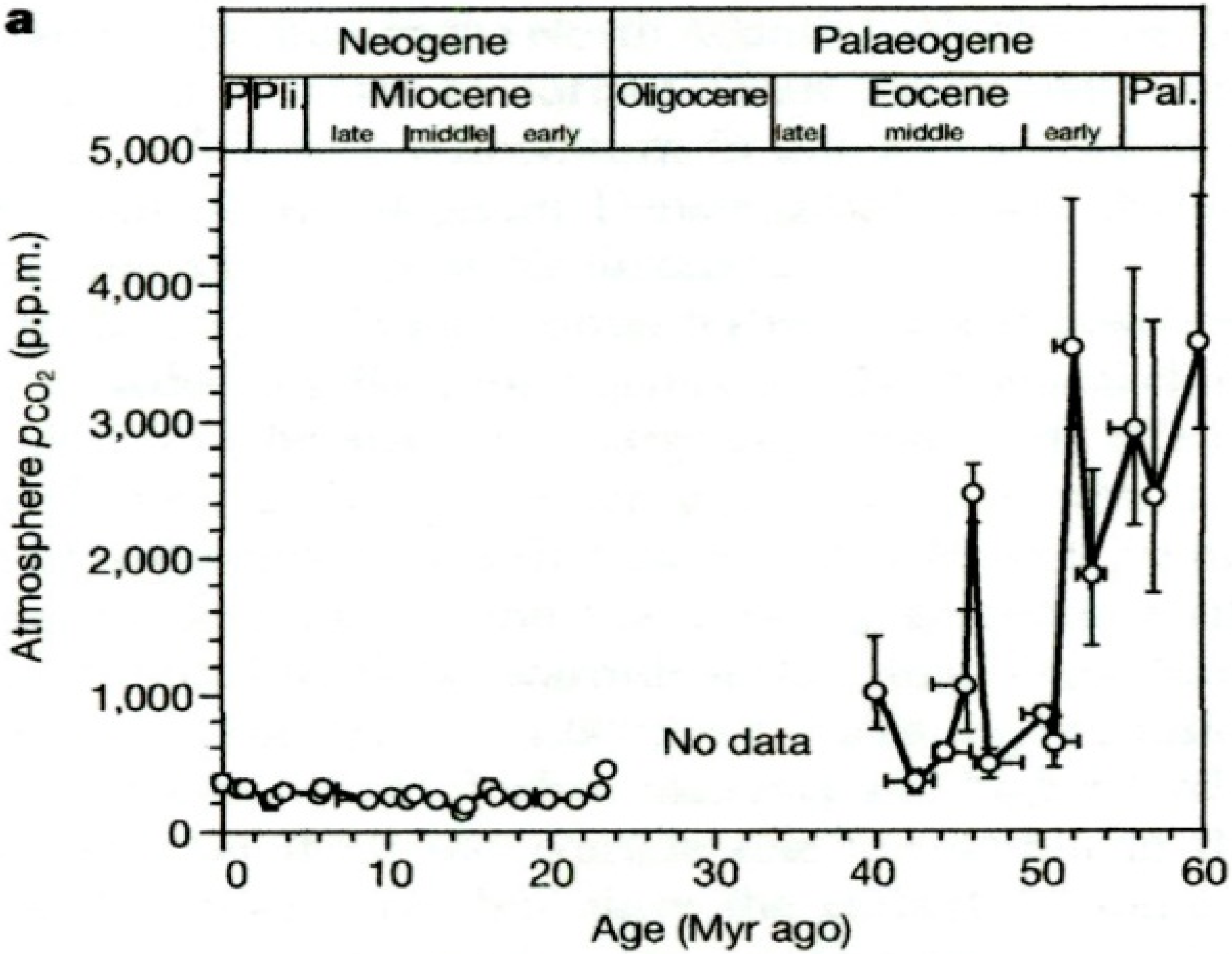
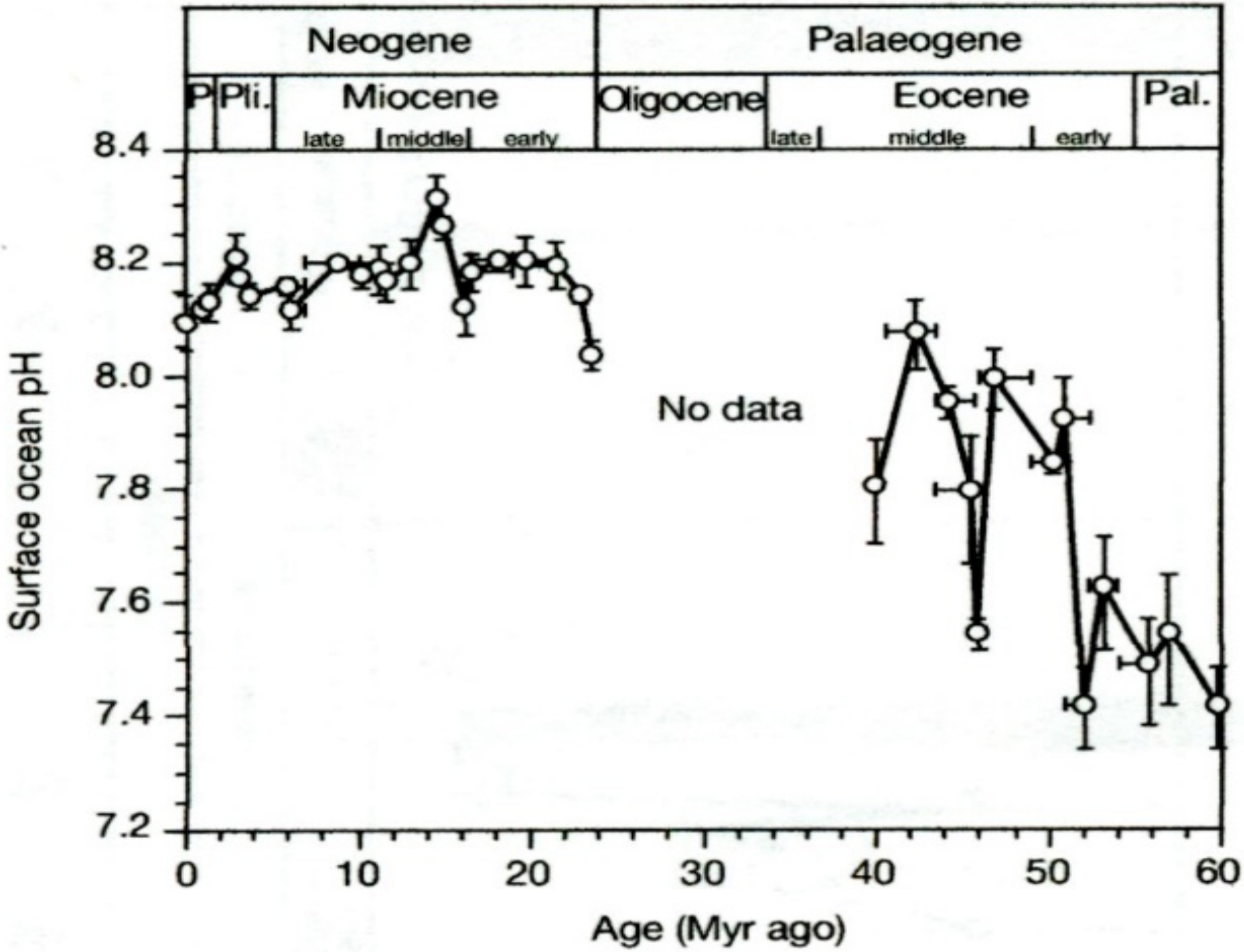
We may keep the corals
but lose the reefs


a
Neogene
Palaeogene
P
Pli.
Miocene
late
middle
early
Oligocene
Eocene
late
middle
early
Pal.
5,000
4,000
3,000
2,000
1,000
0
Atmosphere pCO_2 (p.p.m.)
No data
0
10
20
30
40
50
60
Age (Myr ago)


Neogene
Palaeogene
P
Pli.
Miocene
late
middle
early
Oligocene
Eocene
late
middle
early
Pal.
No data
Surface ocean pH
8.4
8.2
8.0
7.8
7.6
7.4
7.2
0
10
20
30
40
50
60
Age (Myr ago)

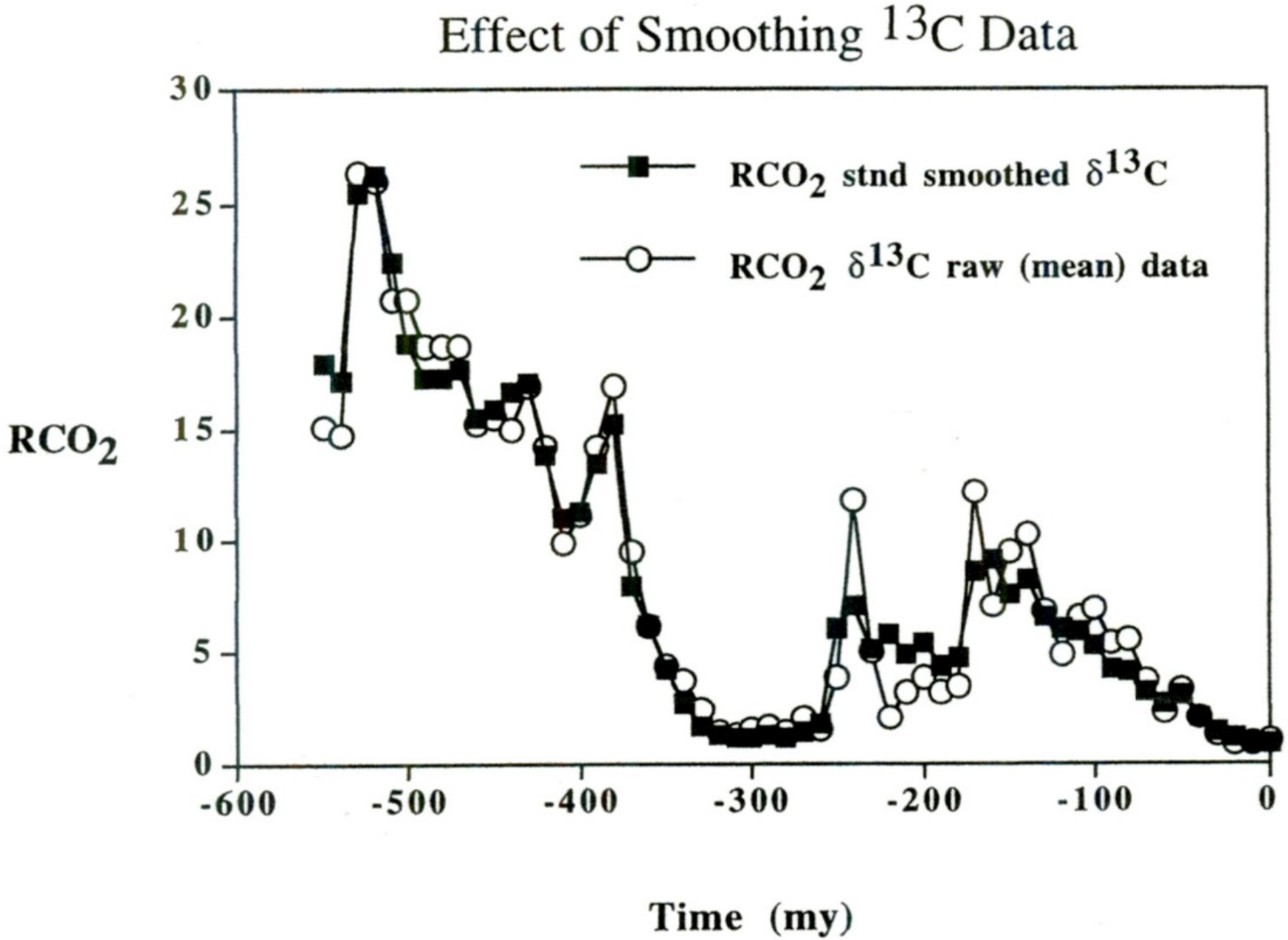


Fig. 8. Effect of using raw mean data for $\delta^{13}C$ vs time (Veizer and others, 1999) vs first order smoothing of the same data as used in the standard formulation.

source	estimated Cretaceous shallow seawater temperature
Wilson et al. 1996 Pearson et al. 2001 Wilson et al. 2002 Kleypas et al. 2008	probably 30°C - 33°C, not higher than 32°C - 36°C
Poulsen et al. 1999	34°C max
Zeebe 2001	31°C – 34.5°C
Norris et al. 2002 Jenkyns et al. 2004	tropical 34°C (Arctic up to 20°C)
Steuber et al. 2005	35°C - 37°C
Littler et al. 2011	32°C at 15-20°N
Schouten et al. 2015	Atlantic 32°C – 36°C Pacific 27°C – 32°C
Poulsen et al. 2015	max > 35°C

"**What doesn't kill you makes you stronger**" - Friedrich Nietzsche

Corals more tolerant of warm temperatures after first major bleaching

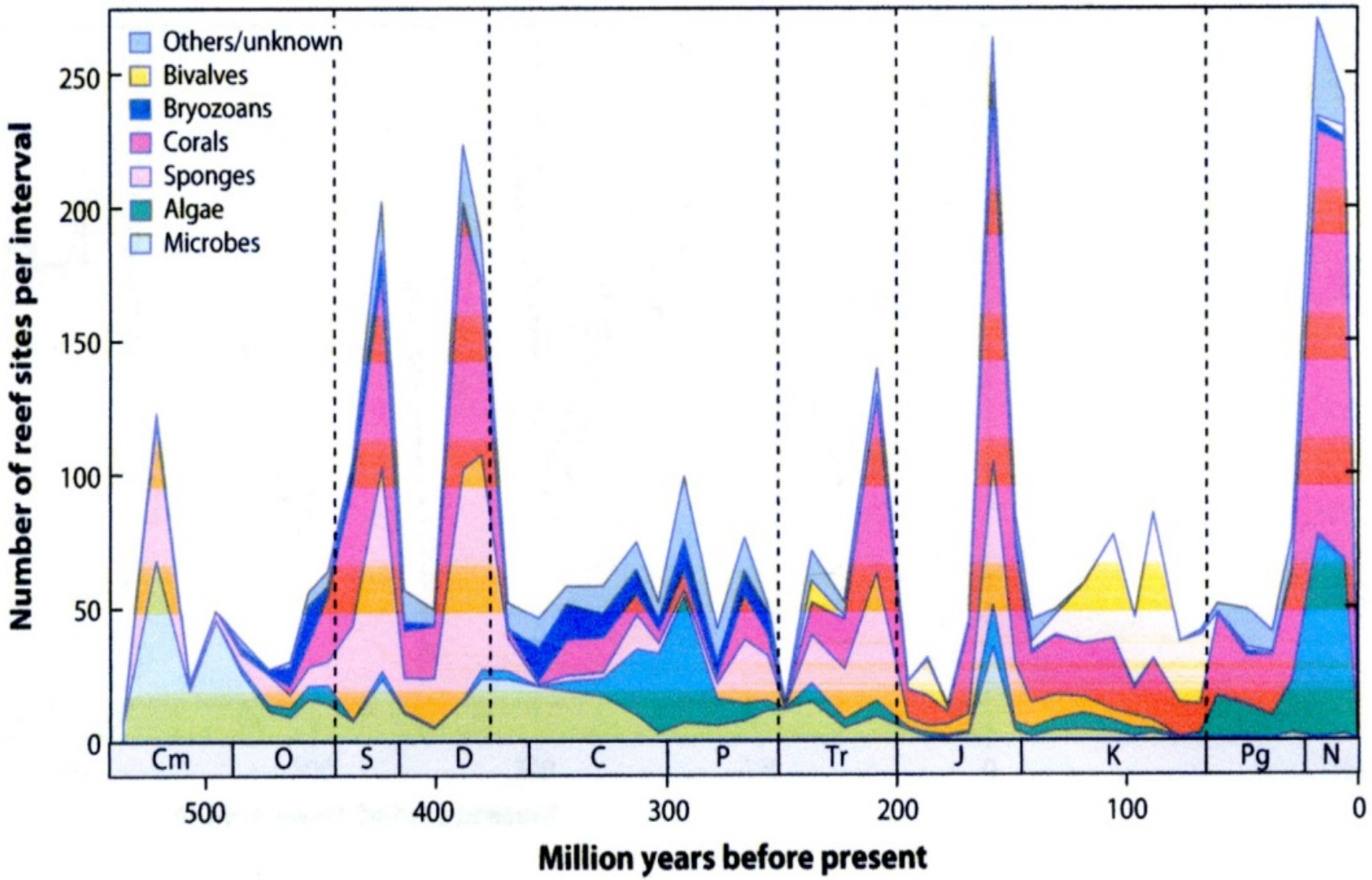
eastern tropical Pacific
French Polynesia
Great Barrier Reef
Thailand

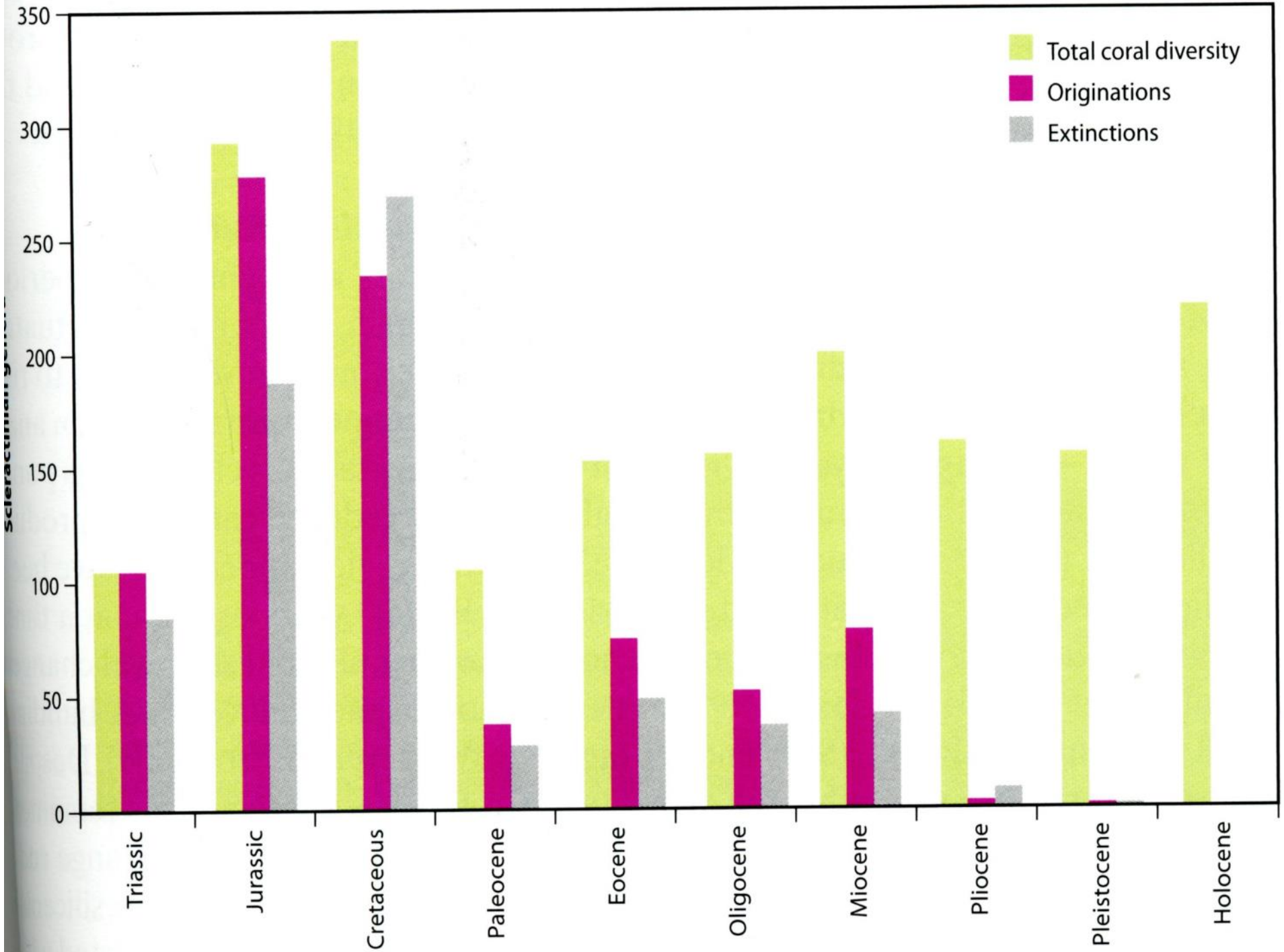
Corals closer to equator have higher thermal tolerance

Arabian / Persian Gulf – corals not bleach eight weeks at 34 °C for 8 weeks
(with three of the weeks above 35 °C)

Gulf of Oman daily fluctuations 8.2 °C to 36 °C with no signs of stress, annually 11.4 °C to 36 °C

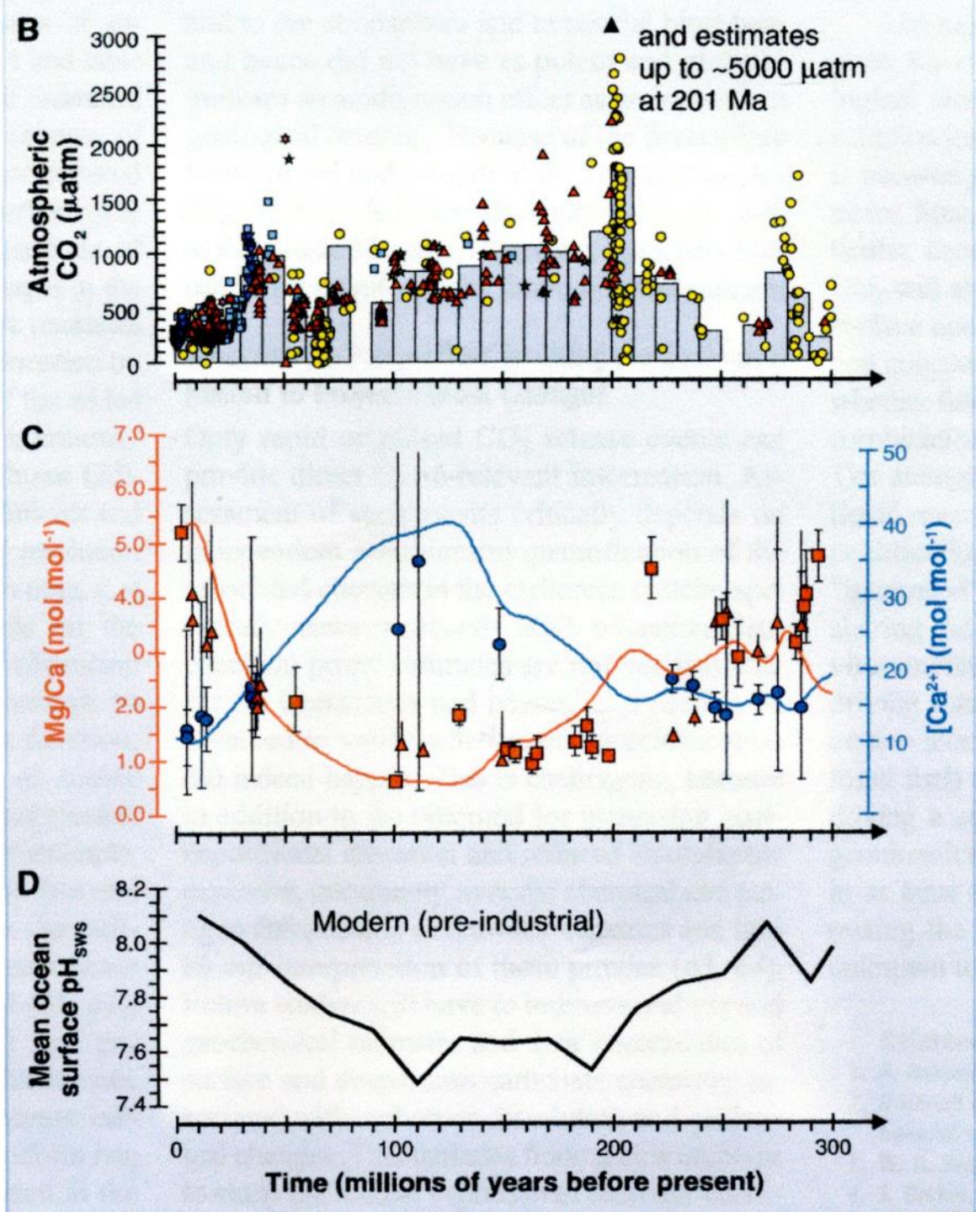
At least 26 genera of scleractinians survived Cretaceous mass extinction and
Paleocene-Eocene Thermal Maximum

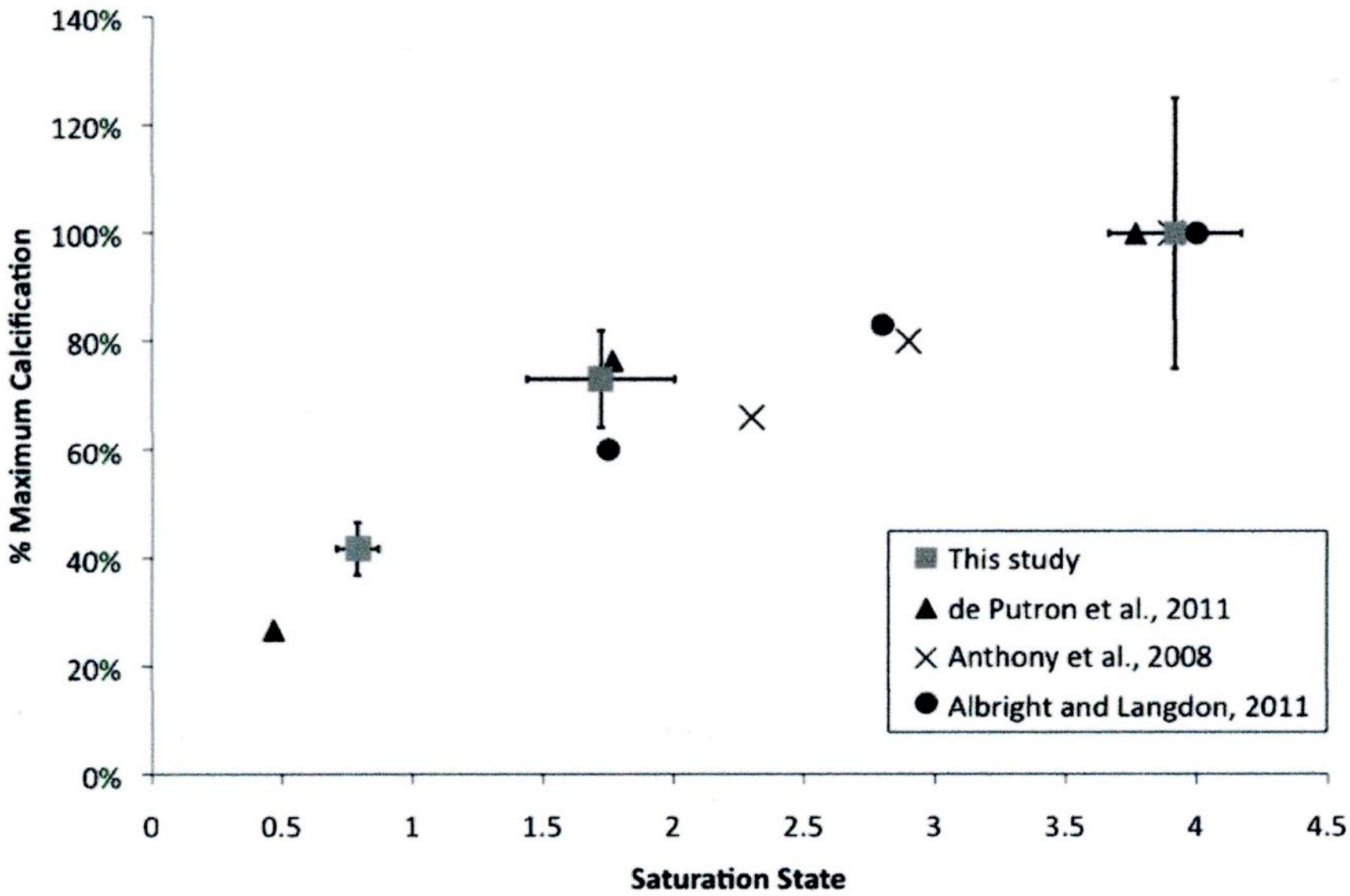

Others/unknown
Bivalves
Bryozoans
Corals
Sponges
Algae
Microbes
Number of reef sites per interval
0
50
100
150
200
250
Cm
O
S
D
C
P
Tr
J
K
Pg
N
500
400
300
200
100
0
Million years before present

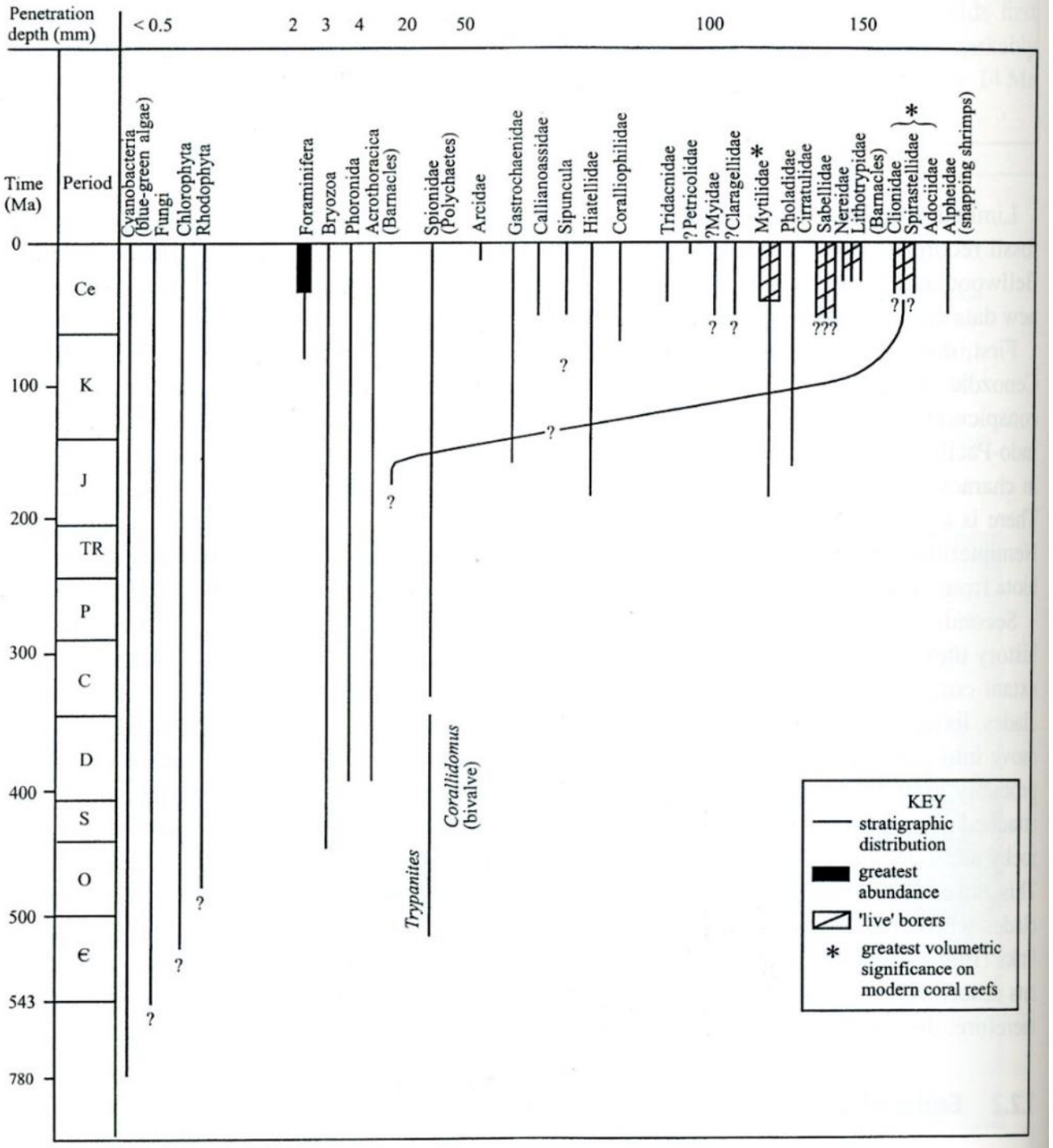

Total coral diversity
Originations
Extinctions
350
300
250
200
150
100
50
0
Triassic
Jurassic
Cretaceous
Paleocene
Eocene
Oligocene
Miocene
Pliocene
Pleistocene
Holocene

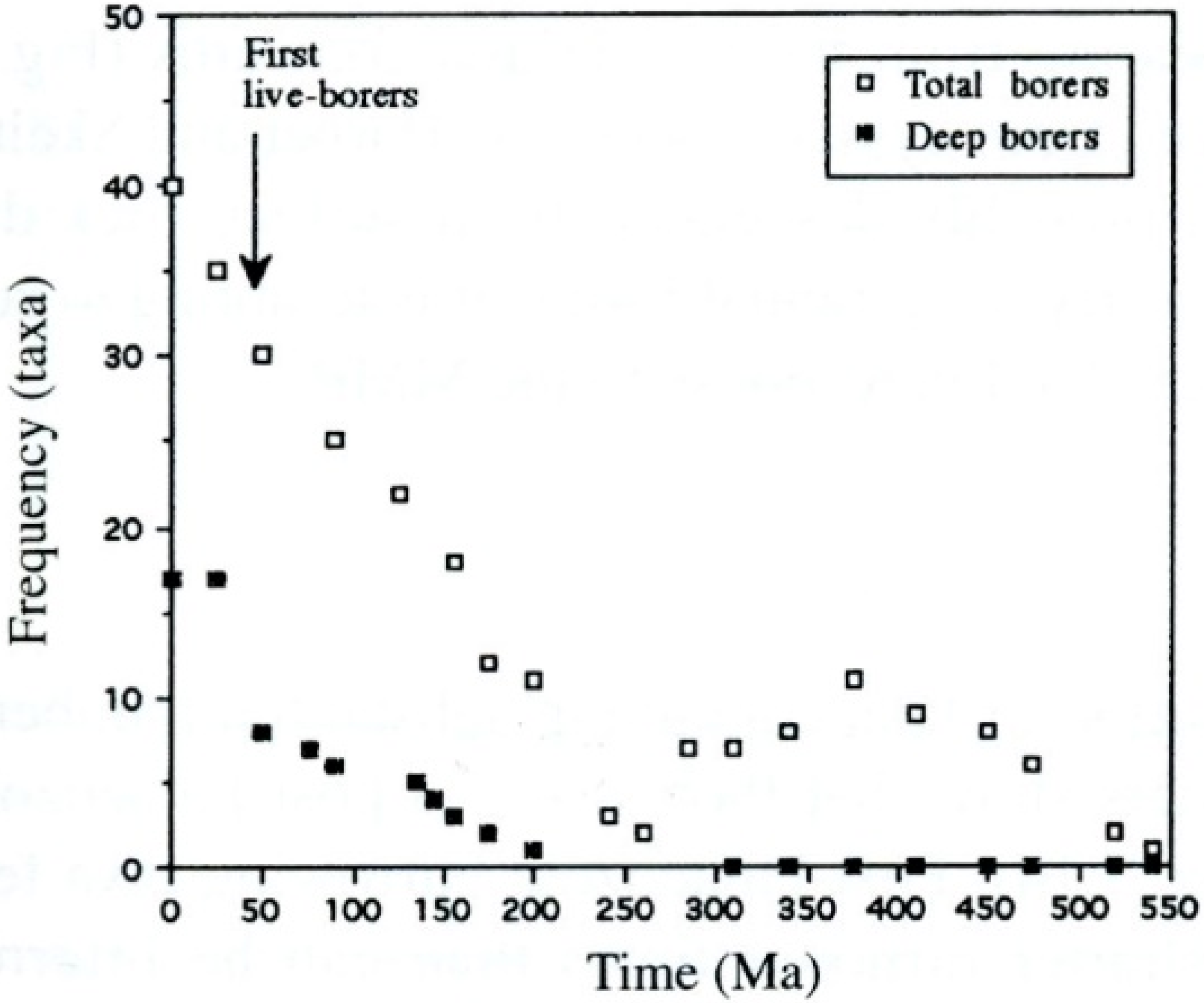
"Like obesity, a massive reef accumulation may be the result of remaining stationary for too long under good conditions."

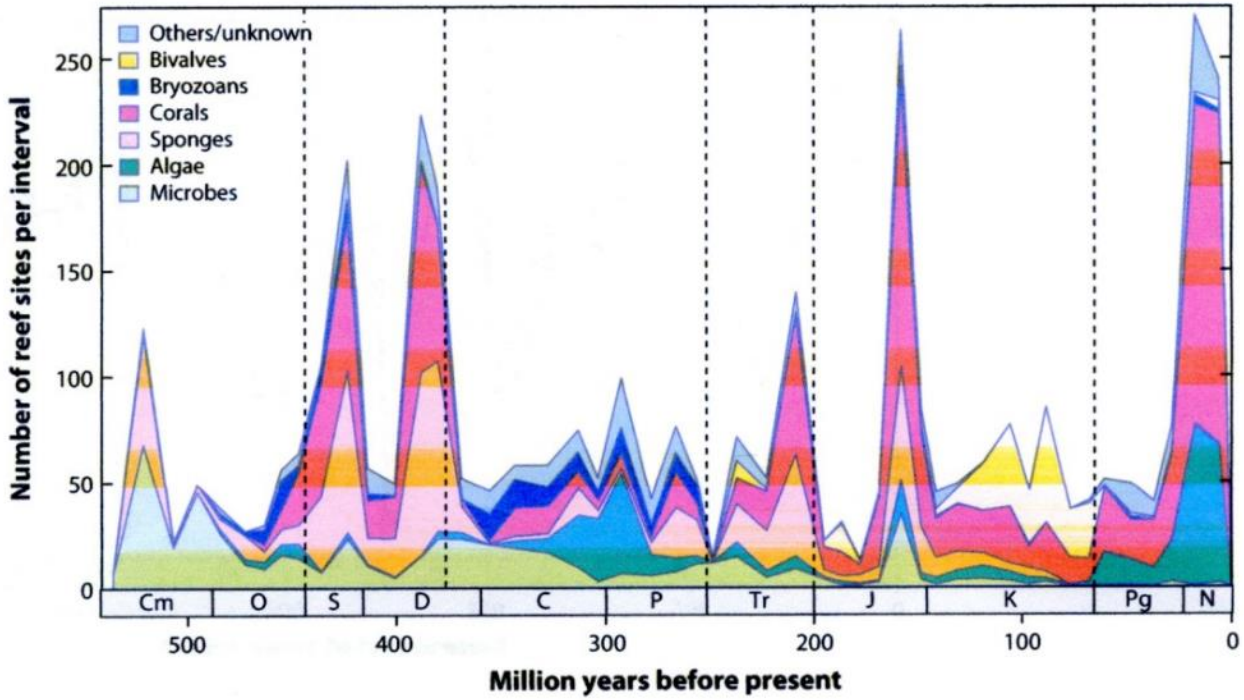
Buddemeier and Kinzie 1998

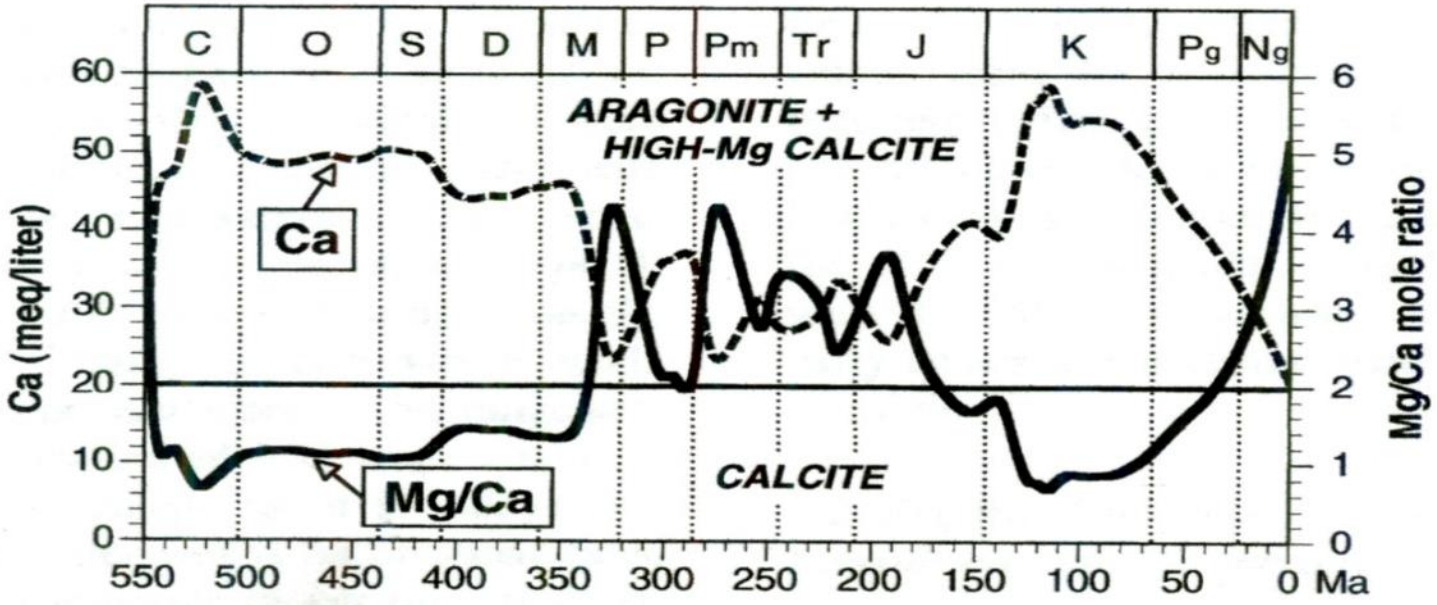

B
and estimates
up to ~5000 µatm
at 201 Ma
Atmospheric CO_2 (µatm)
3000
2500
2000
1500
1000
500
0
C
Mg/Ca (mol mol^{-1})
7.0
6.0
5.0
4.0
0
2.0
1.0
0.0
[Ca^{2+}] (mol mol^{-1})
50
40
30
20
10
D
Modern (pre-industrial)
Mean ocean surface pH_{sws}
8.2
8.0
7.8
7.6
7.4
0
100
200
300
Time (millions of years before present)

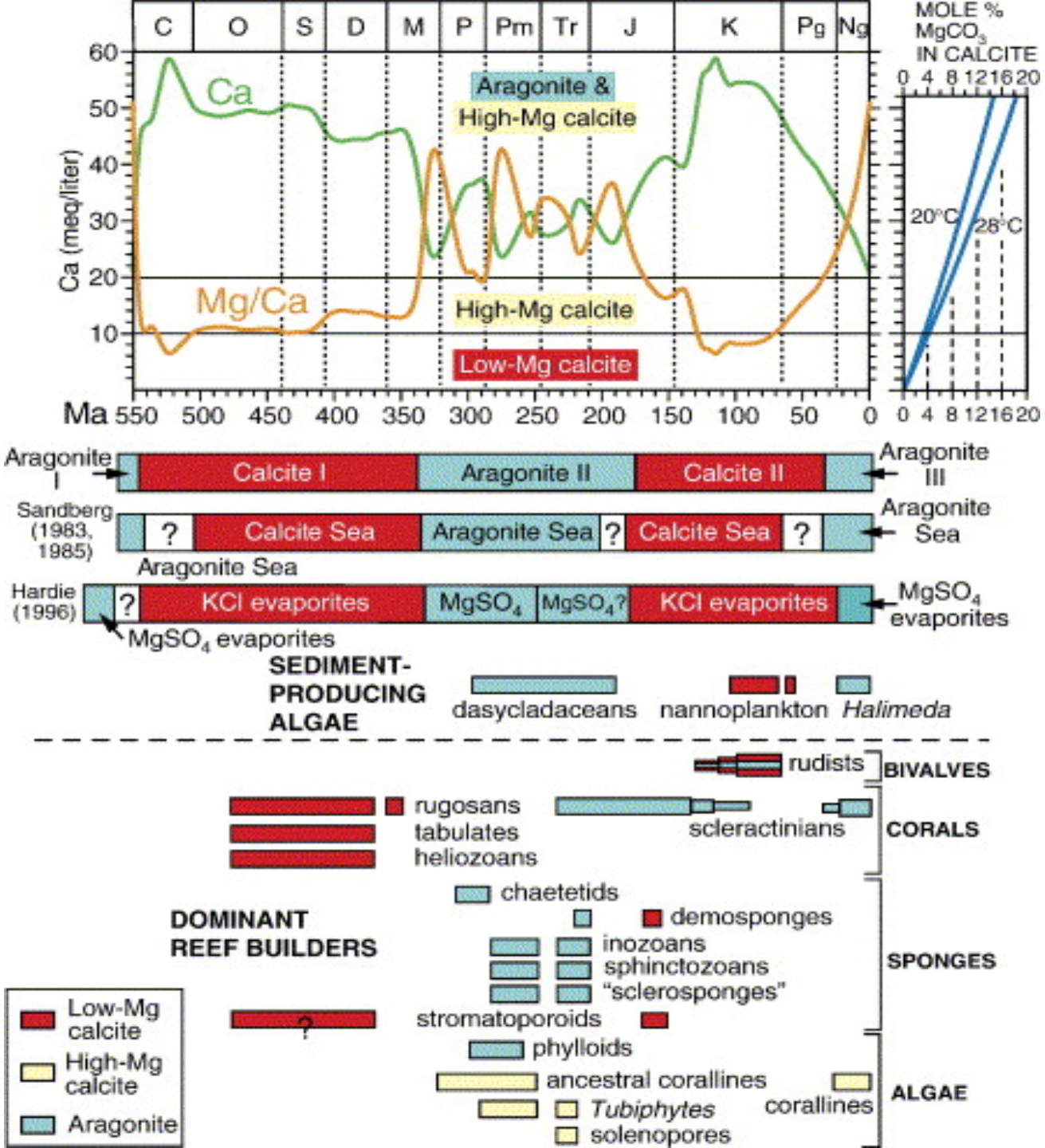

140%
120%
100%
80%
60%
40%
20%
0%
% Maximum Calcification
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Saturation State
This study
de Putron et al., 2011
Anthony et al., 2008
Albright and Langdon, 2011

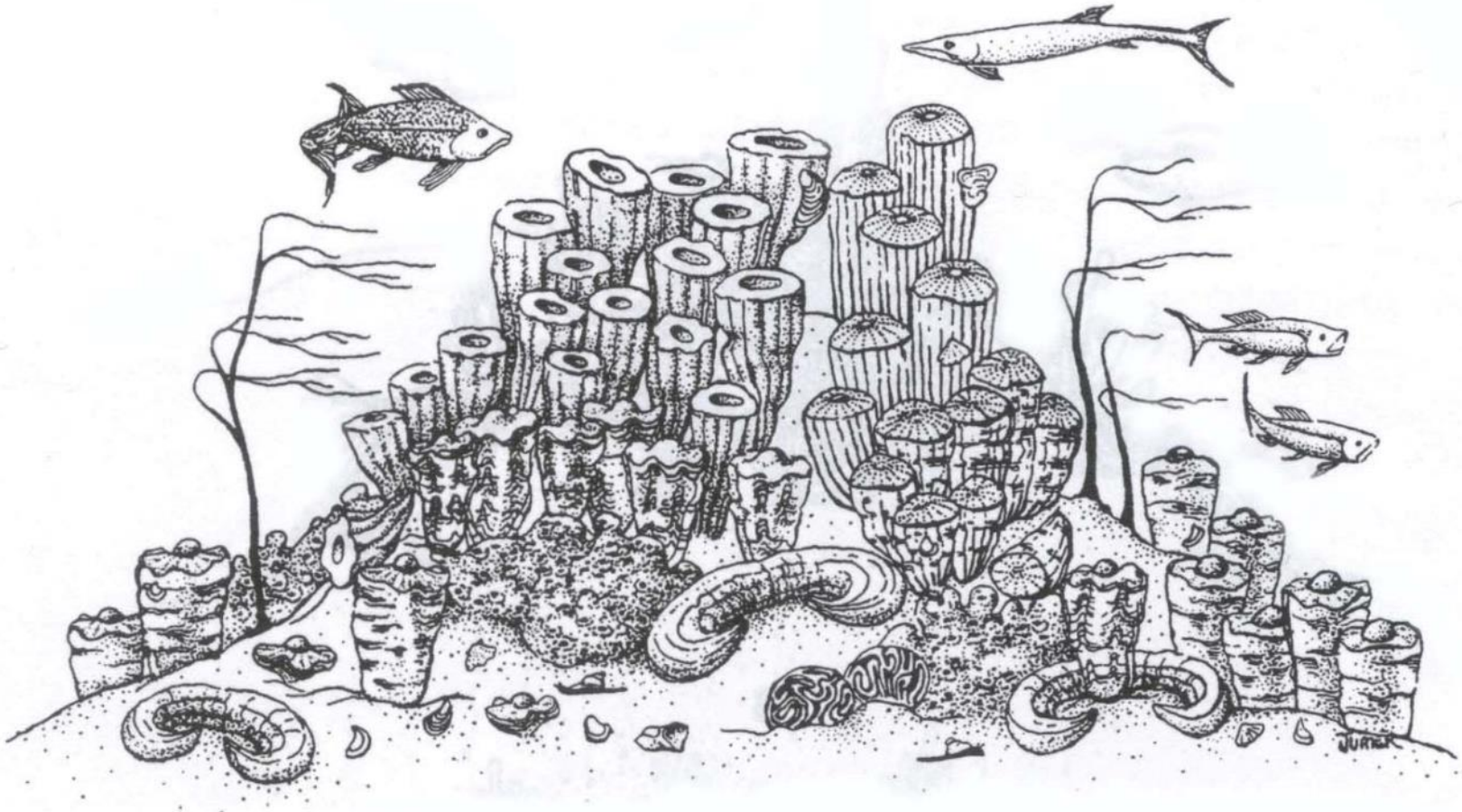

Penetration depth (mm)
< 0.5
2
3
4
20
50
100
150
Time (Ma)
Period
0
100
200
300
400
500
543
780
Ce
K
J
TR
P
C
D
S
O
Є
Cyanobacteria (blue-green algae)
Fungi
Chlorophyta
Rhodophyta
Foraminifera
Bryozoa
Phoronida
Acrothoracica (Barnacles)
Spionidae (Polychaetes)
Arcidae
Gastrochaenidae
Callianoassidae
Sipuncula
Hiatellidae
Coralliophilidae
Tridacnidae
? Petricolidae
?Myidae
?Claragellidae
Mytilidae *
Pholadidae
Cirratulidae
Sabellidae
Nereidae
Lithotrypidae (Barnacles)
Clionidae
Spirastellidae
*
Adociidae
Alpheidae (snapping shrimps)
Trypanites
Corallidomus (bivalve)
KEY
stratigraphic distribution
greatest abundance
'live' borers
* greatest volumetric significance on modern coral reefs

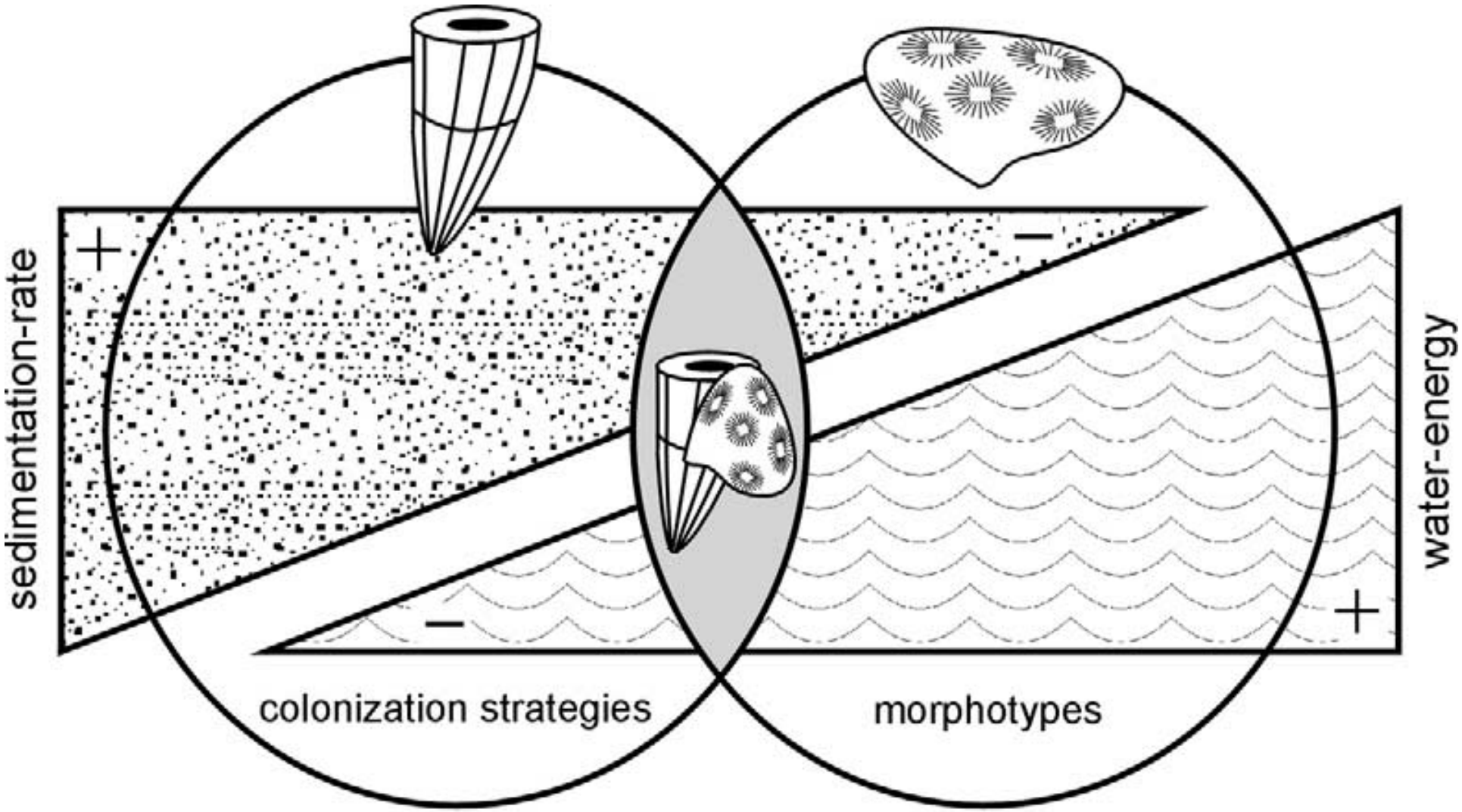

First
live-borers
Total borers
Deep borers
Frequency (taxa)
Time (Ma)
0
10
20
30
40
50
0
50
100
150
200
250
300
350
400
450
500
550

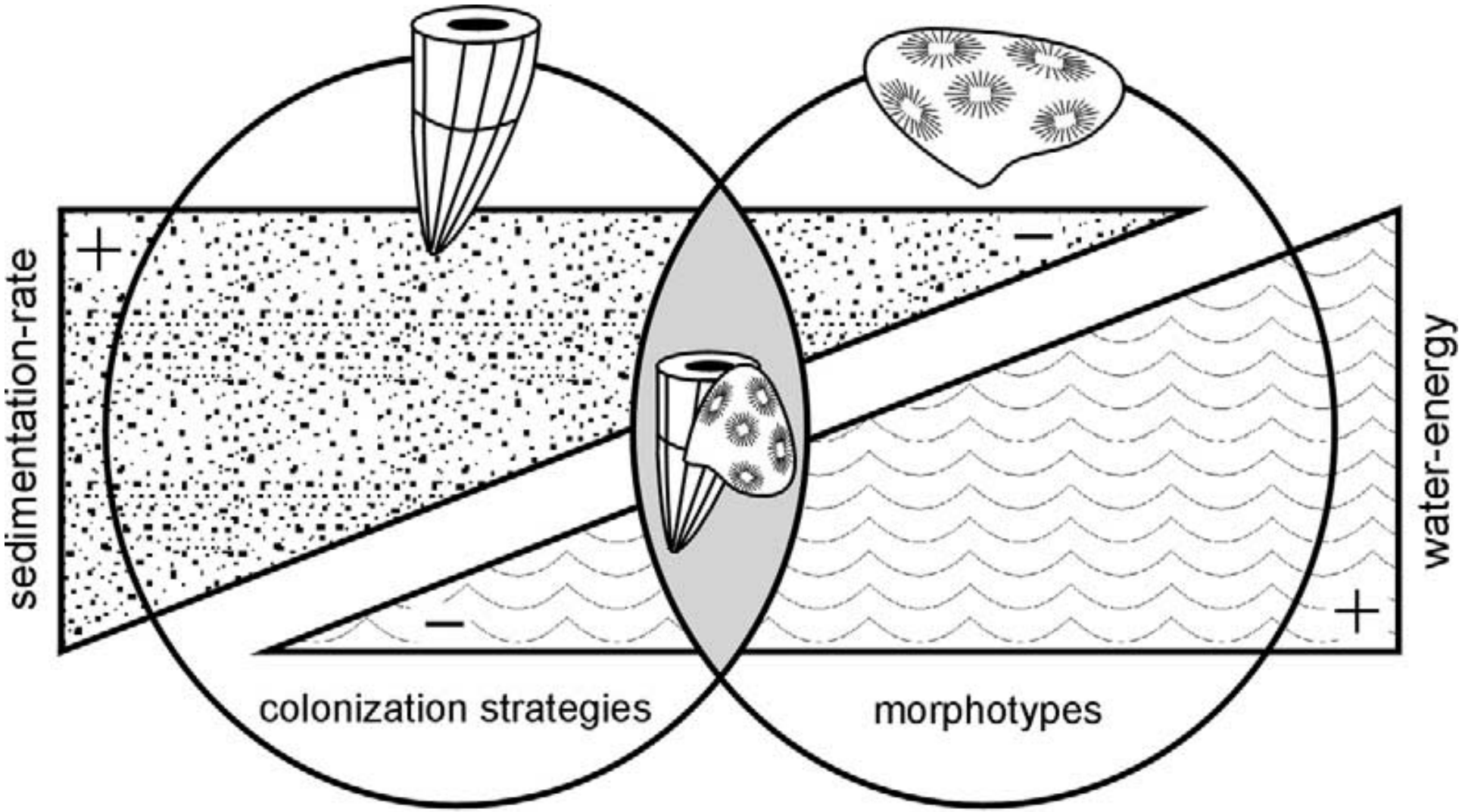

Others/unknown
Bivalves
Bryozoans
Corals
Sponges
Algae
Microbes
Number of reef sites per interval
0
50
100
150
200
250
Cm
O
S
D
C
P
Tr
J
K
Pg
N
500
400
300
200
100
0
Million years before present


C
O
S
D
M
P
Pm
Tr
J
K
Pg
Ng
ARAGONITE +
HIGH-Mg CALCITE
Ca
Mg/Ca
CALCITE
Ca (meq/liter)
Mg/Ca mole ratio
0
10
20
30
40
50
60
0
1
2
3
4
5
6
550
500
450
400
350
300
250
200
150
100
50
0 Ma


C
O
S
D
M
P
Pm
Tr
J
K
Pg
Ng
Ca
Mg/Ca
Aragonite &
High-Mg calcite
High-Mg calcite
Low-Mg calcite
Ca (meq/liter)
Ma
MOLE % MgCO3 IN CALCITE
20°C
28°C
Aragonite I
Calcite I
Aragonite II
Calcite II
Aragonite III
Sandberg (1983, 1985)
Calcite Sea
Aragonite Sea
Calcite Sea
Aragonite Sea
Hardie (1996)
KCl evaporites
MgSO4
MgSO4?
KCl evaporites
MgSO4 evaporites
MgSO4 evaporites
SEDIMENT-PRODUCING ALGAE
dasycladaceans
nannoplankton
Halimeda
DOMINANT REEF BUILDERS
rudists
BIVALVES
rugosans
tabulates
heliozoans
scleractinians
CORALS
chaetetids
demosponges
inozoans
sphinctozoans
"sclerosponges"
stromatoporoids
SPONGES
phylloids
ancestral corallines
Tubiphytes
solenopores
corallines
ALGAE
Low-Mg calcite
High-Mg calcite
Aragonite

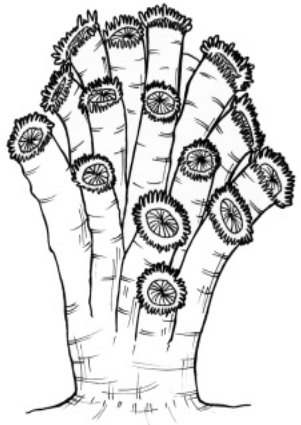



sedimentation-rate
+
−
−
+
water-energy
colonization strategies
morphotypes


sedimentation-rate
+
−
−
+
water-energy
colonization strategies
morphotypes

survival	Triassic/Jurassic mass extinction	Cretaceous/Paleogene mass extinction
scleractinian genera	27%	70 ± 4%
all marine animal genera	53.2%	52.6
continued survival when reef-building accelerated and many new genera originated	5%	55%

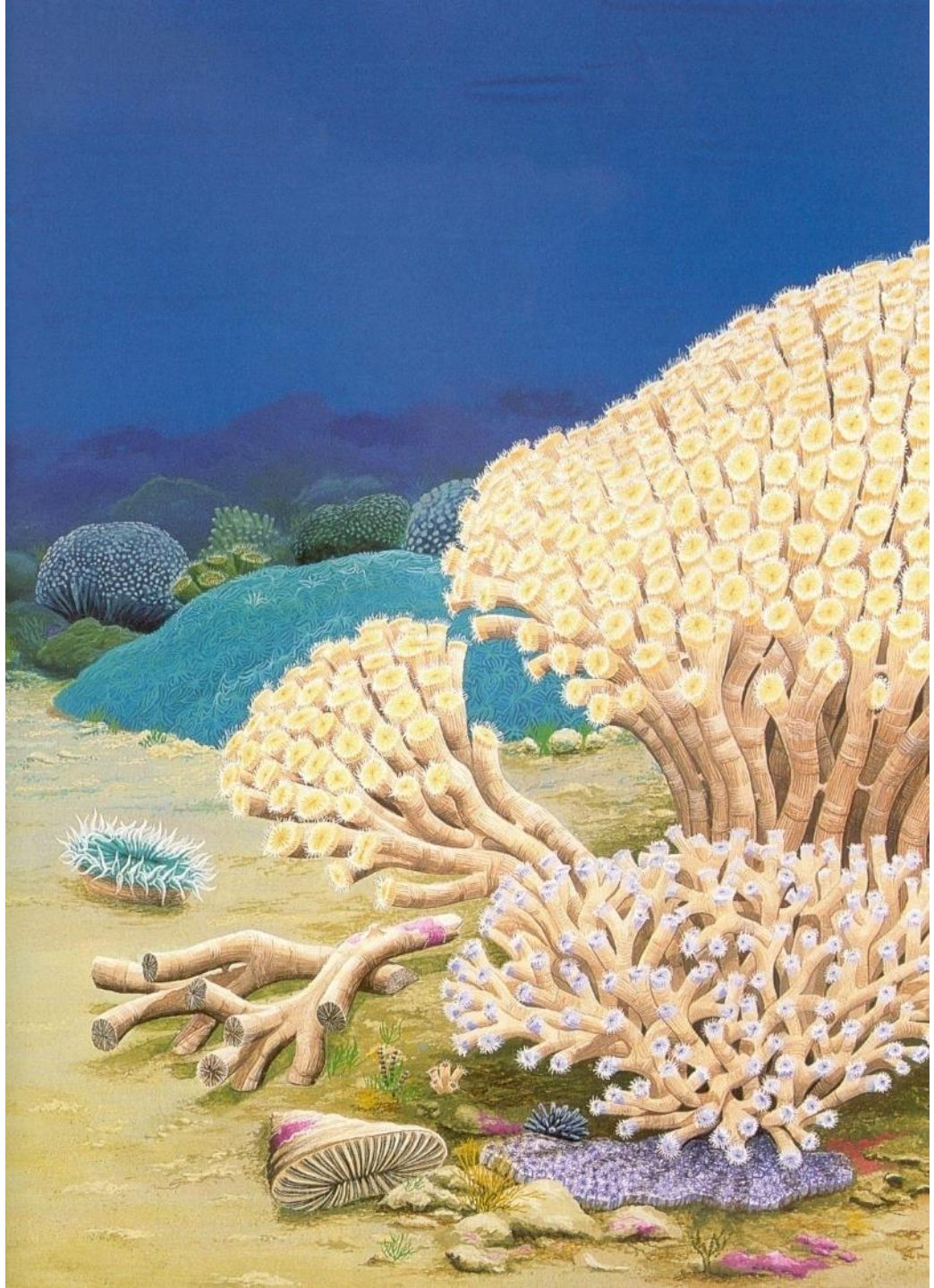
	Survived Mesozoic	Originated Cenozoic	
	LAZARUS CORALS	FAUSTIAN CORALS	
Massive or encrusting	*Stephanocoenia*		
	Madracis		
	Astreopora		
	Siderastrea		
	Dichocoenia		
	(*Dendrogyra*)		
	Cycloseris ?		
	Astrangia		
	Hydnophora		
	Favia		
	Diploria		
	Montastraea		
	Diploastrea		
	(*Favites*)		
	(*Goniastrea*?)		
	Leptoria		
	(*Leptastrea*)		
	(*Oulastrea*)		
	(*Plesiastrea*)		
	Goniopora		
	(*Alveopora*)		
	Porites ?		
	Heteropsammia ?		
	Heliopora		
Phaceloid	*Cladocora*		
Branching	*Oculina*	*Stylophora*	(Paleocene)
		Pocillopora	(Eocene)
		Acropora	(Eocene)
		Seriatopora	(Miocene)
		Anacropora	(recent)
		Palauastrea	(recent)
		Paraclavarina	(recent)

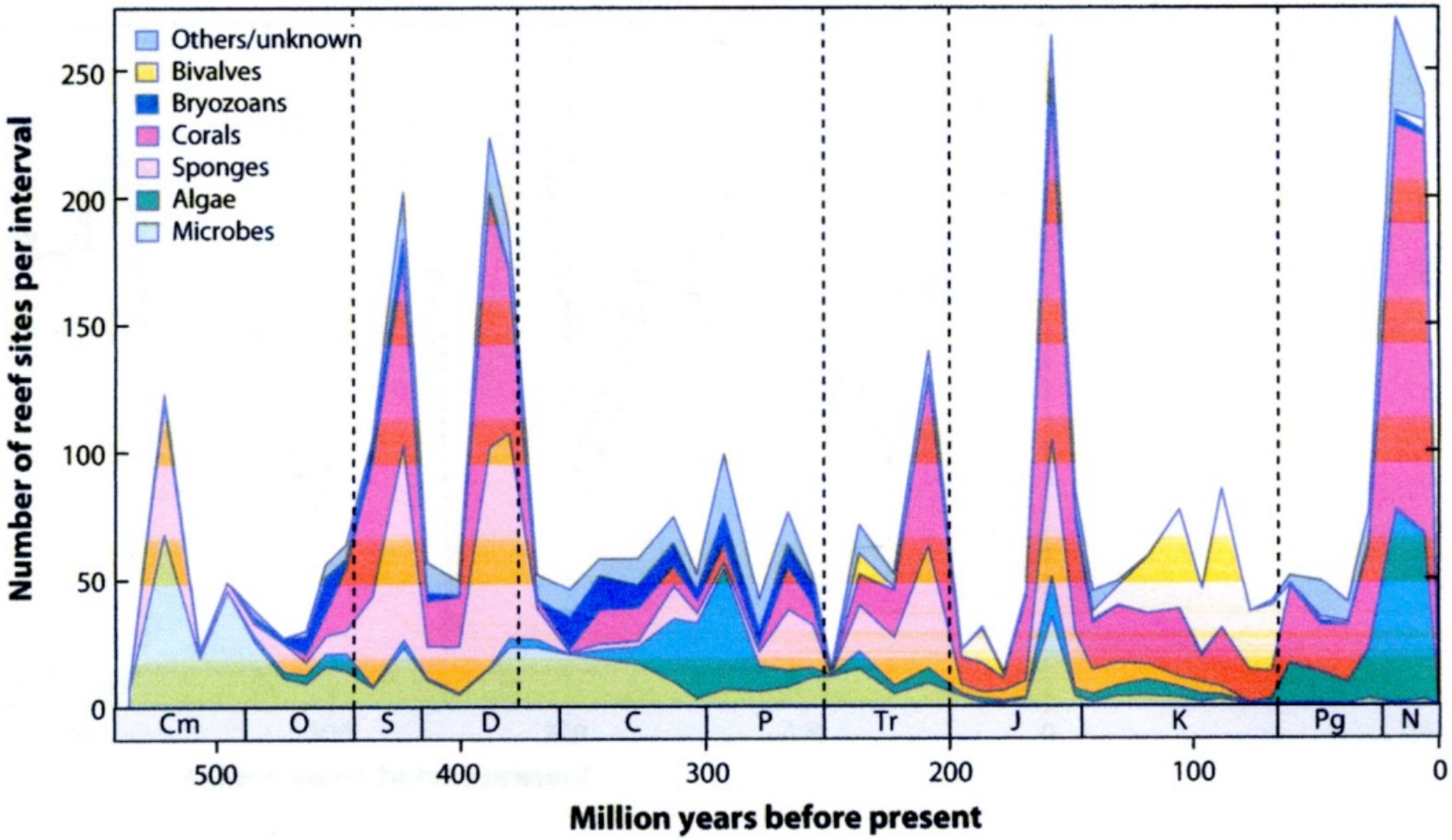


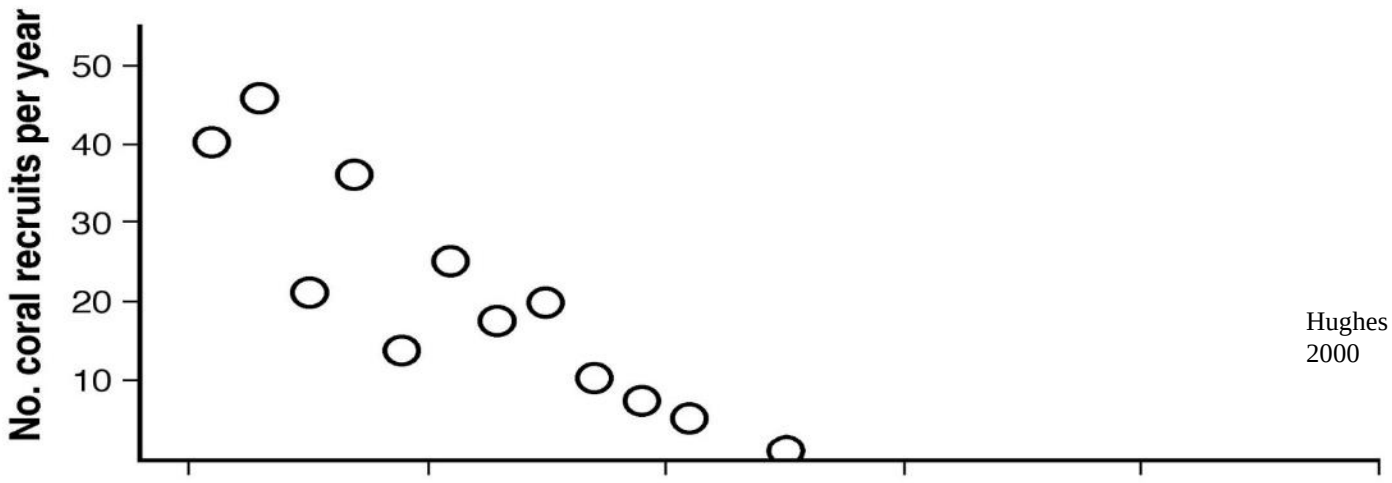
phaceloid

dendroid

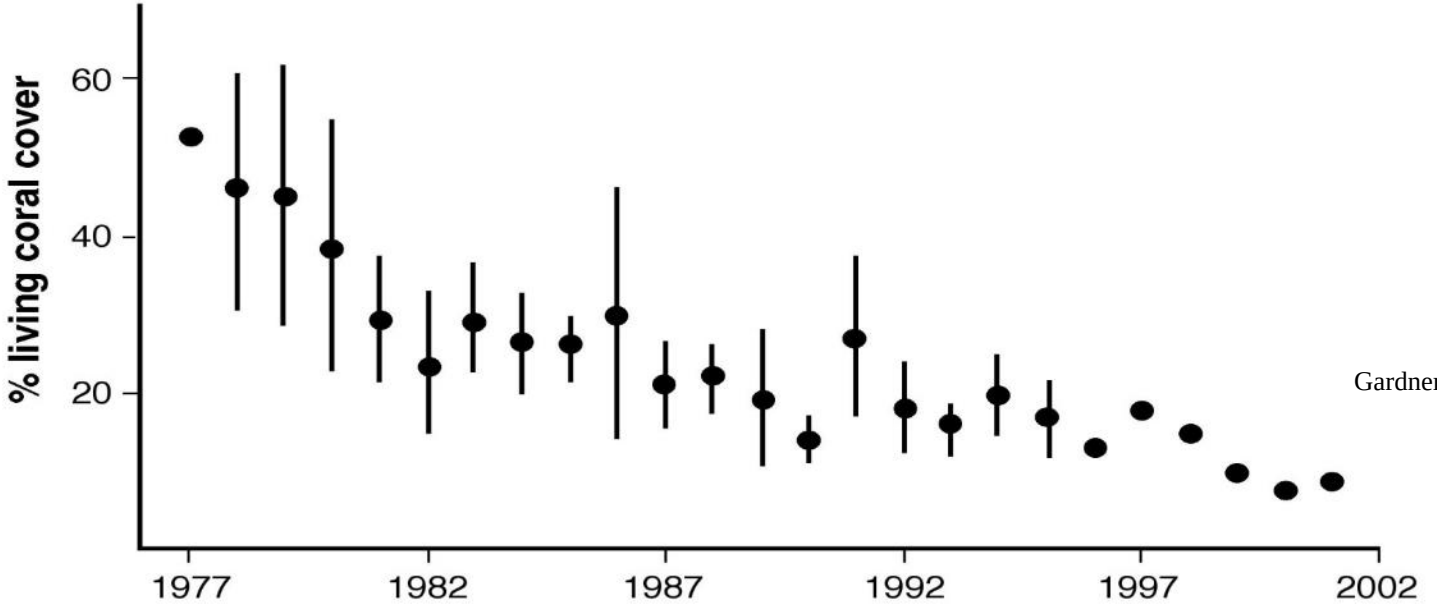
branching



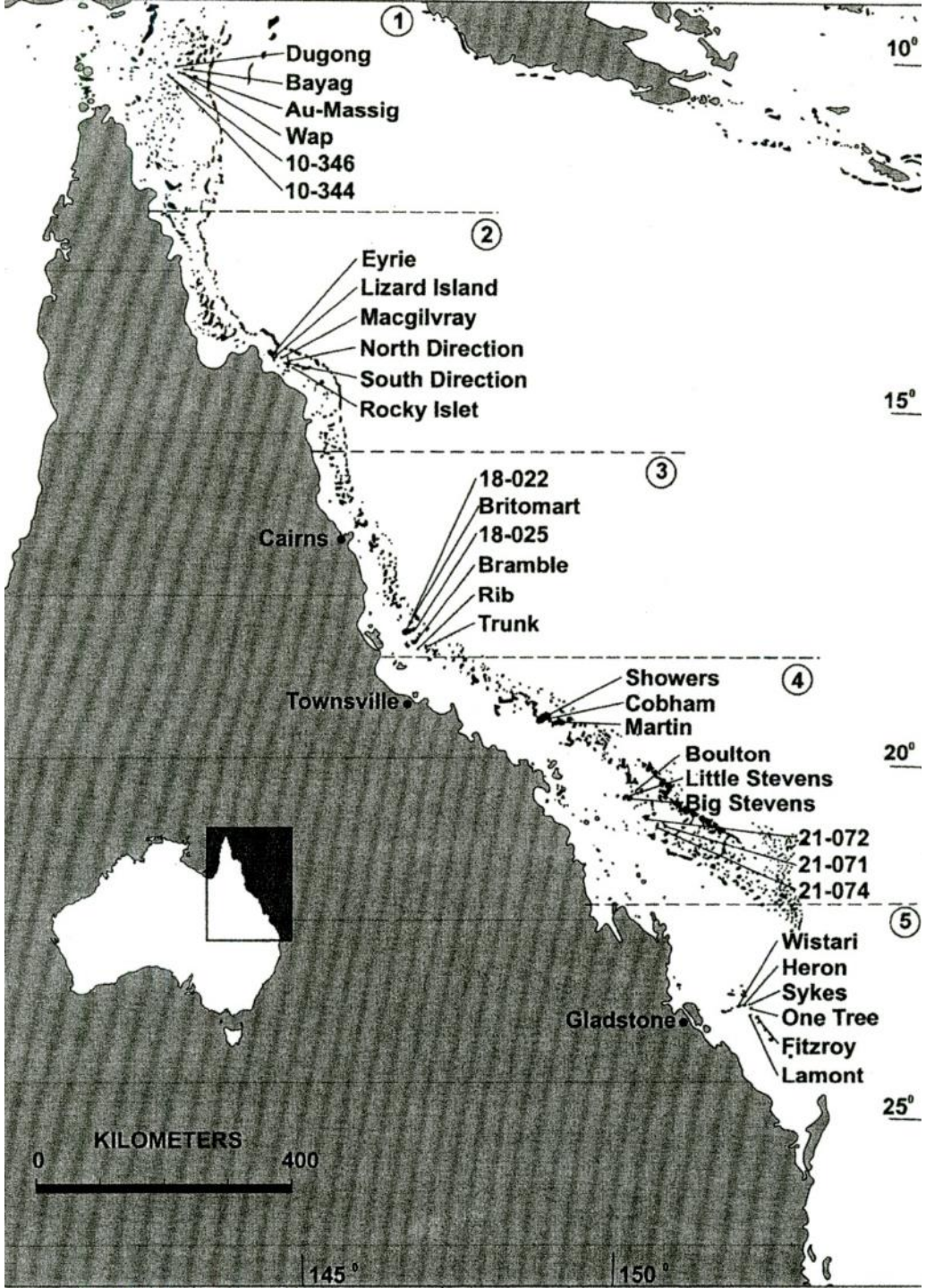

Others/unknown
Bivalves
Bryozoans
Corals
Sponges
Algae
Microbes
Number of reef sites per interval
0
50
100
150
200
250
Cm
O
S
D
C
P
Tr
J
K
Pg
N
500
400
300
200
100
0
Million years before present

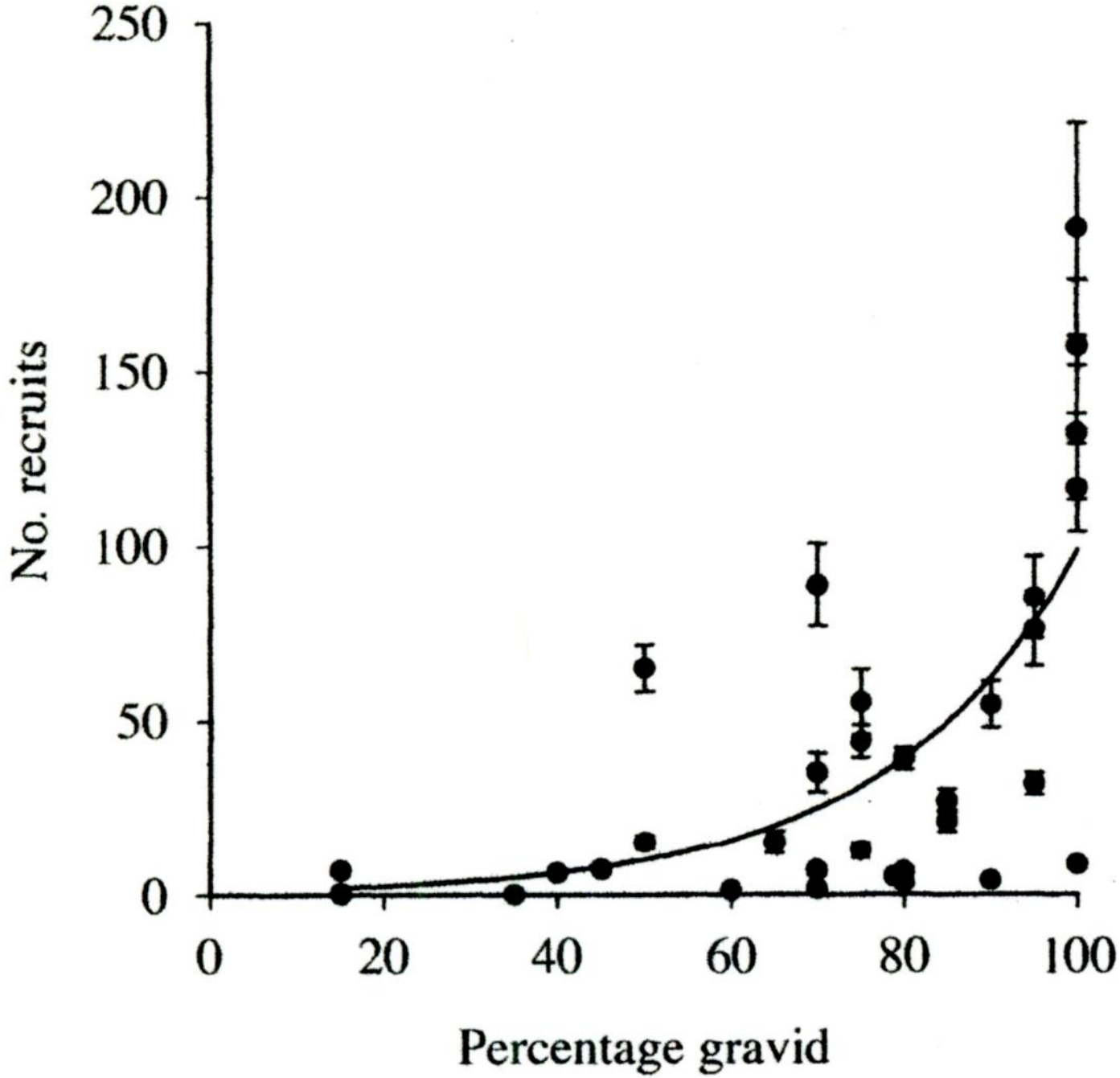


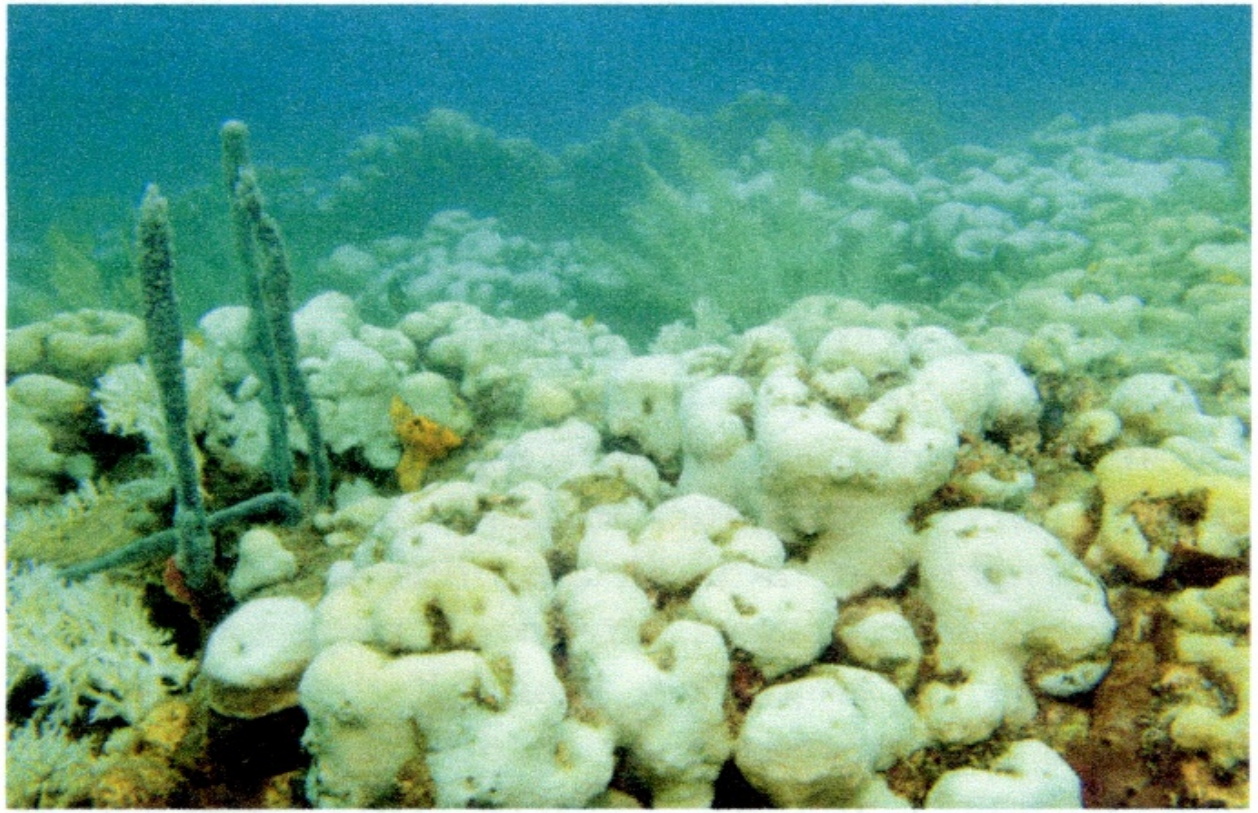
Hughes and Tanner 2000



Gardner et al. 2003


1
Dugong
Bayag
Au-Massig
Wap
10-346
10-344
10°
2
Eyrie
Lizard Island
Macgilvray
North Direction
South Direction
Rocky Islet
15°
3
18-022
Britomart
18-025
Bramble
Rib
Trunk
Cairns
4
Showers
Cobham
Martin
Townsville
Boulton
Little Stevens
Big Stevens
20°
21-072
21-071
21-074
5
Wistari
Heron
Sykes
One Tree
Fitzroy
Lamont
Gladstone
25°
KILOMETERS
0
400
145°
150°


250
200
150
100
50
0
No. recruits
0
20
40
60
80
100
Percentage gravid



A severe coral bleaching event reduced the likelihood of spawning in both visibly bleached and unbleached corals for 4 years.

Photo: Raphael Ritson-Williams

Bleaching event reduced spawning in both visibly bleached and unbleached corals for 4 years (Levitan et al. 2014)

Tissue damage can suspend gamete production for several years (Lirman 2000)

Bleaching in one season can prevent completion of a gametogenic cycle the following year (Szmant and Gassman 1990)

Repair of damaged tissue in *Goniastrea* costs energy otherwise allocated for gamete production (Kojis and Quinn 1985)

Coral spat vulnerable:

Juvenile corals have immature immune systems **(Frank et al. 1997)**

Lack adequately developed protective microbial association **(Apprill et al. 2009)**

Especially susceptible to harmful microbes **(Vermeij et al. 2009)**

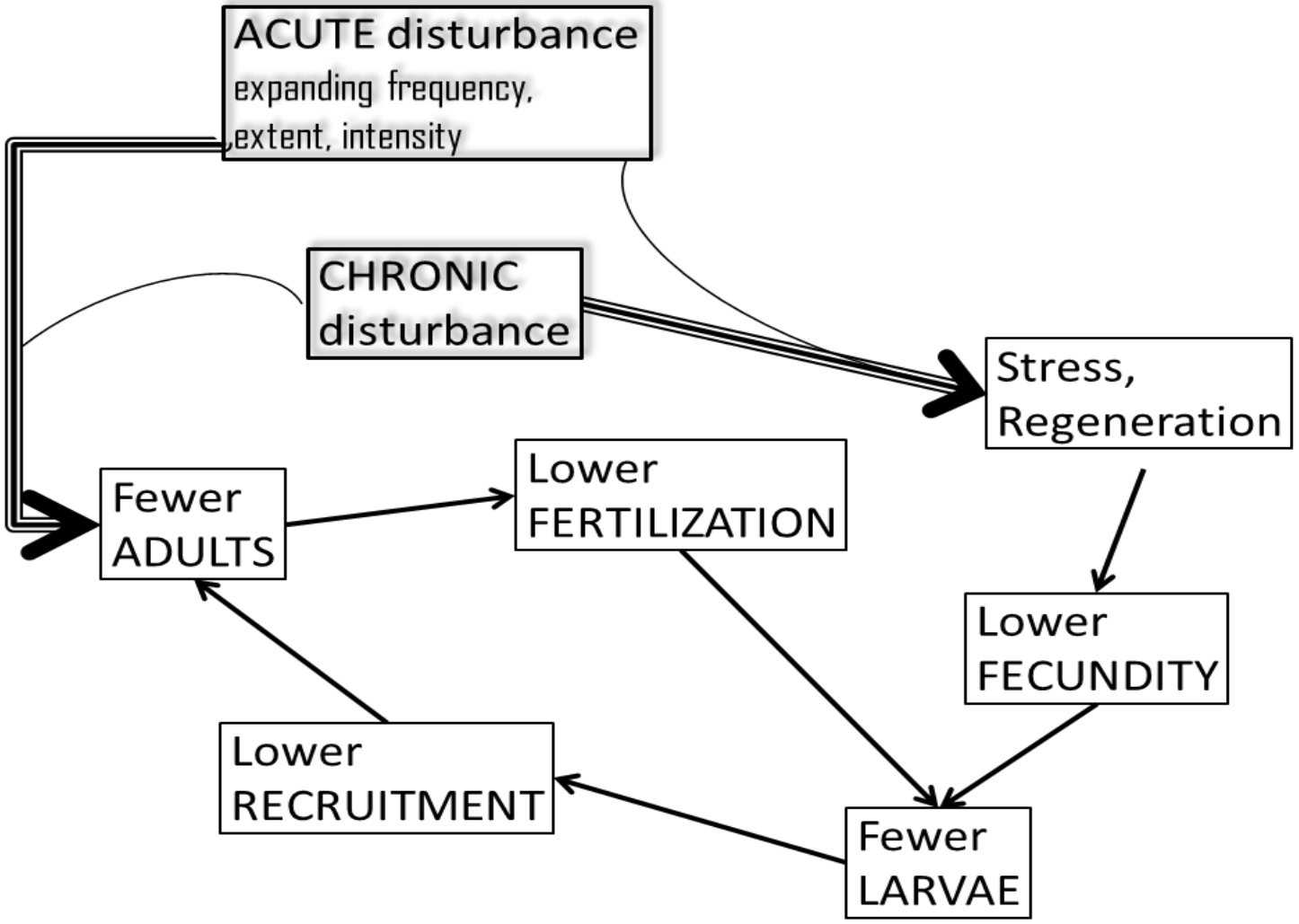
Low pH affects coral recruits during first CaCO3 deposition **(Albright et al. 2008)**

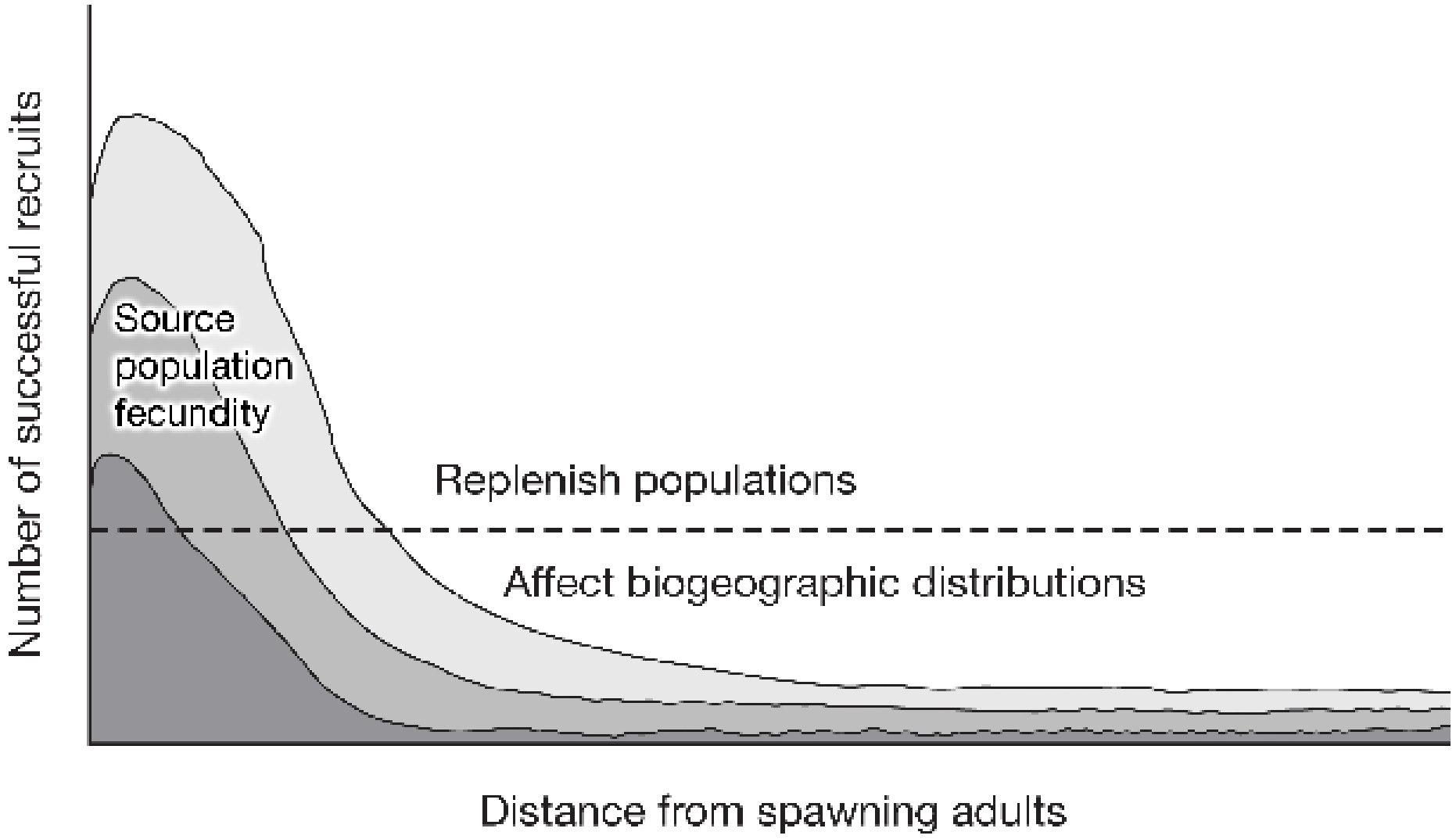
Coral recruits affected by lower availability of carbonate ions **(Kleypas et al. 1999a,b)**

Macroalgae and filamentous turfs preempt available space, trap sediment, intercept light, physically abrade the small coral recruit, transmit coral diseases and allelopathic chemicals, increase the growth of microbes on the surface mucus of corals

Fecundity decreases with

- **Physiological stress**
- **Tissue damage**
- **Disease**
- **Population turnover:**
  - **Fewer**
  - **Smaller**
  - **Younger colonies (of the same colony size as older, Kojis and Quinn 1985)**


ACUTE disturbance
expanding frequency,
extent, intensity
CHRONIC
disturbance
Stress,
Regeneration
Fewer
ADULTS
Lower
FERTILIZATION
Lower
FECUNDITY
Lower
RECRUITMENT
Fewer
LARVAE

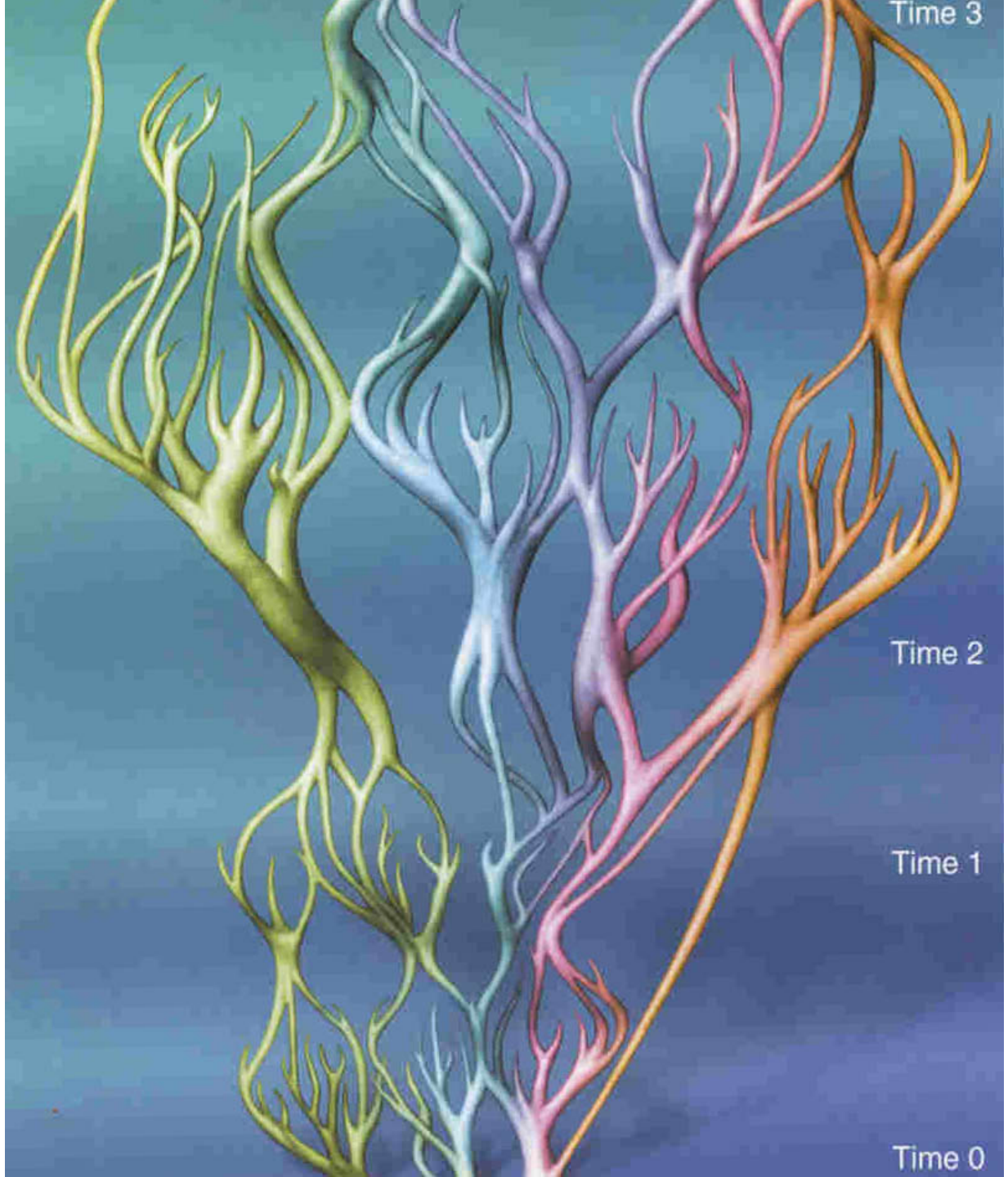

Number of successful recruits
Source population fecundity
Replenish populations
Affect biogeographic distributions
Distance from spawning adults

Pearls and Hermes Reef, NWHI

1928-29	150,000 pearl oysters taken
Surveys	1930 ~ 1994 ~ 2000 ~ 2003

LOSS of CONNECTIVITY:

- Fecundity reduced
- Appropriate habitats reduced and more patchily distributed
- Water quality barriers (Puritz and Toonen 2011)
- Faster larval development in warmer waters


Time 3
Time 2
Time 1
Time 0

"We define resilience as the ability of reefs to **absorb** recurrent disturbances...**<u>and</u> rebuild** coral-dominated systems."

Hughes et al. 2007

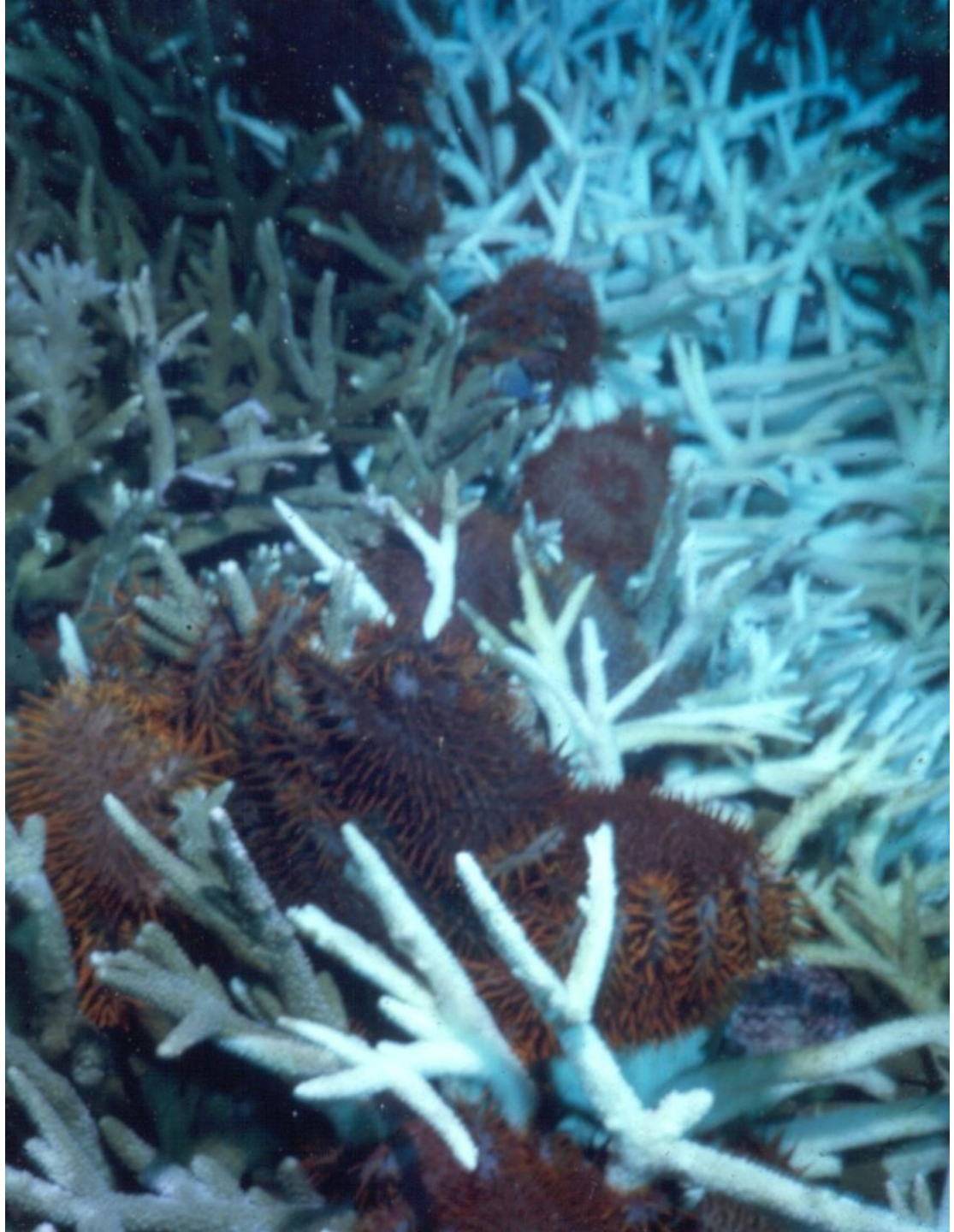
Absorb	--	acclimate	Rebuild	--	reproduce
		adapt			successfully recruit
		tolerate			heal, repair

most massive or encrusting corals

survival > reproduction

Acropora (and other branching corals)

fast growth > survival



Corallivores

Invertebrates	**314 spp.**	**24 families**	**(Stella et al. 2011)**
Fishes	**128 spp.**	**11 families**	**(Cole et al. 2008)**

Corals preyed upon	**28 genera**
Never preyed upon	**83 genera**

OPEN ACCESS Freely available online

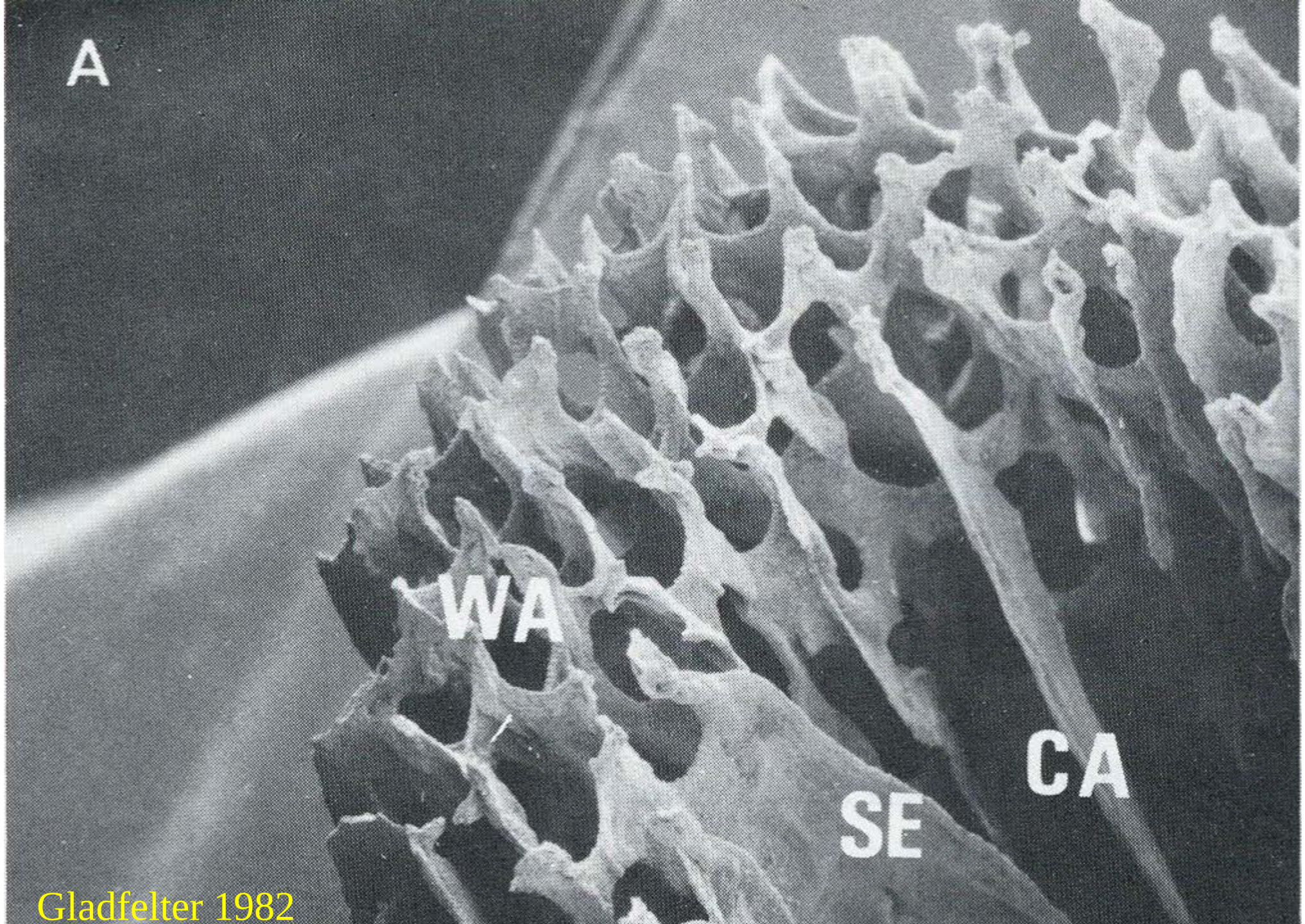
PLOS | ONE

Fast Growth May Impair Regeneration Capacity in the Branching Coral *Acropora muricata*

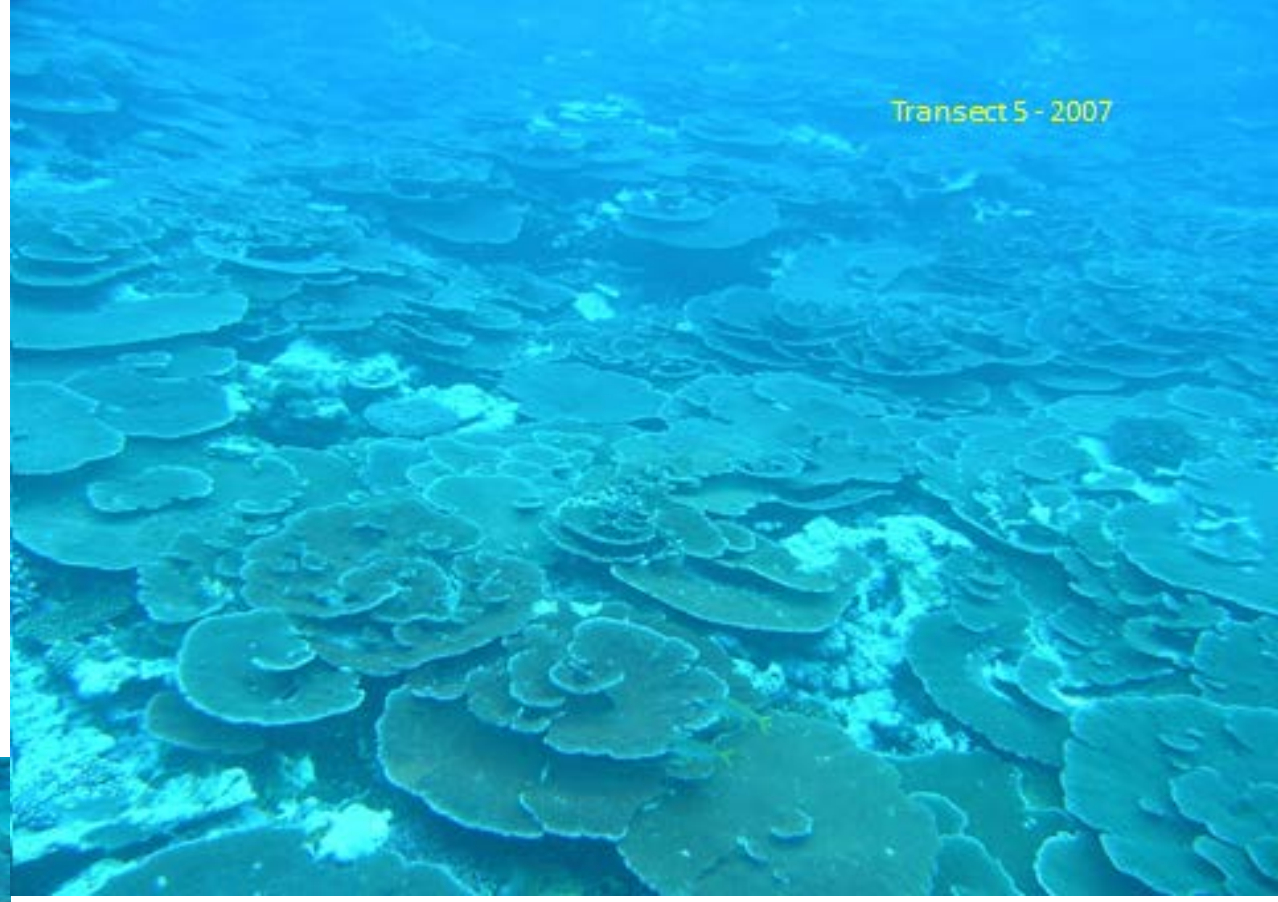
Vianney Denis[1,2*¤a], Mireille M. M. Guillaume[2,1,3], Madeleine Goutx[4,5], Stéphane de Palmas[1¤a], Julien Debreuil[1¤b], Andrew C. Baker[6], Roxane K. Boonstra[6], J. Henrich Bruggemann[1,3]

Table 2 Species susceptibilities to bleaching. Data are the percent of colonies in each of four bleaching categories (moderate 1–50% of colony bleached or entire colony pale but severe >50% of colony bleached) for all taxa for which more than ten colonies were recorded on survey transects. Categories of susceptibility were defined as: severe >15% dead; high >50% severely bleached or dead; moderate >50% of colonies affected by bleaching; low <50% of colonies affected and <1% dead

Taxa	Family	*n*	Unbleached (%)	Moderate (%)	Severe (%)	Dead (%)	Susceptibility
Millepora sp	Milleporidae	34	0	6	9	85	Severe
Isopora	Acroporidae	13	8	8	46	38	Severe
Tabular *Acropora*	Acroporidae	66	36	8	20	36	Severe
Pocillopora damicornis	Pocilloporidae	44	9	2	59	30	Severe
Stylophora pistillata	Pocilloporidae	18	0	6	67	28	Severe
Arborescent *Acropora*	Acroporidae	186	31	5	38	26	Severe
Seriatopora hystrix	Pocilloporidae	11	9	0	73	18	severe
Pachyseris	Agariciidae	34	18	15	62	6	High
Monitipora – plates	Acroporidae	819	46	5	45	5	High
Pectinia	Pectiniidae	59	36	12	49	3	High
Monipora – branching	Acroporidae	50	46	1	50	3	High
Sinularia	Alcyonacae	240	28	9	62	1	High
Merulina	Merulinidae	30	23	23	53	0	High
Lobophytum	Alcyonacae	27	41	7	52	0	High
Acanthastrea	Mussidae	18	22	28	50	0	High
Platygyra	Faviidae	52	25	27	48	0	Moderate
Hydnophora	Merulinidae	16	38	19	44	0	Moderate
Sarcophyton	Alcyonacae	112	38	18	43	1	Moderate
Montastrea	Faviidae	21	48	10	43	0	moderate
Oxypora	Pectiniidae	32	41	16	41	3	Moderate
Favites	Faviidae	222	44	20	35	1	Moderate
Favia	Faviidae	373	40	25	35	1	Moderate
Echinopora	Faviidae	41	39	27	32	2	Moderate
Goniastrea	Faviidae	104	38	30	30	1	Moderate
Porites – massive	Poritidae	225	36	32	30	1	Moderate
Lobophyllia	Mussidae	66	47	24	27	2	Moderate
Leptoria	Faviidae	15	47	27	27	0	Moderate
Fungiidae	Fungiidae	29	52	14	34	0	Low
Echinophyllia	Agariciidae	20	55	20	25	0	Low
Leptastrea	Faviidae	19	68	26	5	0	Low
Psammocora	Siderastreidae	10	70	30	0	0	Low
Symphyllia	Mussidae	37	78	19	3	0	Low
Galaxea	Oculinidae	144	87	10	3	1	Low
Goniopora	Poritidae	72	92	3	6	0	Low
Cyphastrea	Faviidae	154	96	4	0	0	Low
Turbinaria	Dendrophylliidae	300	97	3	0	0	Low
Caespitose *Acropora*	Acroporidae	85	61	7	22	9	Mixed
Corymbose *Acropora*	Acroporidae	307	65	8	14	13	Mixed
Pavona	Agariciidae	22	45	32	18	5	Mixed
Mycedium	Pectiniidae	12	42	33	17	8	Mixed



Gladfelter 1982


Transect 5 - 2007

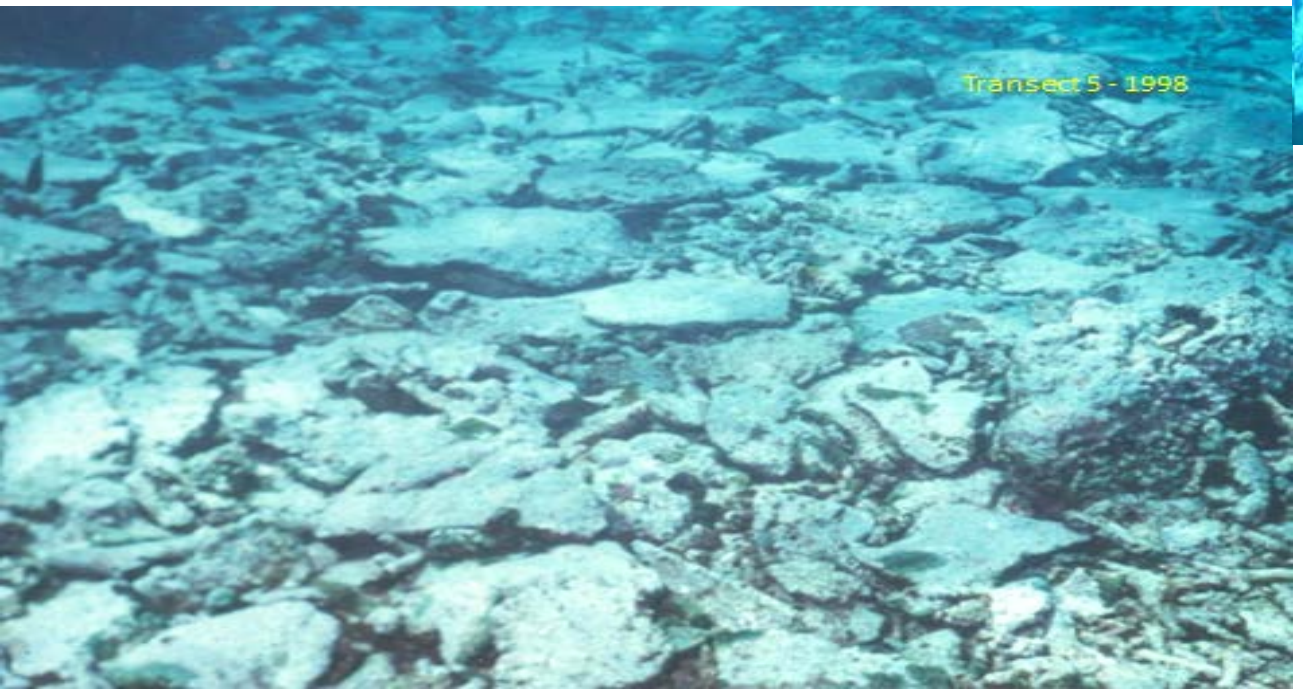

Transect 5 - 1998

Table 1 Longevity and median lifetime estimates for each coral species

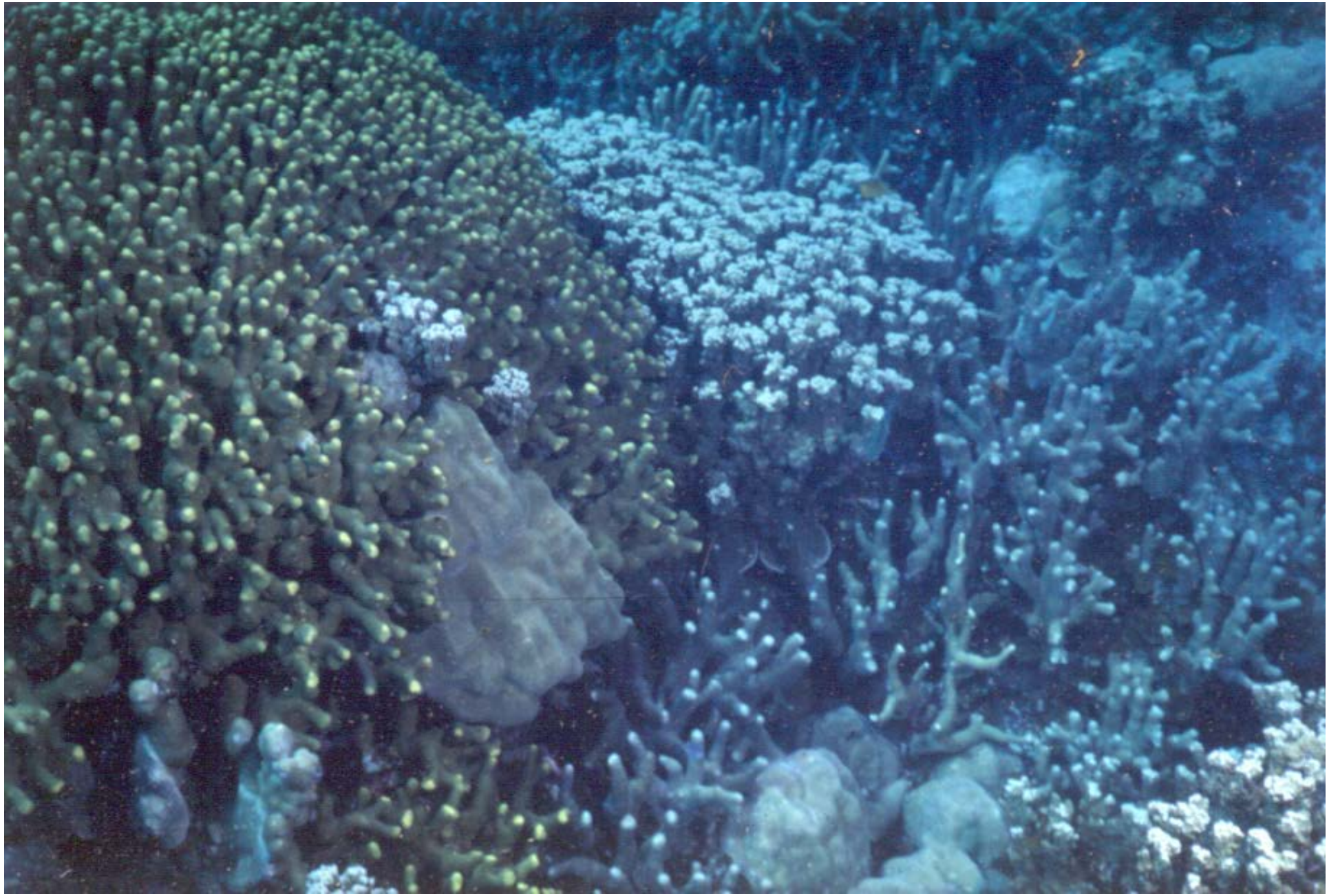
Species	Kaplan–Meier median estimates (d)			Maximum longevity (d)
	Replicates			
	Min	Max	Pooled	
Acropora latistella	4	32	4	209
Favia pallida	10	101	19	195
Pectinia paeonia	3	75	53	209
Goniastrea aspera	124	152	138	215
Montastraea magnistellata	101	138	124	244

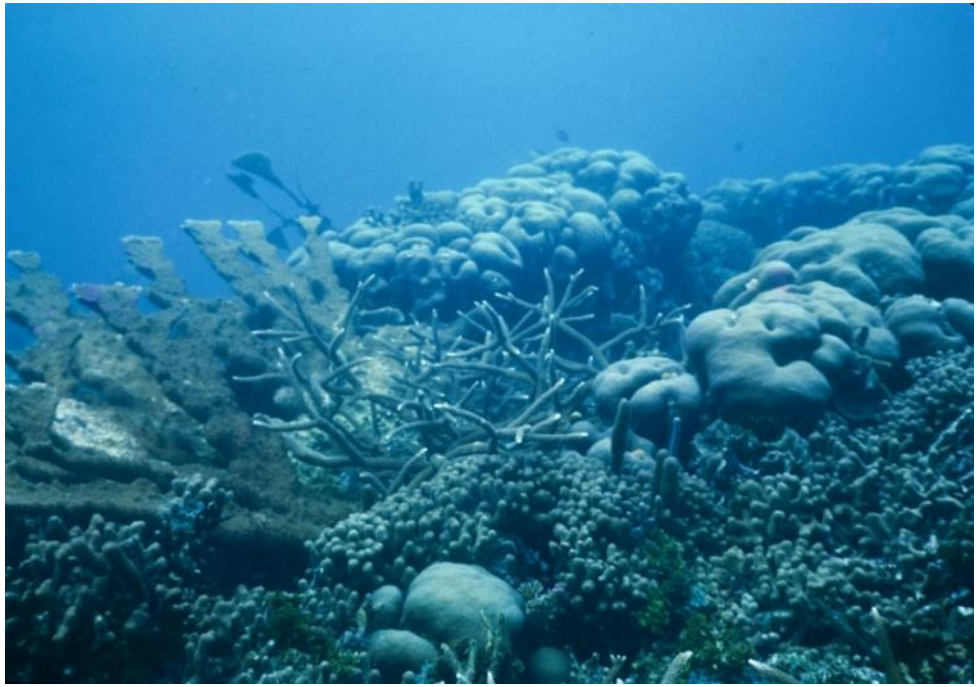
Min and *Max* refer to the shortest and longest median survival times for the replicates analyzed separately, and *Pooled* refers to the median survival time when data from all replicates were pooled before analysis

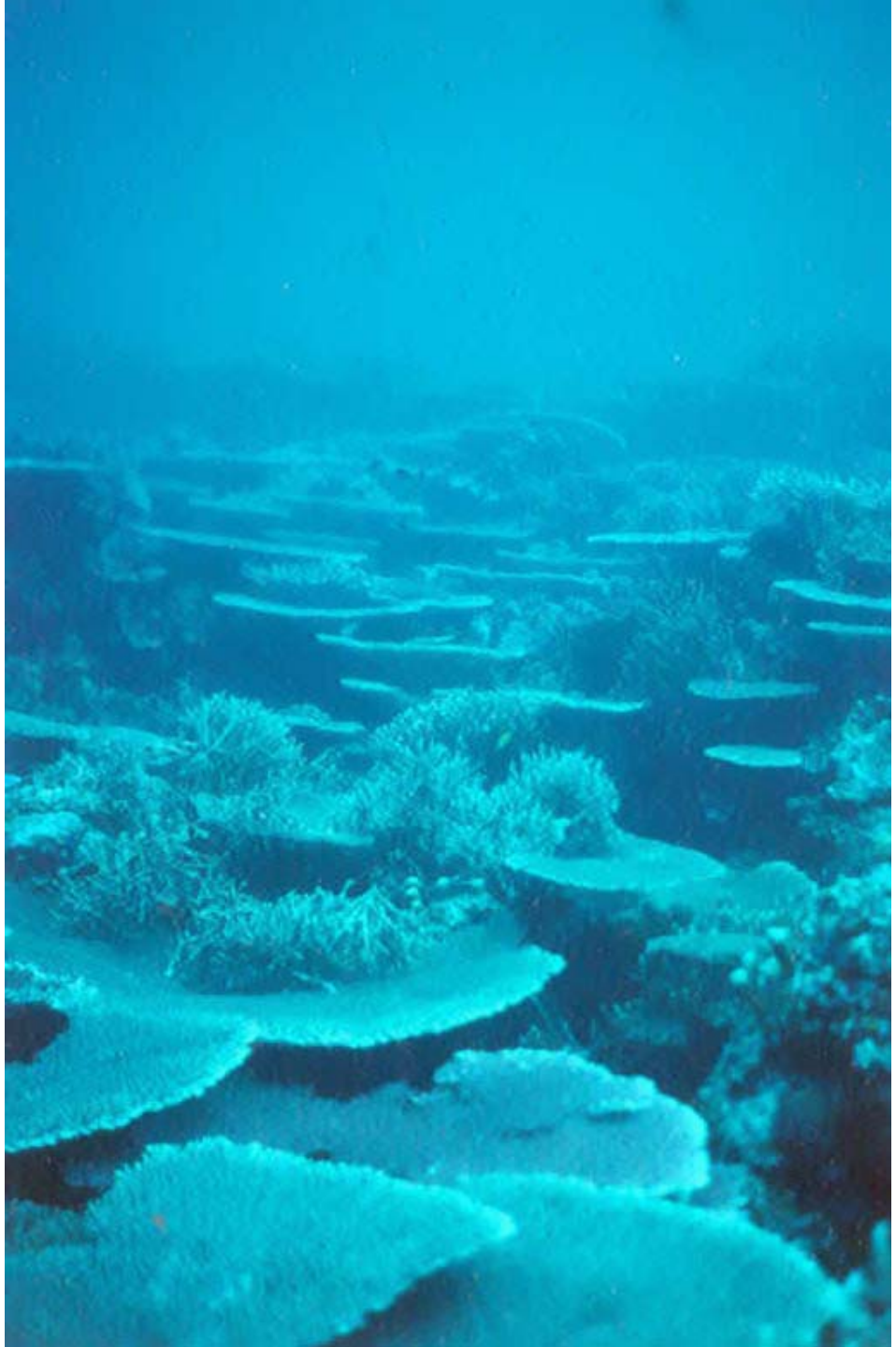
Coral species	Growth form	Tissue thickness (mm)
Winning species		
Porites lutea	Massive	2.6 ± 0.009
Goniastrea aspera	Massive	3.6 ± 0.006
Platygyra ryukyuensis	Massive	4.0 ± 0.096
Porites rus	Massive	1.9 ± 0.300
Favites chinensis	Massive	9.4 ± 0.174
Goniastrea retiformis	Massive	2.8 ± 0.196
Favia pallida	Massive	3.1 ± 0.011
Mean		3.9 ± 0.110
Losing species		
Porites cylindrica	Branched	1.3 ± 0.180
Pocillopora damicornis	Branched	0.9 ± 0.043
Porites sillimaniani	Branched	1.3 ± 0.135
Stylophora pistillata	Branched	1.5 ± 0.279
Pocillopora verrucosa	Branched	0.4 ± 0.006
Montipora digitata	Branched	0.9 ± 0.006
Acropora gemmifera	Branched	1.9 ± 0.018
Acropora digitifera	Branched	1.9 ± 0.105
Acropora aspera	Branched	1.0 ± 0.329
Mean		1.2 ± 0.120

Coral species	% nitrogen (± se)	% carbon (± se)
Acropora cervicornis	1.81 (0.32)	11.74 (1.92)
Acropora palmata	1.55 (0.24)	11.83 (1.81)
Millepora complanata	1.50 (0.21)	9.54 (1.26)
**********		
Montastraea cavernosa	4.65 (0.26)	25.92 (0.91)
Montastraea annularis	2.82 (0.36)	21.53 (0.47)
Montastraea faveolata	2.96 (0.43)	19.01 (2.69)
Montastraea franksi	4.59 (0.21)	25.51 (1.01)
Meandrina meandrites	4.32	31.41
Colpophyllia natans	2.66 (0.42)	18.59 (0.99)
Diploria clivosa	4.50 (0.30)	27.59 (1.52)
Diploria labyrinthiformis	3.52 (0.80)	21.98 (3.81)
Diploria strigosa	3.98 (0.22)	24.25 (1.34)
Dichocoenia stokesii	3.30 (0.37)	23.47 (1.56)
Agaricia agaricites	3.21 (0.30)	22.58 (1.92)
Agaricia tenuifolia	4.23 (0.01)	24.05 (0.01)

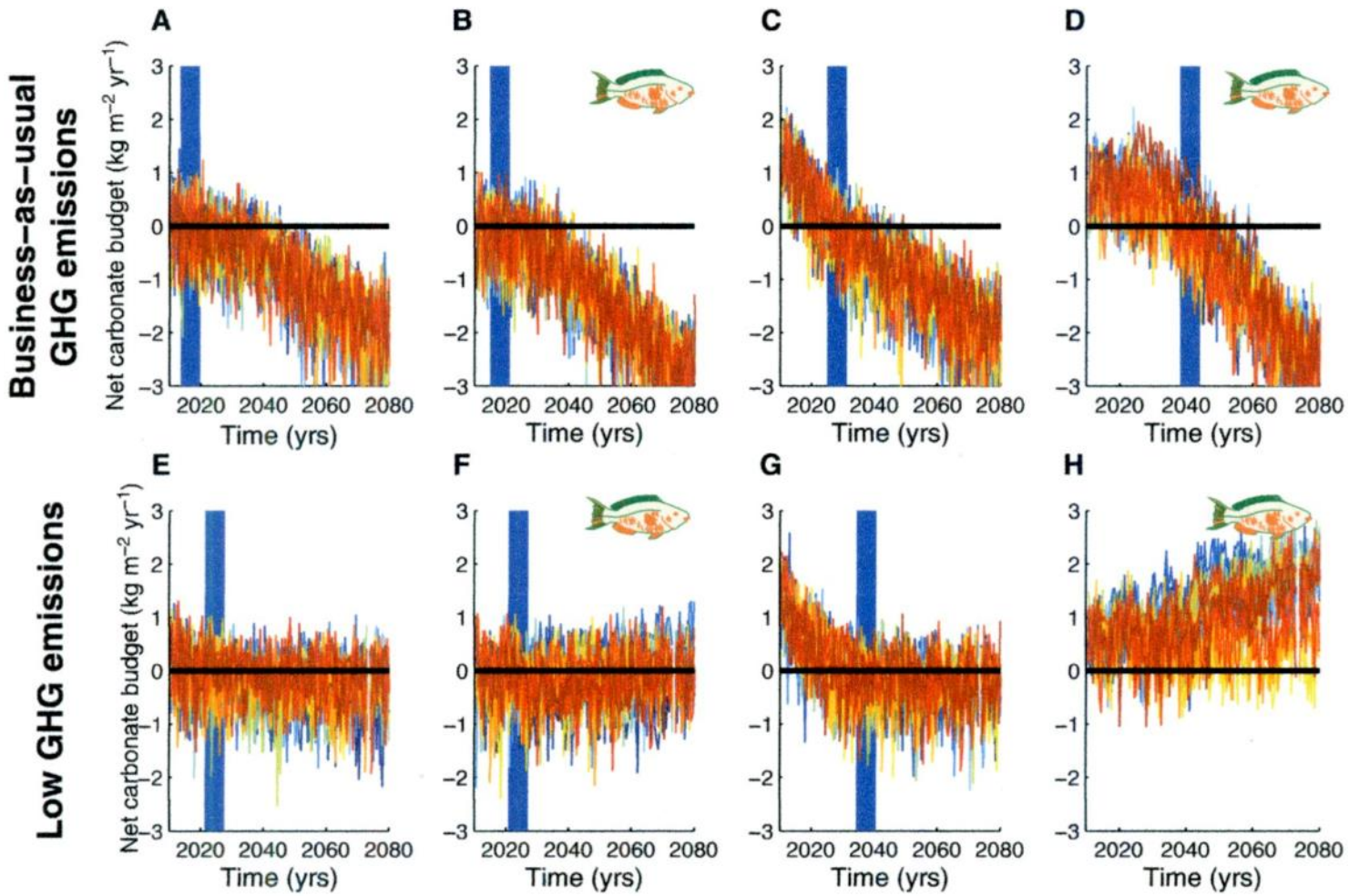
Randi Rotjan 2007

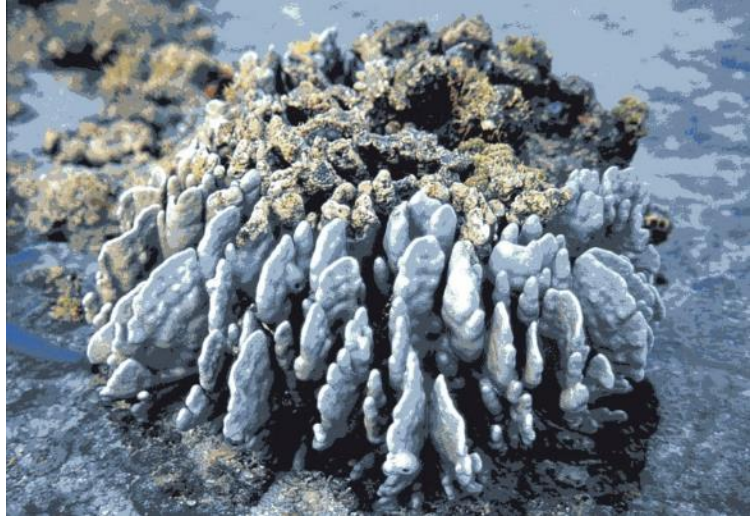


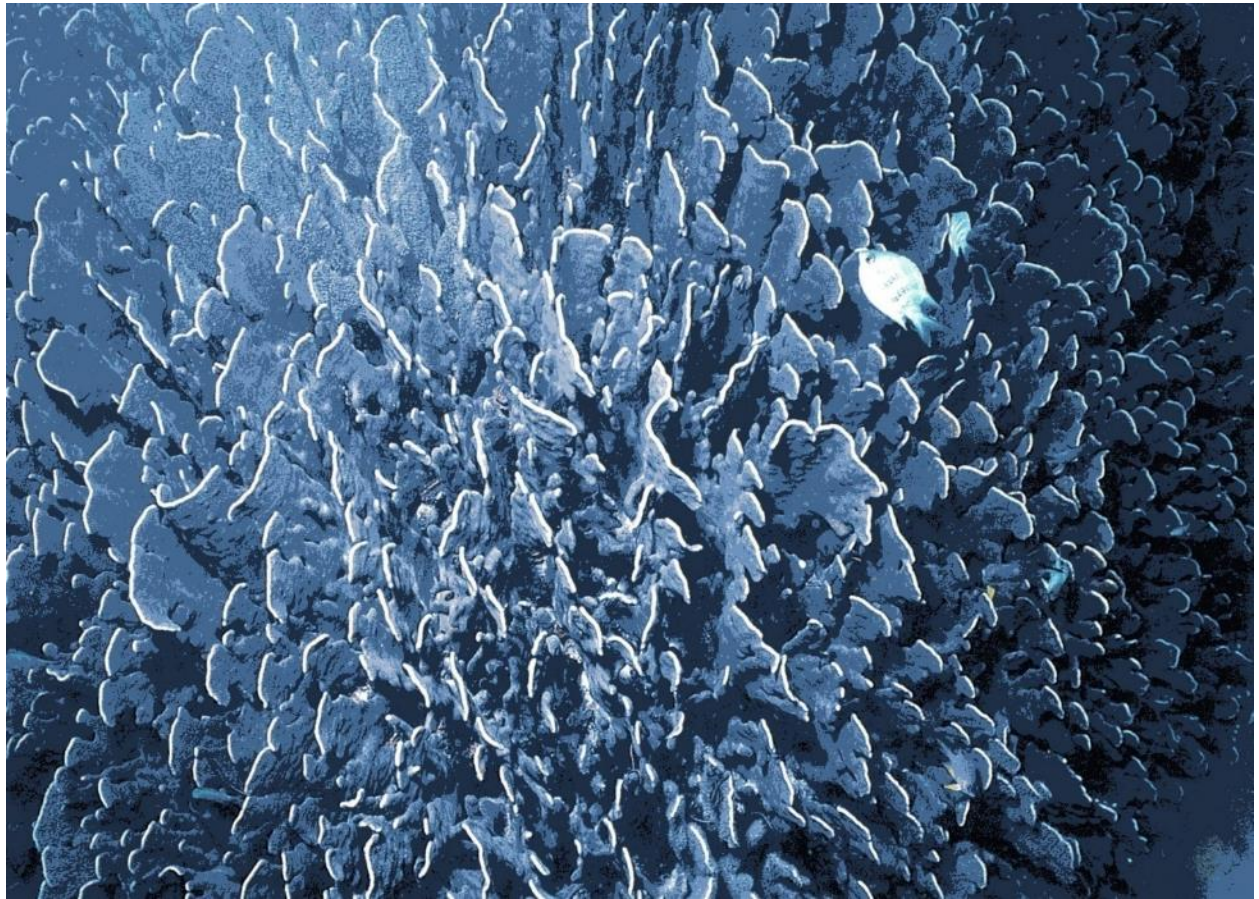




Tomascik et al. 1996 Coral Reefs 15: 169-175
1991 - 1996


Business-as-usual GHG emissions
Low GHG emissions
A
B
C
D
E
F
G
H
Net carbonate budget (kg m^{-2} yr^{-1})
3
2
1
0
−1
−2
−3
2020 2040 2060 2080
Time (yrs)





"With all due respect to those contributing effort and funding towards protecting coral reefs, the millions of dollars that are being spent will be of no avail unless there is a concentrated effort to obtain explicit progress in reducing CO_2 emissions"

Ove Hoegh-Guldberg