroneis subtilis 140 (0.8)

Quantitative variation of F

Caloneis silicula 100 (0.5)
Fragilaria brevistriata 530 (0.1)
Navicula cuspidata 530 (1)
Neidium affine minor
Neidium apiculatum
Neidium sauramoi
Pinnularia lata 325 (0.6) 890 (0.4)
Pinnularia microstauron ambigua
Stauroneis acuta 100 (1)

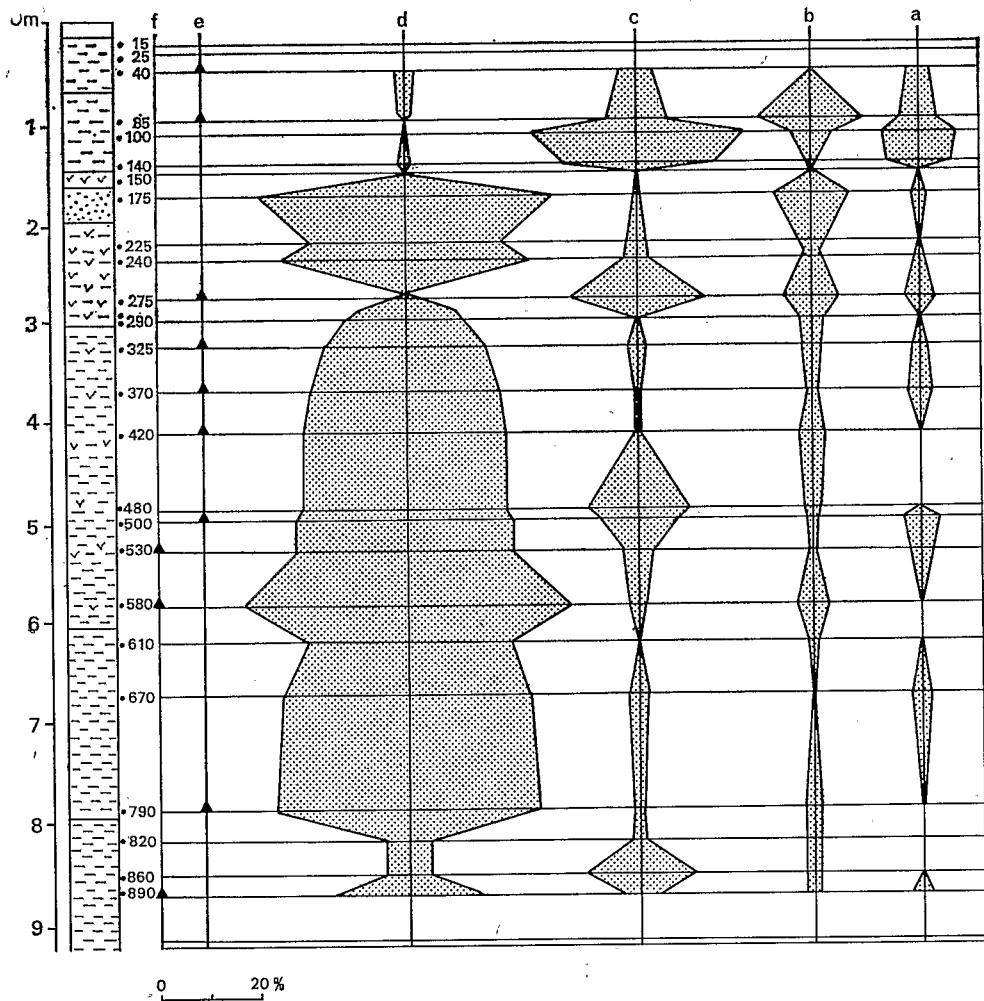


Fig. 7. Frequencies of non-restricted species assemblages along the core

Quantitative variation of a /

Cymbella norvegica 40 (0.4) 85 (0.5) 140 (0.6) 275 (0.6) 325 (0.3)

Cymbella microcephala 40 (0.8) 275 (0.6) 420 (0.5) 500 (1) 530 (0.5)

Eunotia exigua 140 (0.4) 500 (1)

Frustulia frenguelli 40 (0.4) 85 (0.4) 140 (0.8) 175 (1.4) 530 (0.5)

Pinnularia borealis 40 (2) 85 (1) 100 (3.3) 140 (7.2) 275 (2.5)

Pinnularia microstauron brebissonii 40 (2.1) 85 (1.5) 100 (3.3) 140 (1.6) 175 (1.2)

Pinnularia divergens 40 (0.4) 85 (0.6) 100 (4)

Stauroneis anceps 40 (0.4) 85 (0.6) 100 (1.6) 530 (0.5)

Synedra vaucheriae 85 (4) 100 (2.2) 140 (0.8) 240 (1.6) 275 (0.6) 325 (1.4) 370 (3.5) 480 (0.5)
500 (6.1) 670 (0.9) 890 (0.4)

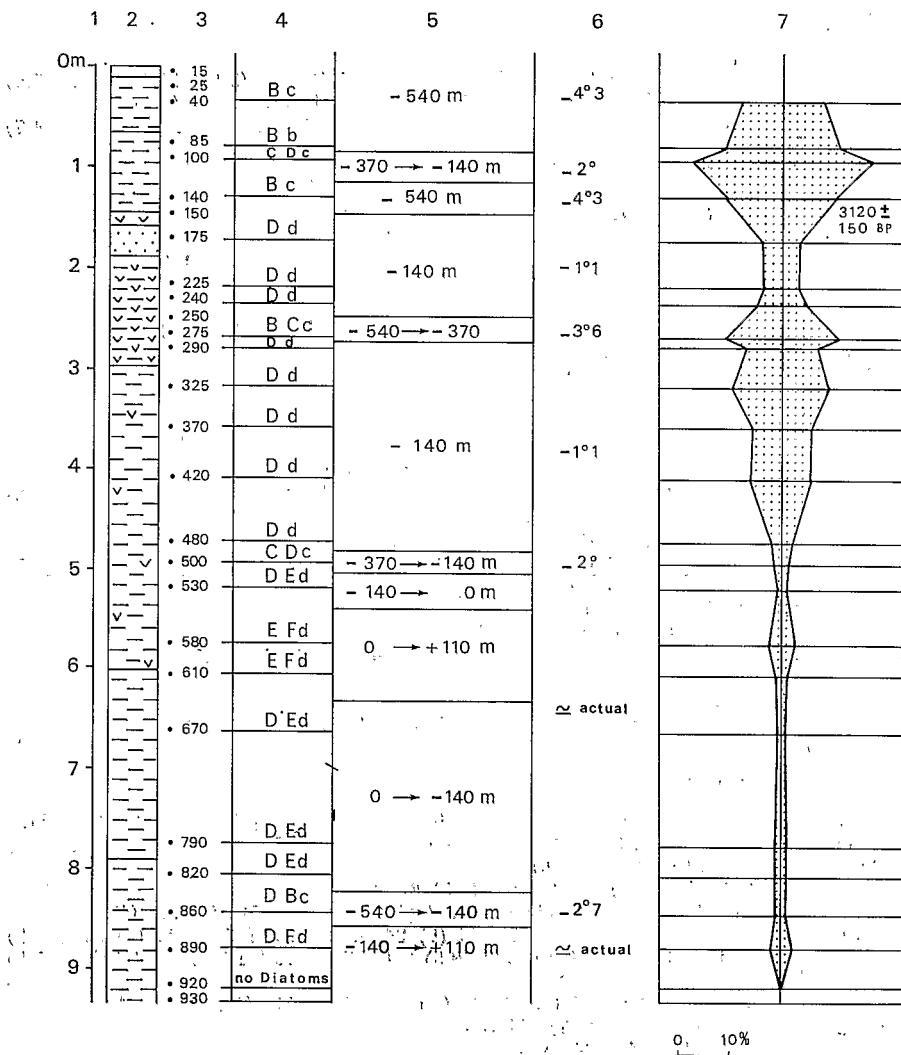


Fig. 8. Interpretation

- 1 — Depth — 2 — Lithology — 3 — Samples — 4 — Localisation of the diatom assemblages — 5 — Evaluation of the assemblages' position — 6 — Evaluation of temperature fluctuations — 7 — Quantitative frequency variations of psychrophilic diatoms. List of psychrophilic diatoms.
Achnanthes coarctata 85 (0.5) 175 (1.5) 240 (0.4) 325 (0.3) 420 (0.5) 790 (0.4)
Achnanthes pseudotanensis 240 (5.3) 275 (10.3) 500 (1)
Ceratoneis arcus 85 (0.5) 225 (0.4) 240 (0.6) 325 (0.3) 420 (0.5) 500 (2) 580 (2) 610 (0.5) 790 (0.4) 820 (0.7) 890 (0.4)
Ceratoneis arcus amphioxys 325 (0.3) 480 (0.5) 580 (1) 860 (0.4)
Cymbella heteropleura 40 (0.8) 85 (0.8) 225 (1) 240 (0.4) 325 (0.3)
Cymbella norvegica 40 (0.8) 85 (0.8) 140 (0.6) 275 (0.6) 325 (0.3)
Diatoma anceps subsconstricta 85 (0.5) 100 (1.6) 370 (0.7)
Diatoma hiemale mesodon 40 (5) 85 (13.3) 100 (25) 140 (1.6) 175 (1) 240 (1) 275 (20.4) 325 (0.6) 370 (1.4) 420 (1) 480 (0.5) 790 (0.4) 860 (0.7)
Eunotia arcus 40 (0.4)

- Eunotia faba* 530 (0.5) 580 (1.6)
Eunotia fallax 500 (1)
Eunotia praerupta bidens 85 (1) 275 (0.6)
Eunotia robusta tetraedon 140 (0.8) 480 (0.5) 790 (0.4)
Eunotia tecta 100 (0.5) 275 (0.6)
Fragilaria virescens 40 (1.2) 100 (2.2) 175 (10.2) 225 (14.1) 240 (11.8) 275 (1.2) 325 (38.3)
 370 (18.5) 420 (20.8) 480 (6.3) 500 (5.1) 530 (1.7) 670 (0.9) 890 (0.4)
Frustulia frenguelli 40 (0.4) 85 (0.4) 140 (0.8) 175 (1.4) 530 (0.5)
Melosira distans alpigena 40 (17.8) 85 (7.6) 140 (27.8) 275 (3.7)
Melosira patagonica 40 (0.4) 85 (16.3) 100 (27.7) 140 (2.4)
Navicula lapidosa 85 (1) 240 (0.4) 275 (0.6) 530 (0.5)
Navicula perpusilla 85 (0.6) 100 (0.5)
Navicula pseudoscutiformis 85 (0.5) 175 (2.9) 225 (1) 275 (1.4) 325 (0.3) 370 (4.2)
Navicula wittrockii 325 (0.3) 530 (0.5) 670 (0.5) 890 (0.4)
Navicula subtilissima 240 (0.4) 480 (0.4) 530 (0.5) 790 (0.4)
Neidium magellanicum 820 (1.4) 860 (0.4)
Pinnularia acrospheria 85 (1) 325 (0.3)
Pinnularia borealis 40 (2) 85 (1) 100 (9.3) 140 (7.3) 275 (2.5) 890 (0.4)
Pinnularia microstauron brebissonii 40 (2.1) 85 (1.5) 100 (3.3) 140 (1.6) 275 (1.2)
Pinnularia brevicostata 40 (0.8) 140 (0.8) 275 (0.6) 610 (0.5) 890 (0.4)
Pinnularia crucicula 40 (3.8) 275 (0.6)
Pinnularia divergentissima 40 (2) 85 (1.5) 100 (2.7) 140 (2.4) 275 (1.2) 325 (0.3) 890 (0.4)
Pinnularia streptoraphe 100 (0.3)
Surirella islandica 85 (1.5) 140 (0.8) 275 (0.6) 860 (0.4) 890 (0.4)

PLATE I

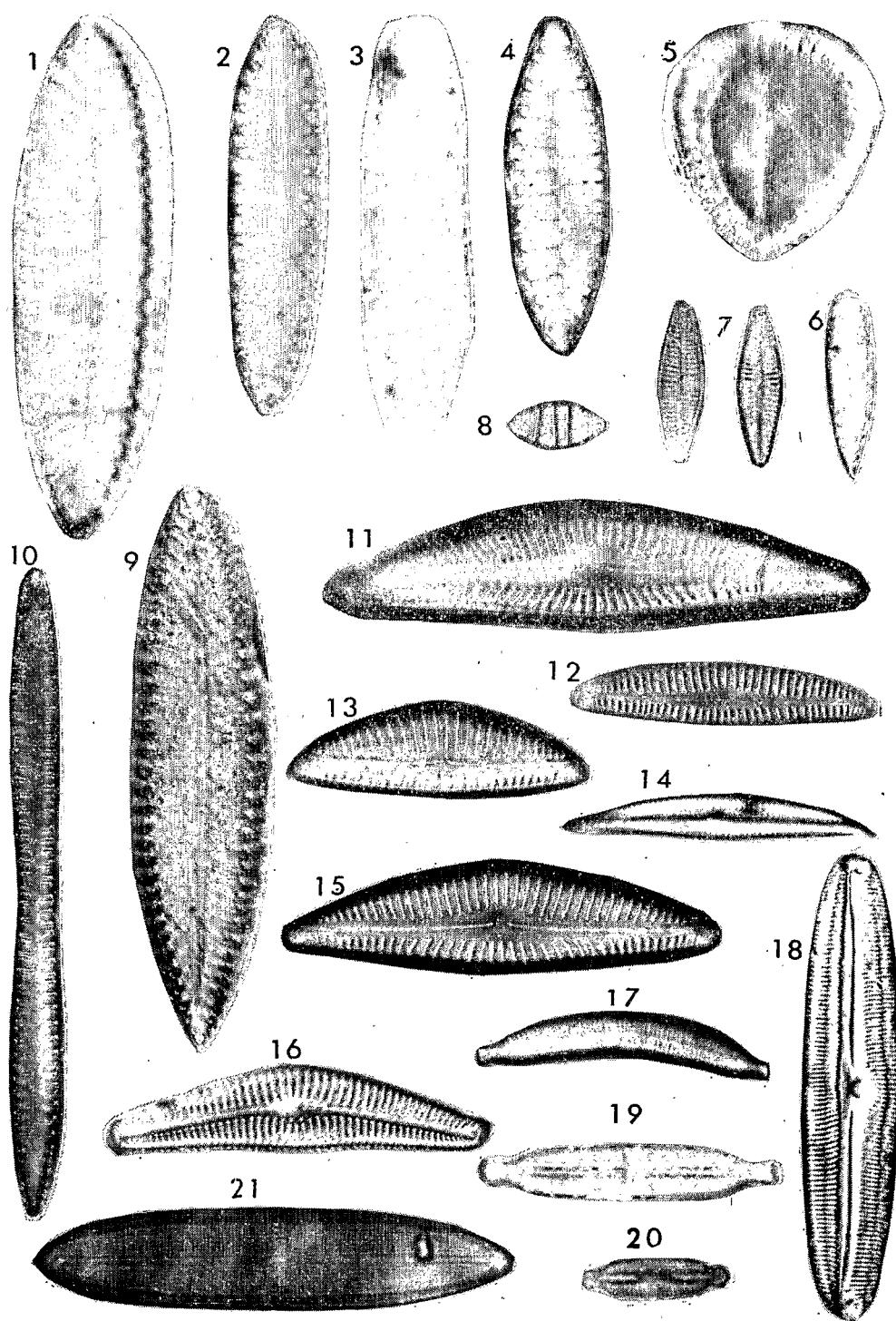


PLATE II

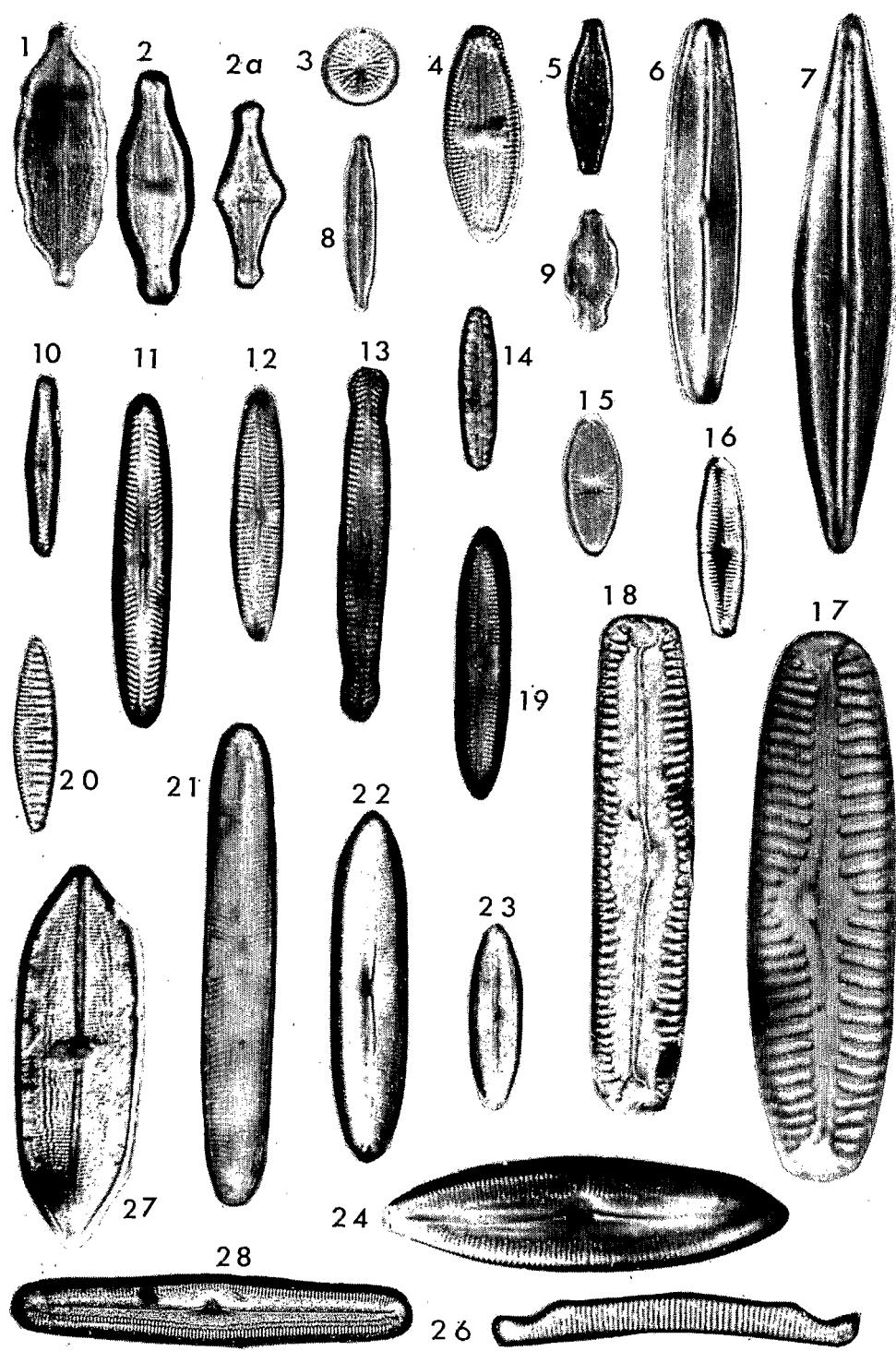


PLATE III

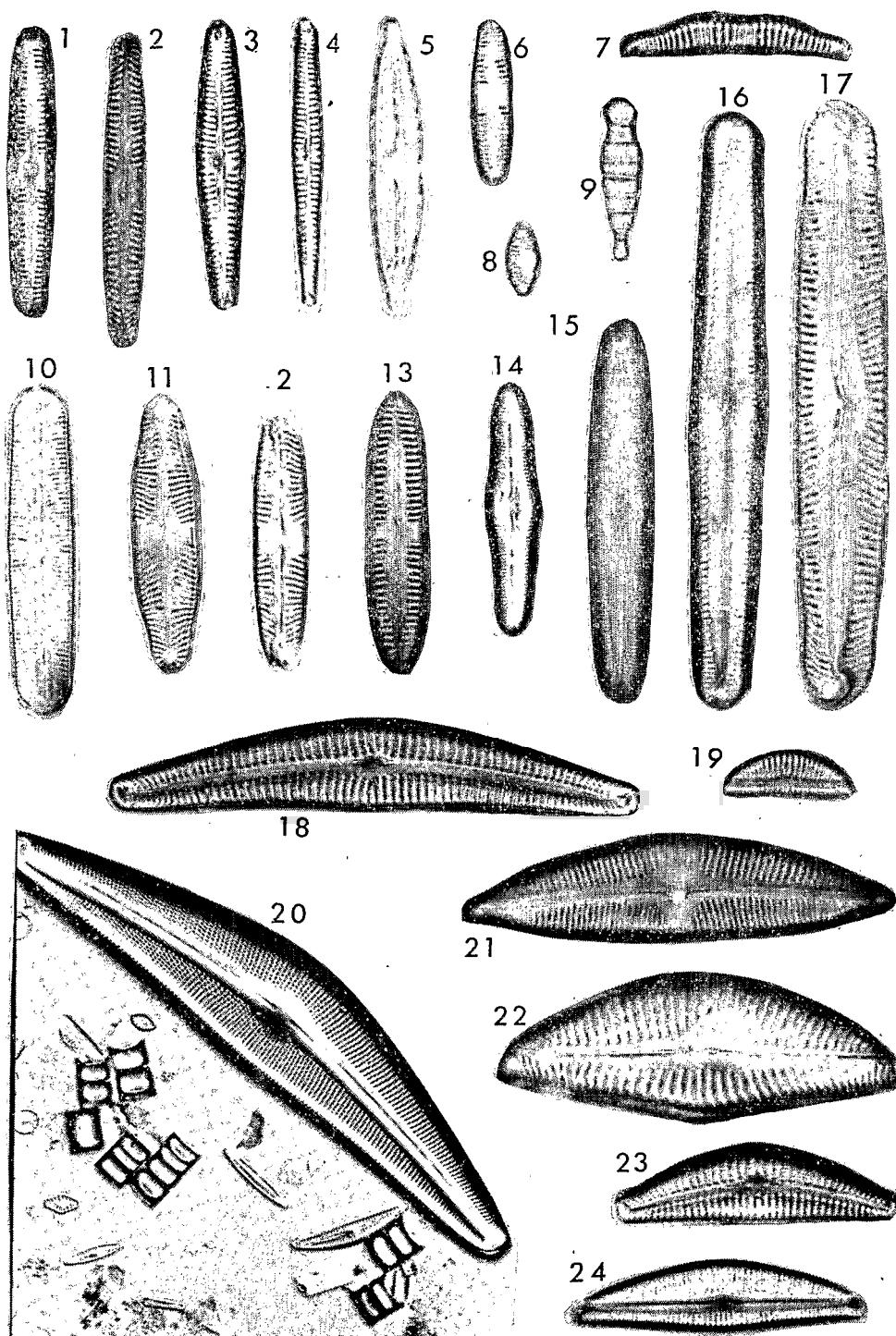
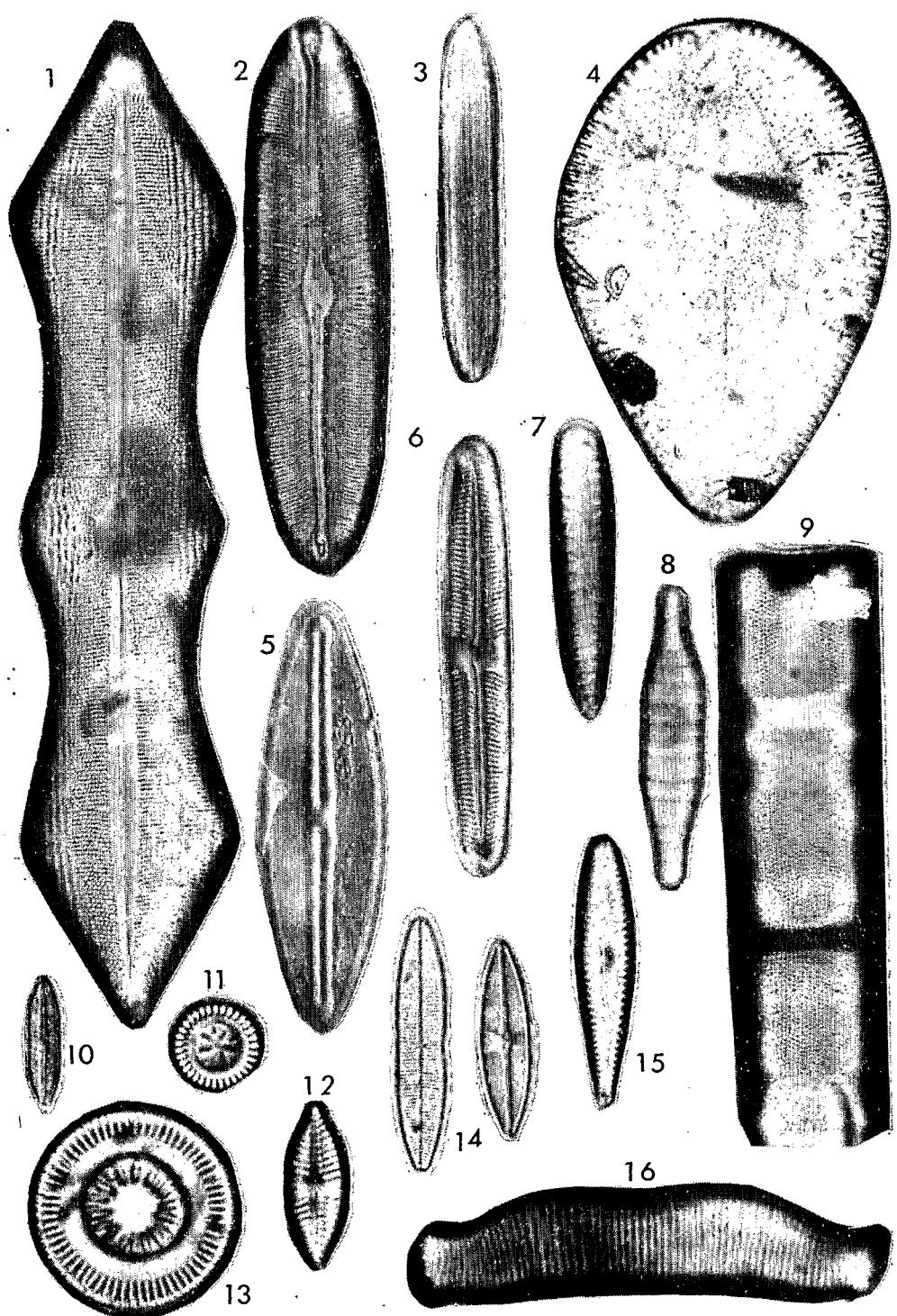


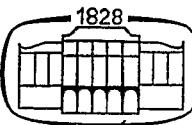
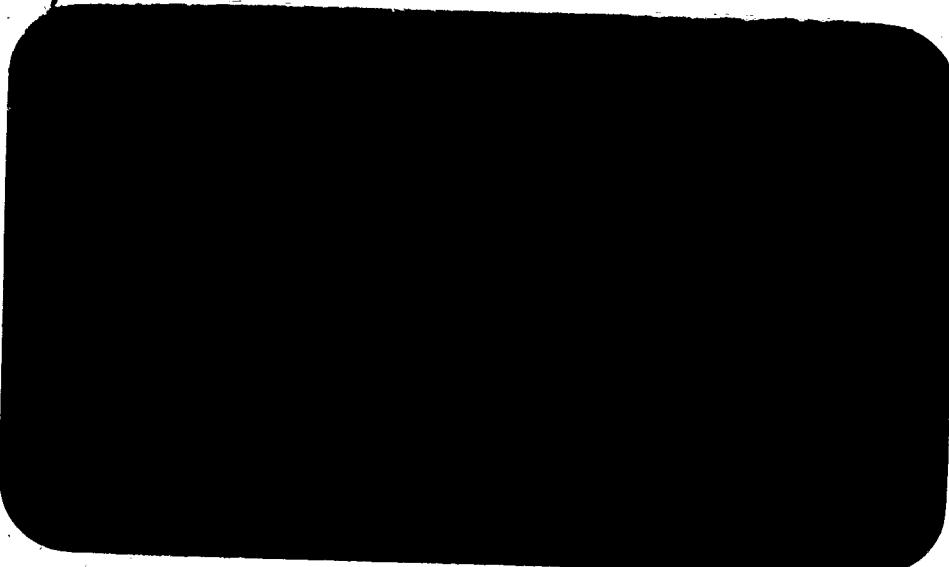
PLATE IV



Román K. Riso Štefan
5/12/82

SEPARATUM

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