2. Lithostratigraphy

2.1 Type of lithostratigraphic unit

☆ **Lithostratigraphic units** (岩石地層單位) are bodies of sedimentary, extrusive igneous, metasedimentary, or metavolcanic rock distinguished on the basis of lithologic characteristics. Lithostratigraphic units are defined solely on lithic criteria and are independent of time concept.

☆ **Lithologic characteristics** – Distinctive lithic characteristics include chemical and mineralogical composition, texture, and such supplementary features as colour, primary sedimentary or volcanic structures, fossils (viewed as rock-forming particles), or other organic content (coal, oil-shale). A unit distinguishable only by the taxonomy of its fossils is not a lithostratigraphic but a biostratigraphic unit.

☆ **Hierarchy of lithostratigraphic units:**

Supergroup (超群)
Group (群)
Formation (層)
Member (段)/Lens (透鏡體) /Tongue (岩舌)
Bed (小層)/Flow (岩流層)

2.2 Stratigraphic contacts

Both vertical and lateral boundaries of lithostratigraphic units are placed at positions of lithic change. Boundaries are placed at distinct contacts or may be fixed arbitrarily within zones of gradation.

☆ **Contact between conformable strata**
◎ abrupt contacts (diastems: minor depositional breaks)
◎ gradational contacts

☆ **Contact between laterally adjacent lithosomes**
pinch-outs (尖滅)
intertonguing (犬牙交錯)
progressive lateral gradation (側向漸變)

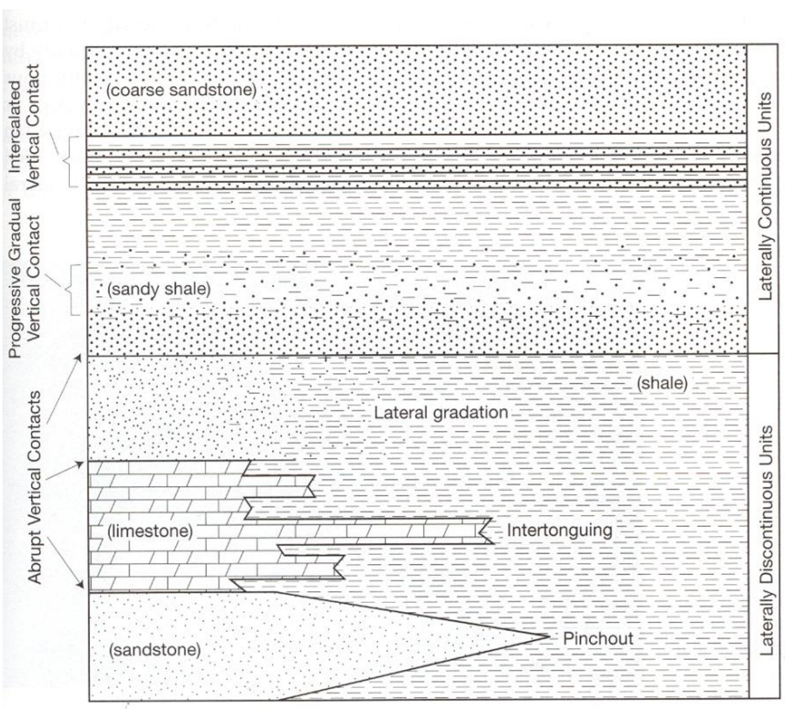
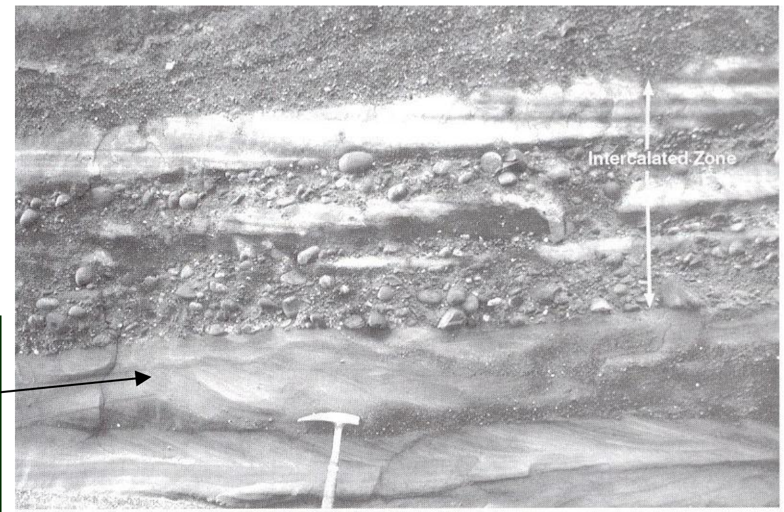


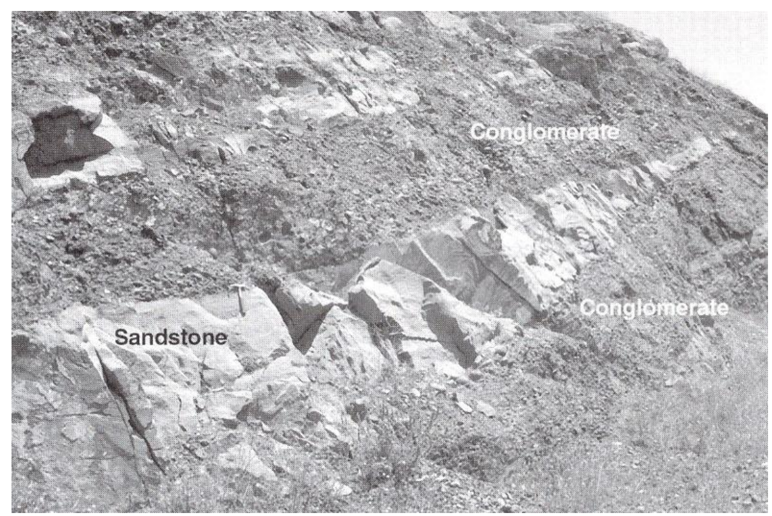
Figure 13.1 Schematic representation of the principal kinds of vertical and lateral contacts between lithologic units. Vertical contacts include abrupt, progressive gradual, and intercalated. Lithologic units may be laterally continuous or they may change laterally by pinchout, intertonguing, or lateral gradation.

Boggs, 2006, p.402

Abrupt contact (arrow) between massive-bedded sandstone below and find-grained conglomerate above.



Gradation from sandstone below through a zone of intercalated thin conglomerates and sandstones to conglomerate at the top of the section.



Pinchout. Note how the sandstone bed (light) pinches out abruptly to the right and disappears into the conglomerate.

Boggs, 2006, p.402-403

☆ Unconformable contacts

An unconformity is a surface of erosion or non-deposition, separating younger strata from older rocks, that represents a significant hiatus. A hiatus is a break or interruption in the continuity of the geological record. It represents periods of geologic time (short or long) for which there are no sediments or strata.

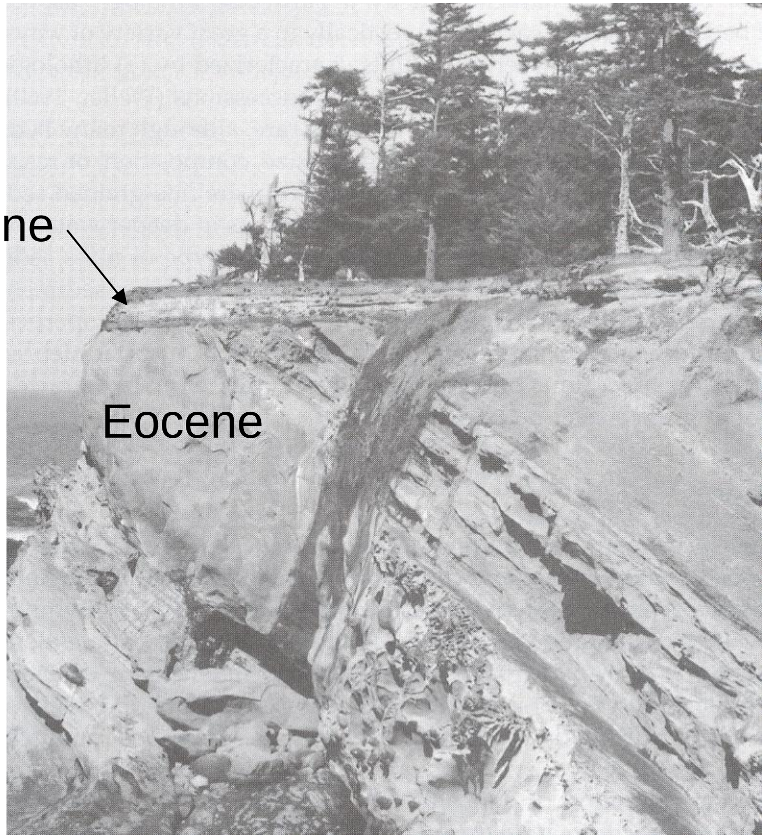
angular unconformity (交角不整合): An unconformity in which younger sediments rest upon the eroded surface of tilted or folded older rocks.

disconformity (假整合): An unconformity surface above and below which the bedding planes are essentially parallel and in which the contact between younger and older beds is marked by a visible, irregular or uneven erosional surface.

paraconformity (似整合): A paraconformity shows marked disparity in age of rocks above and below the unconformable surface but the beds above and below the unconformity contact are parallel and in which no erosional surface or other physical evidence of unconformity is discernible.

nonconformity (非整合): An unconformity developed between sedimentary rock and older metamorphic or igneous rocks that has been exposed to erosion prior to being covered by sediments.

Pleistocene



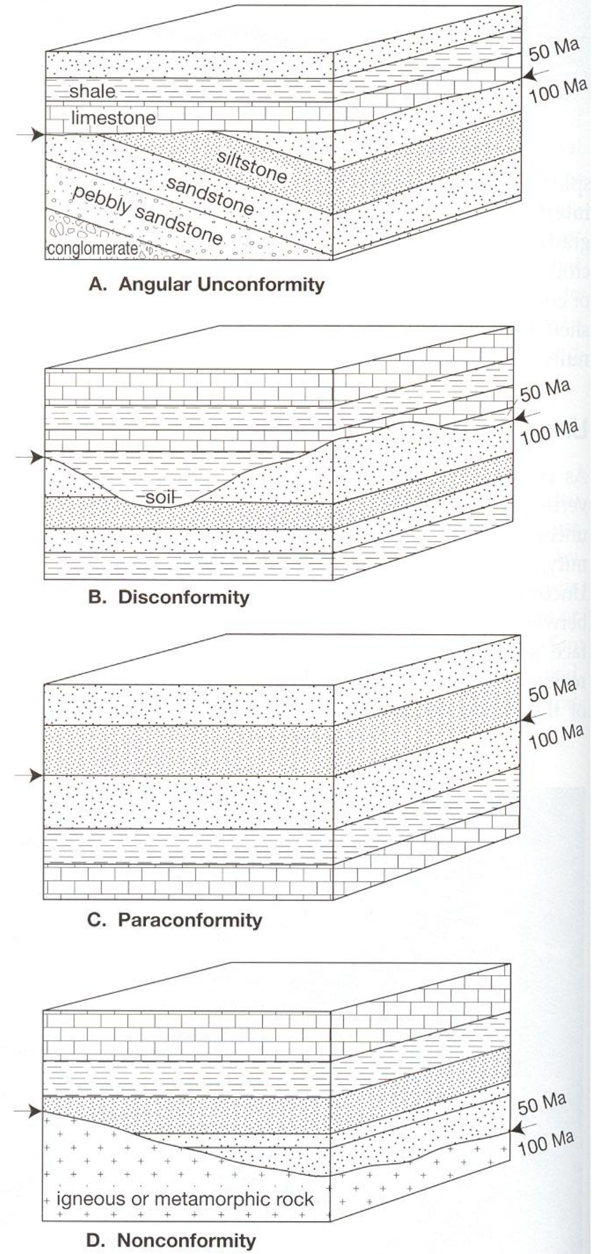
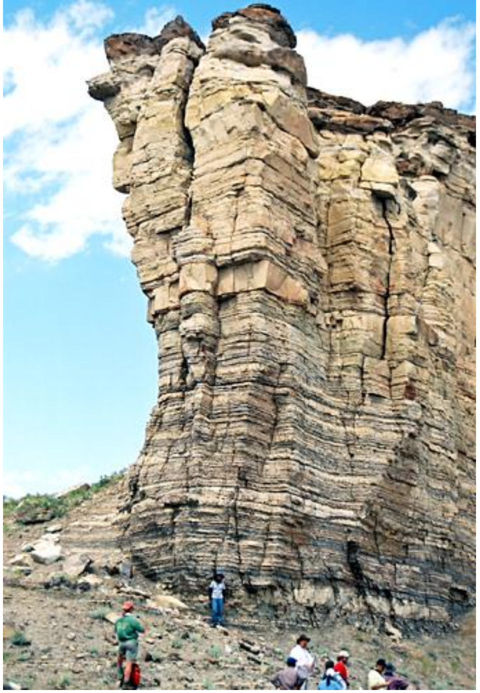


Figure 13.5
Schematic representation of four basic kinds of unconformities. Arrows indicate the unconformity surface. For the purpose of illustration, the youngest strata below the unconformity surface in each diagram is shown to have a (hypothetical) age of 100 million years and the oldest strata above the unconformity surface an age of 50 million years, indicating a hiatus in each case of 50 million years. [Modified from Dunbar, C. O. and J. Rodgers, 1957, Principles of stratigraphy: John Wiley & Sons, New York, Fig. 57, p. 117, reprinted by permission.]

Boggs, 2006, p.404

2.2 Vertical and lateral successions of strata



upward coarsening 'tide-influenced' delta (Late Cretaceous) of Frewens sandstone, Frontier Formation, central Wyoming, U.S.A. http://www.sepm.org/

Boggs, 2006, p.408

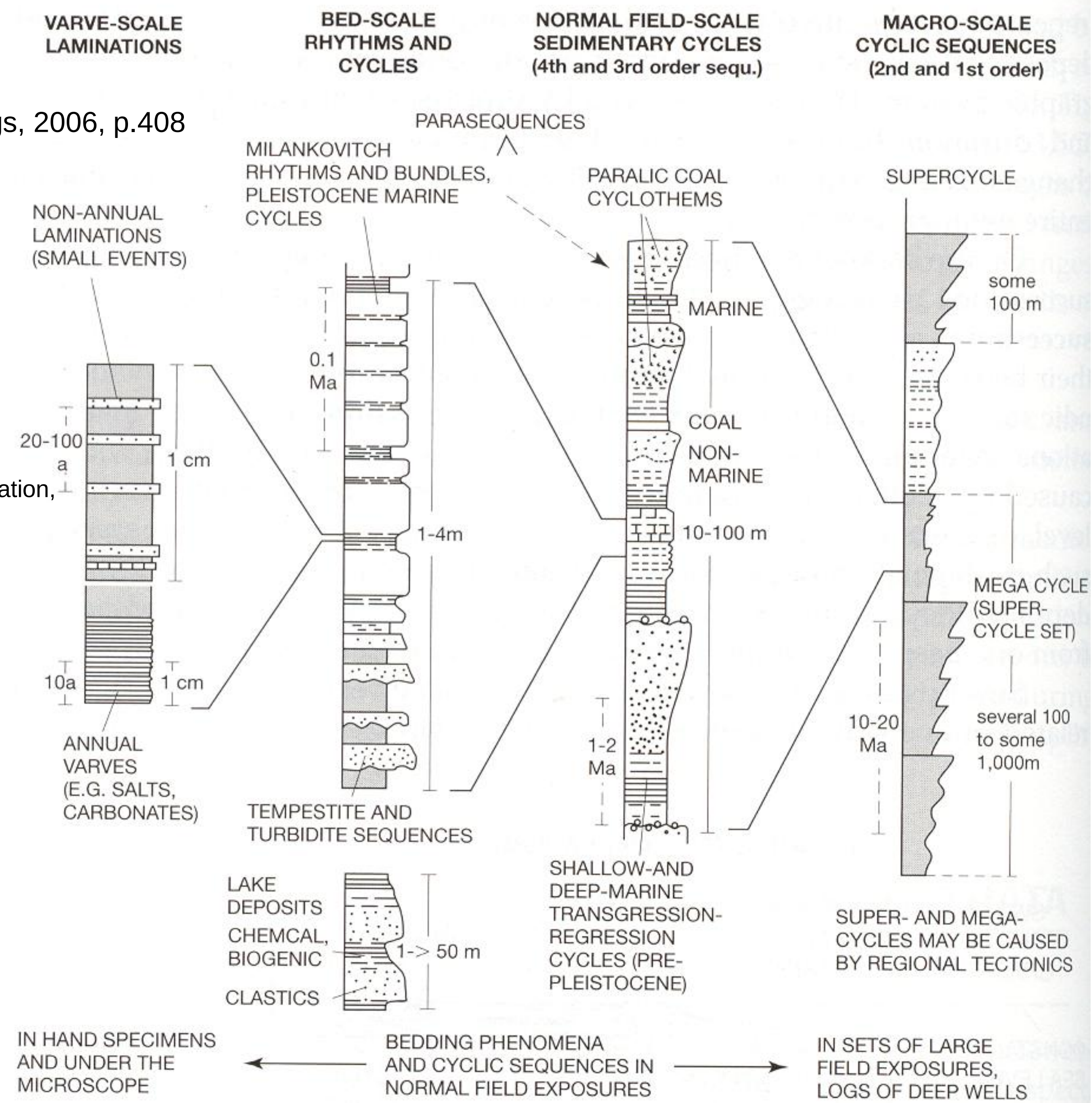


Figure 13.8
Schematic representation of the scale of cyclic sedimentation in the stratigraphic record. Ma = million years, a = years; parasequences are discussed in Chapter 14. [After Einsele, G., W. Ricken, and A. Seilacher, 1991, Cycles and events in stratigraphy—basic concepts and terms, in Einsele, G., W. Ricken, and A. Seilacher (eds.), Cycles and events in stratigraphy, Springer-Verlag, Berlin, Fig. 2, p. 3, reproduced by permission.]

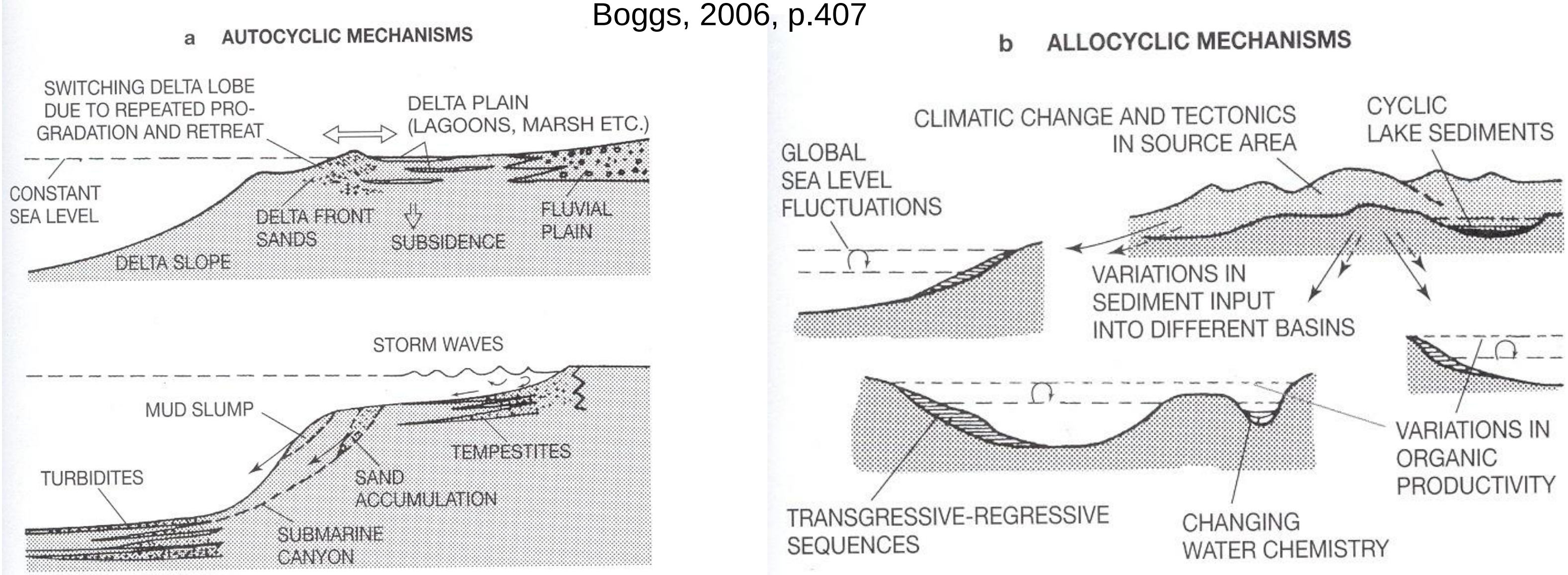
☆ Cyclic successions

Cyclic successions are repetitions of strata that reflect a succession of related depositional processes and conditions that are repeated in the same order. On the basis of the mechanisms that form cyclic deposits, two kinds of cyclic successions are recognized:

◎ Autocyclic successions: These successions are controlled by processes that take place within the basin itself, and their beds show only limited stratigraphic continuity. For examples, storm beds, turbidites, successions caused by delta-lobe switching etc.

◎ Allocyclic successions: These successions are caused by variations external to the depositional basin. Fundamentally, these variations are caused by changes in climate and tectonic movements. Postulated orders and causes of allocyclic successions:

Boggs, 2006, p.407



First-order cycles: Two first-order cycles lasting 200-400 m.y. are recognized in the Phanerozoic, and are widely interpreted to be related to the accretion (causing a fall of sea level) and subsequent splitting apart (causing a rise of sea level) of supercontinents.

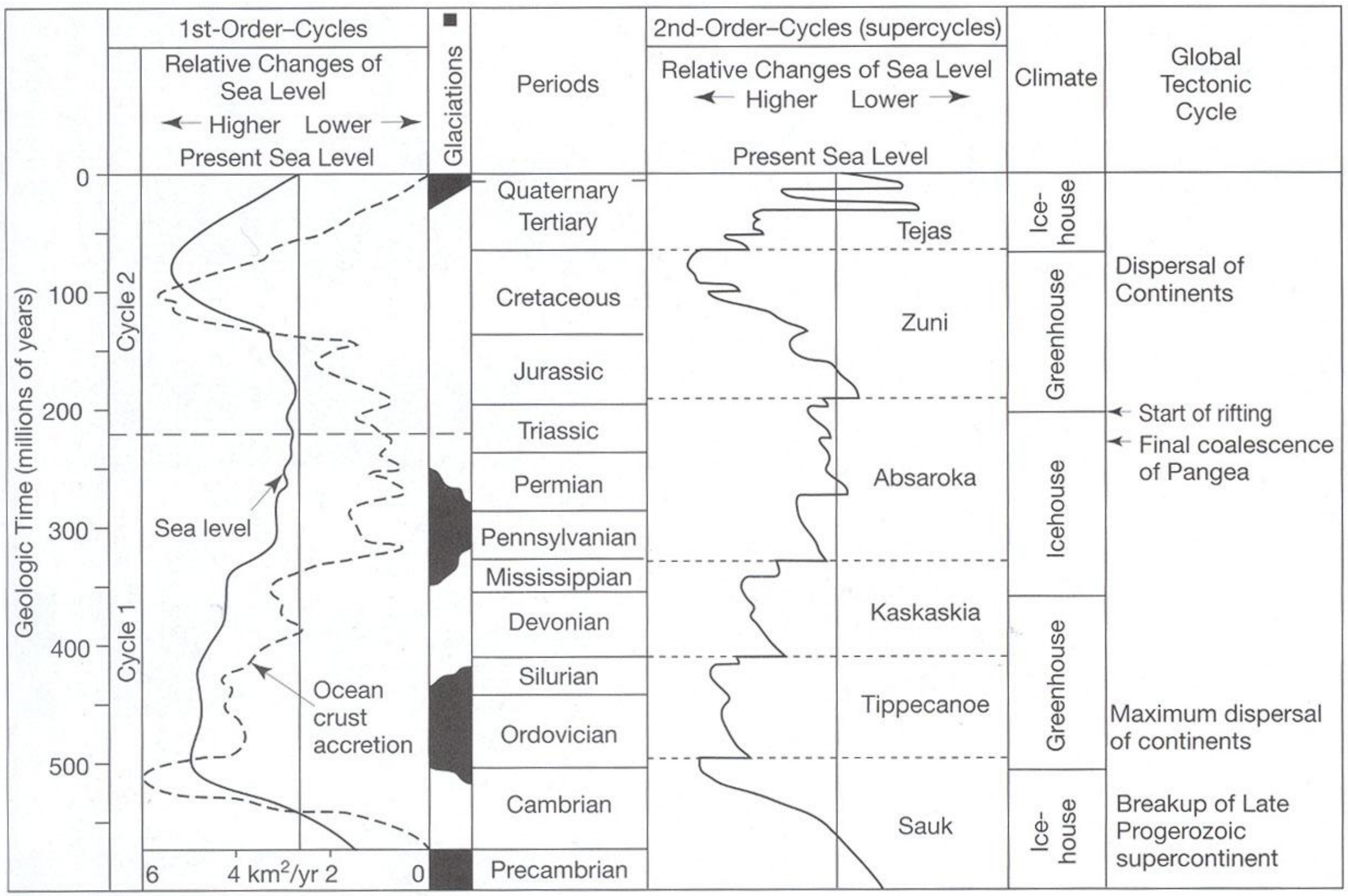


Figure 12.9
Illustration of first-order and second-order global sea-level cycles. First-order cycles reflect variations in production of new oceanic crust (in km^2/yr) related to formation and breakup of continents, which cause major, long-term changes in sea level. Second-order cycles are related to changes in volume of oceanic spreading centers. [Modified from Plint et al., 1992, Control of sea-level changes, *in* Walker, R. G., and N. P. James (eds.), Facies models—Response to sea level change: Geol. Assoc. Canada, Fig. 3, p. 18, reproduced by permission. Climate states are after Fischer (1981); the second-order cycles (Tejas, Zuni, etc. are named for Sloss' (1963) sequences.]

Boggs, 2006, p.409

Table 13.1 Stratigraphic Cycles and Their Postulated Causes

Type	Other terms	Duration, m.y.	Probable cause
First-order	—	200–400	Major eustatic cycles caused by formation and breakup of supercontinents
Second-order	Super cycle (Vail, Mitchum, and Thompson, 1977b); sequence (Sloss, 1963)	10–100	Eustatic cycles induced by volume changes in global mid-ocean spreading ridge system
Third-order	Mesothem (Ramsbottom, 1979); megacyclothem (Heckel, 1986)	1–10	Possibly produced by ridge changes and continental ice growth and decay
Fourth-order	Cyclothem (Wanless and Weller, 1932); major cycle (Heckel, 1986)	0.2–0.5	Milankovich glacioeustatic cycles, astronomical forcing
Fifth-order	Minor cycle (Heckel, 1986)	0.01–0.2	Milankovich glacioeustatic cycles, astronomical forcing

Source: Vail, P. R., R. M. Mitchum, Jr., and S. Thompson, III (1977b); Miall (1990, p. 447).

Boggs, 2006, p.408

Second-order cycles: Six second-order cycles (Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, Tejas) are recognized during the Phanerozoic. The second-order cycles may reflect the changes in the volume of oceanic ridges, related to changes in spreading rate i.e. faster spreading rate, higher sea level.

Third-order cycles: Third-order cycles have durations of 1 – 10 m.y. but are typically shorter than 3 m.y. They are ubiquitous in the Phanerozoic record, but their control is problematic and controversial. They have however been attributed mainly to fluctuations in eustatic sea level owing to changes in spreading ridges and/or continental ice growth and decay.

Fourth- and fifth-order cycles: Fourth- (0.2~0.5 m.y.) and fifth-order (0.01~0.2 m.y.) cycles are widely documented in shallow-marine and pelagic rocks in many parts of the world. These cycles are most easily explained by changes in climate driven by various cyclic perturbations of the Earth's tilt and orbit. These astronomical perturbations are known as *Milankovitch cycles.*

Greenhouse vs. Icehouse

Greenhouse state: Warm climate due to the presence of a large amount of greenhouse gases (e.g., CO_2, CH_4, N_2O) in the atmosphere.

Icehouse state: Earth cooling period.

Possible factors for changing earth surface temperature:

- Incoming solar radiation due to changes in earth orbital parameters (Milankovitch cycles);
- Displacement of continents over the poles;
- Variations in greenhouse gases (for example CO_2 content increases due to volcanic eruptions, decreases due to weathering (because of mountain building) and carbonate productions).

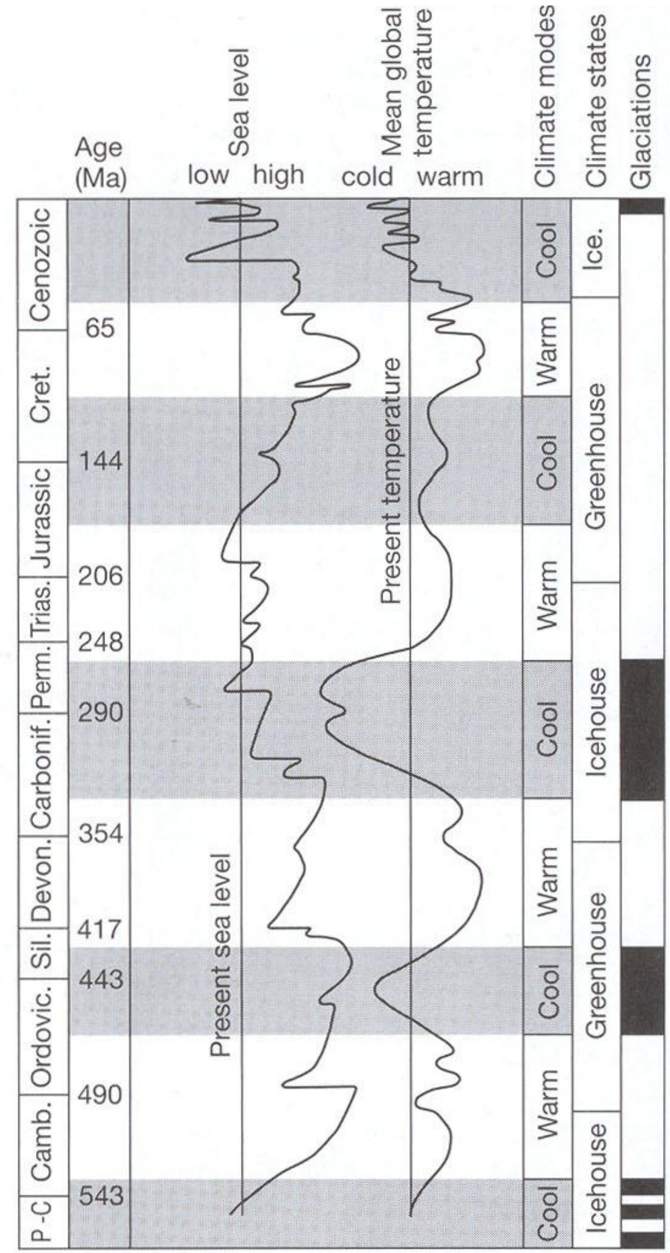
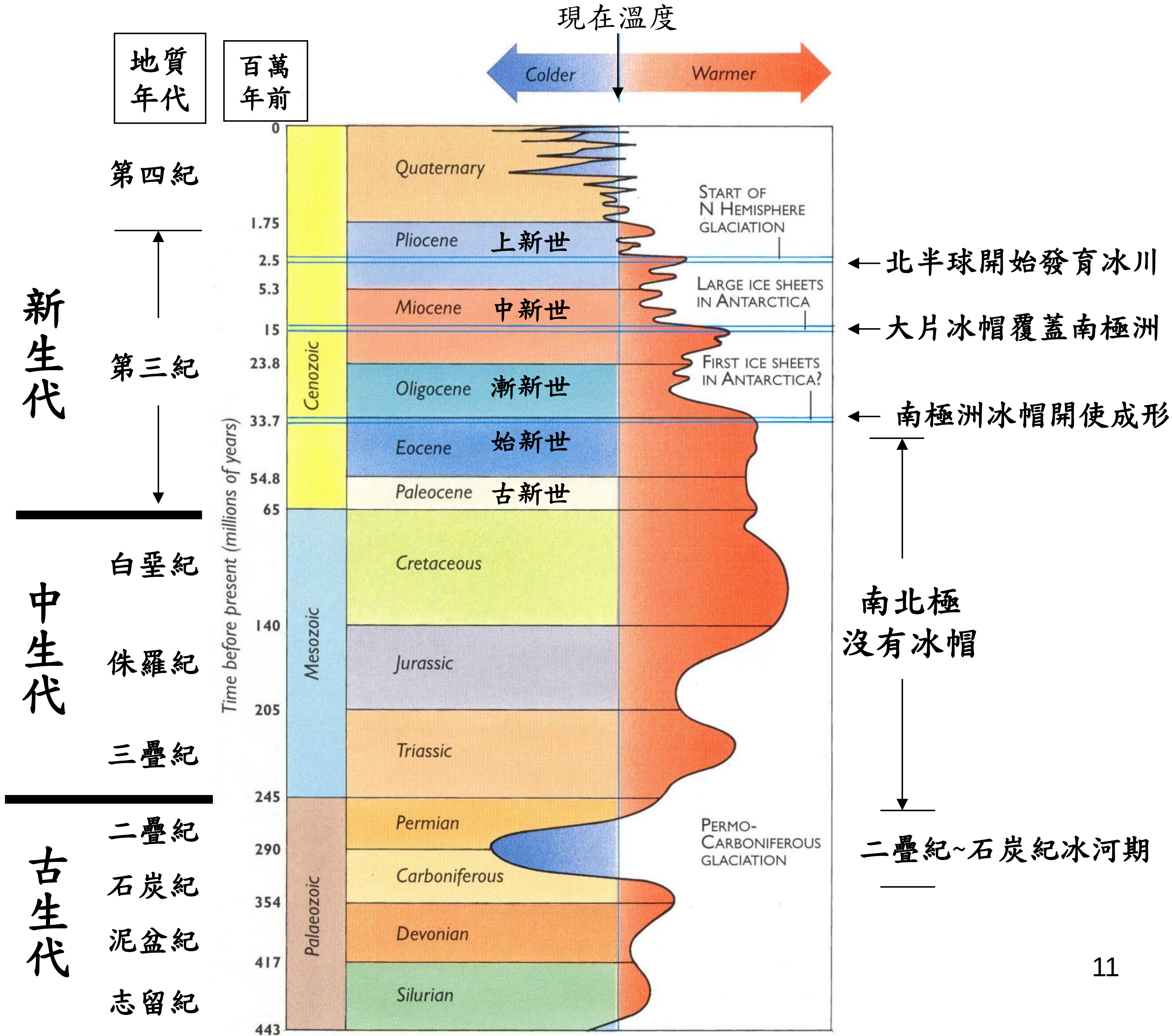


Figure 12.10
Estimated mean global temperature curve for Phanerozoic time and corresponding climate modes (Frakes et al., 1992, p.194), sea-level curve (Vail et al., 1977b), greenhouse-icehouse climate states (Fischer, 1984), and times of major glaciation (Eyles, 1993). Ages from GSA 1999 Geologic Time Scale (see Fig 15.3).

Boggs, 2006, p.410

全球溫度隨地質時間的變化



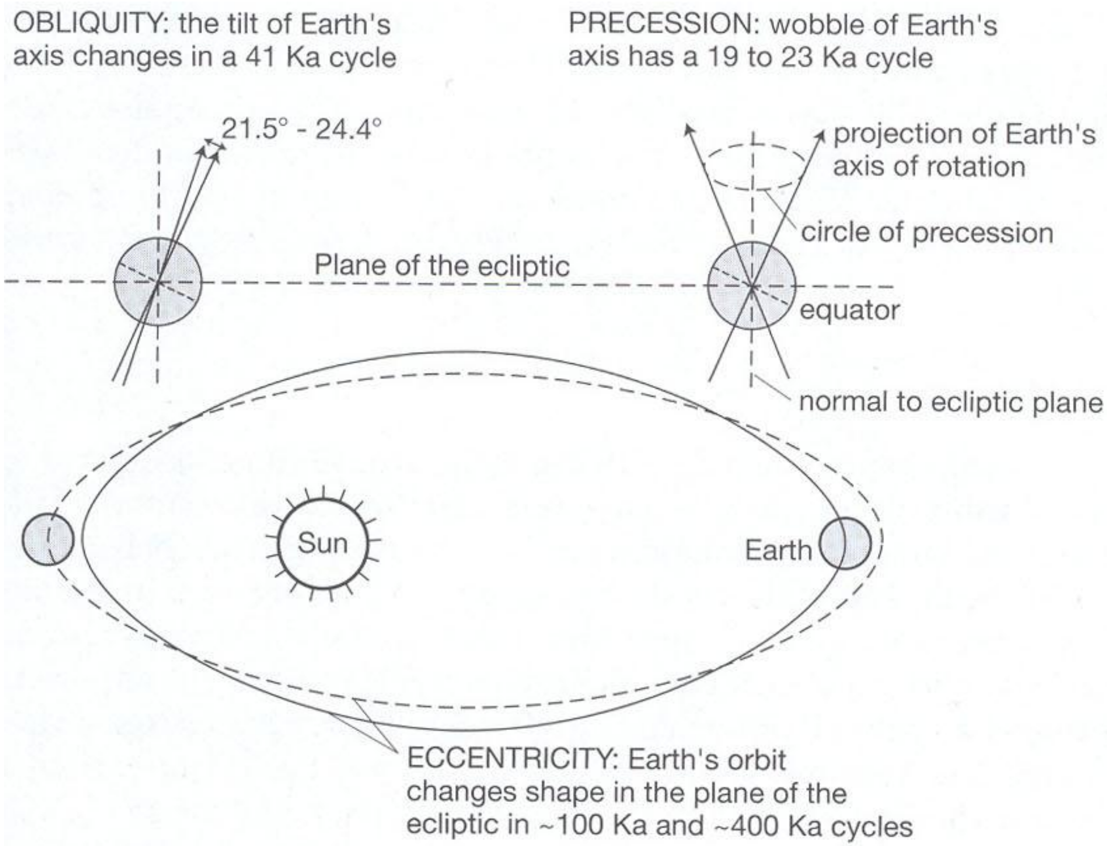
Milankovitch cycles(米蘭科維奇循環)

Three orbital parameters

(a) Eccentricity (地球公轉軌道的偏心率), leading to 410,000 and 106,000 years climatic cycles.

(b) Obliquity (地球自轉軸傾角), leading to 41,000 years climatic cycle

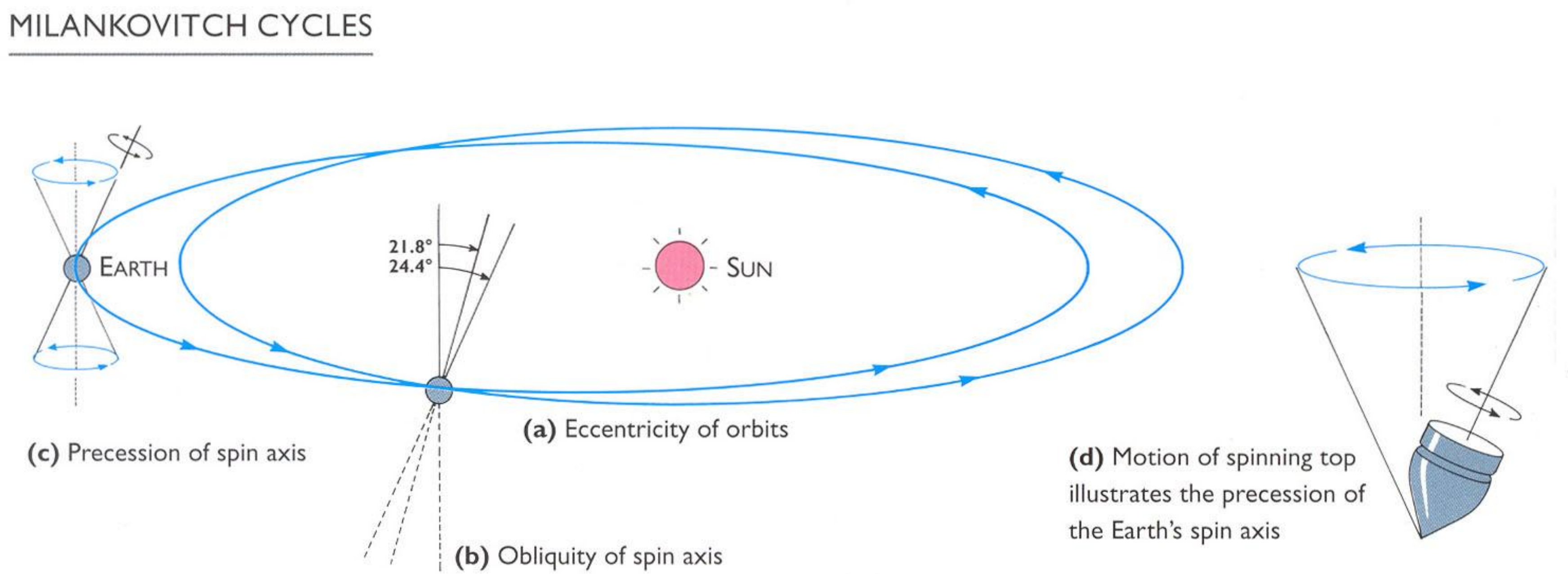
(c) Precession (地球自轉軸繞著垂直軸運轉一圈的週期，即歲差或進動), leading to 19,000 and 23,000 years climatic cycles.



Boggs, 2006, p.411

Figure 12.11
Diagram of the Earth-Moon-Sun system, illustrating the causes of oscillations that produce changes in the amount of solar radiation reaching Earth. These oscillations may, in turn, lead to orbitally forced changes in Earth's climate and thus the sedimentary record (e.g., cycles). [Modified from House, M. R., 1995, Orbital forcing timescales: An introduction, *in* House, M. R., and A. S. Gale (eds.), Orbital forcing timescales and cyclostratigraphy: Geological Society Special Publication 85, Fig. 9, p. 10, reproduced by permission.]

日照量改變:米蘭科維奇循環 (Milankovitch cycles)



The orbit of the Earth around the Sun varies through time in three ways. The Earth follows an elliptical path; however, the shape (eccentricity) of this changes, from more elongate to more circular **(a)**. In addition, the orientation (obliquity) of the Earth's spin axis fluctuates relative to the plane of the Earth's orbit **(b)**. Finally, in detail, the spin axis precesses like a spinning top **(c–d)**. All these factors affect the amount of solar radiation reaching the Earth's surface, and therefore the climate, in characteristic cycles called Milankovitch cycles.

(a) 地球公轉軌道的偏心率 (eccentricity)改變造成41萬年與10萬6千年的氣候循環

(b) 地球自轉軸傾角 (obliquity)的改變造成4萬1千年的氣候循環

(c) 地球自轉軸繞著垂直軸運轉一圈的週期(即歲差或進動, precession) ，造成1萬9千年至2萬3千年的氣候循環

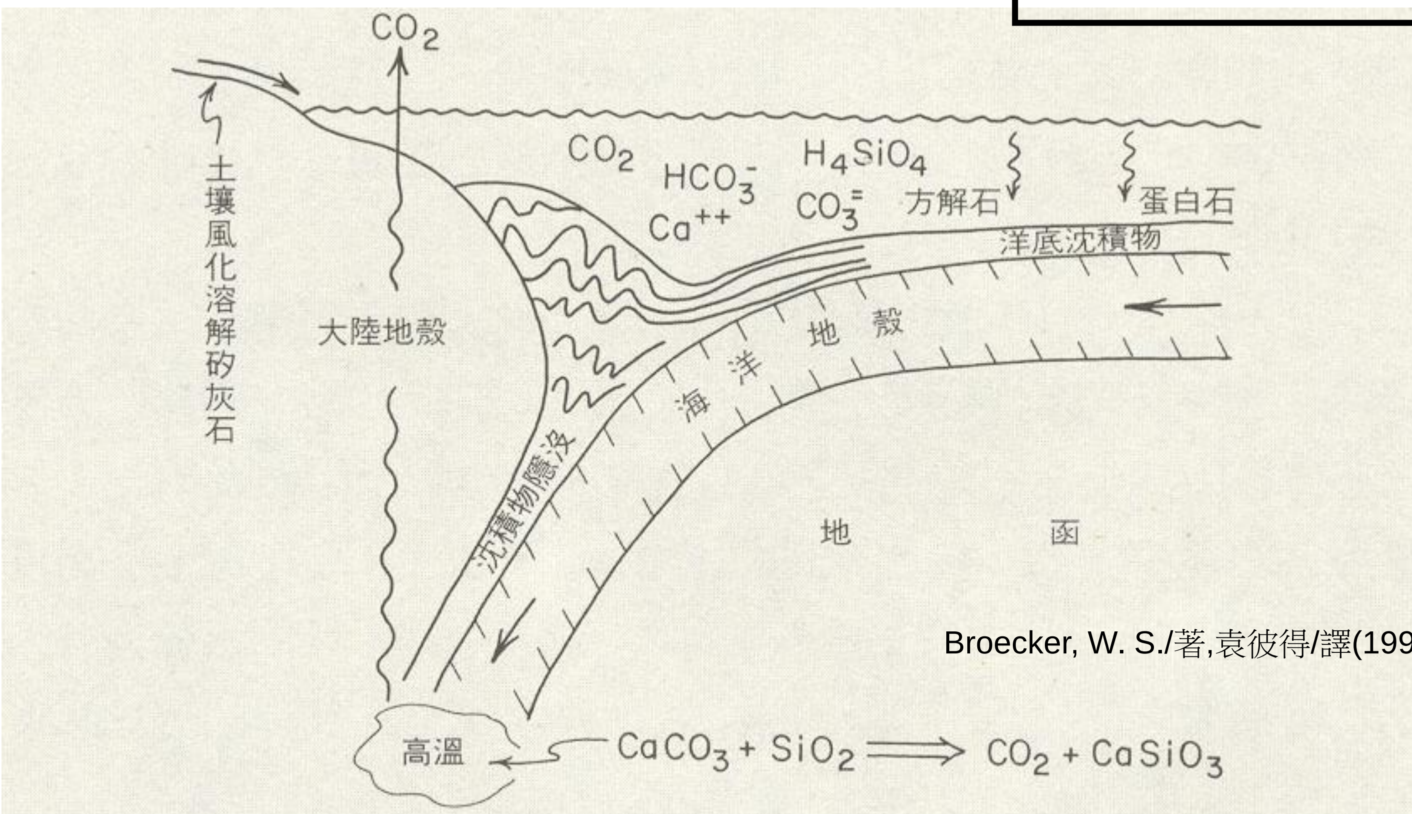
溫室氣體增加的因素：

- 火山活動：噴出CO_2
- 海底下固態的天然氣水合物解離成氣體(甲烷)
- 人類活動排出溫室氣體

地球的冷氣機 →

溫室氣體減少的因素：

- 大量生物繁殖(造成石灰岩將CO_2變成$CaCO_3$或有機物如，白堊紀)
- 大規模造山運動：加速岩石風化，風化過程將CO_2變成風化產物(固體)的一部分

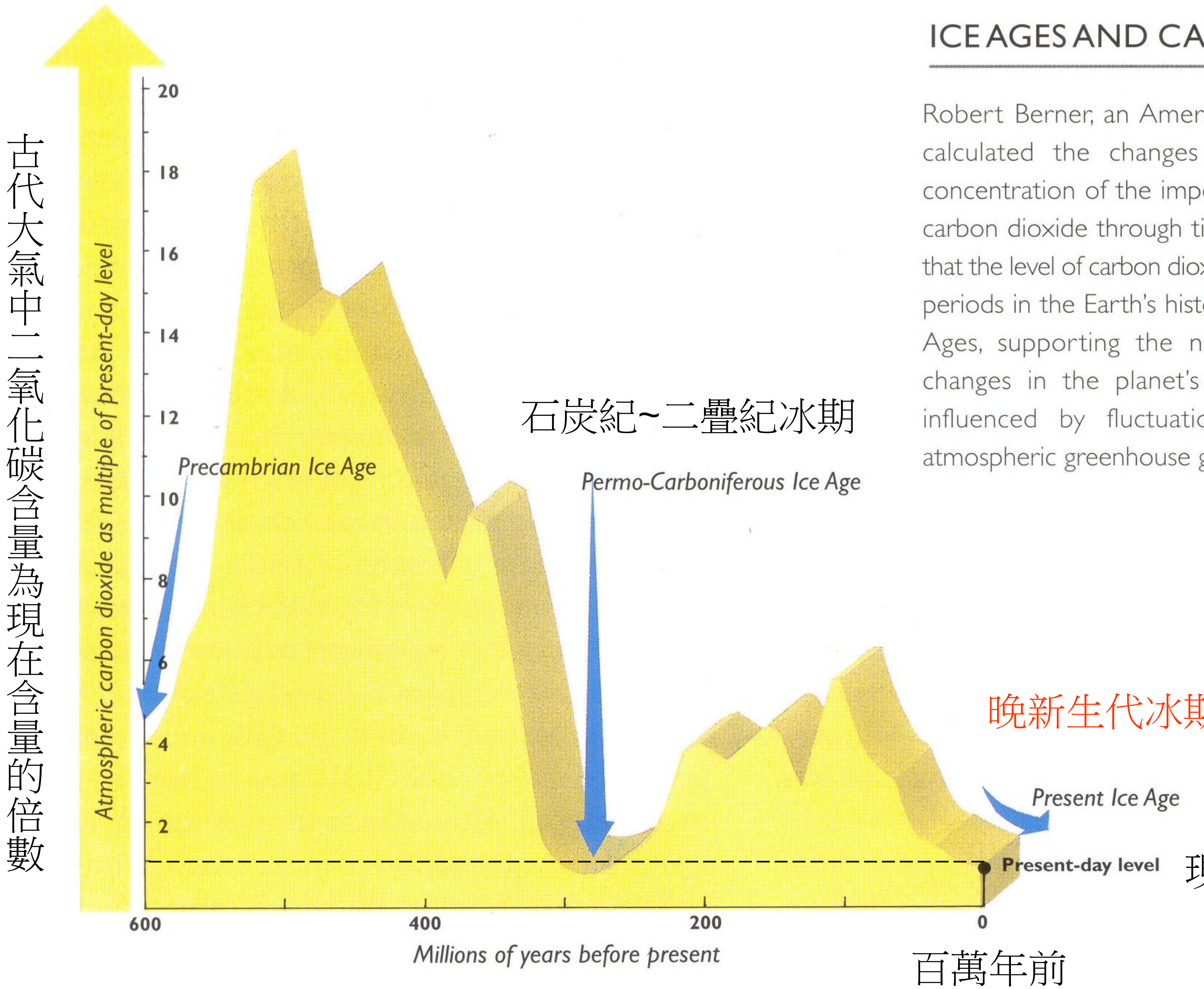


Broecker, W. S./著,袁彼得/譯(1998) 開天闢地. p.186.

圖7-5　海洋地殼隱沒到大陸地殼下方，把部分海底沈積物攜入地函。地函把沈積物加熱及變質，沈積物內的碳酸鹽於是被破壞放出二氧化碳。二氧化碳回到地表，又進入海洋及大氣。最後，二氧化碳被海洋生物利用，與鈣結合成方解石，沈降至海底，再次進入隱沒帶。

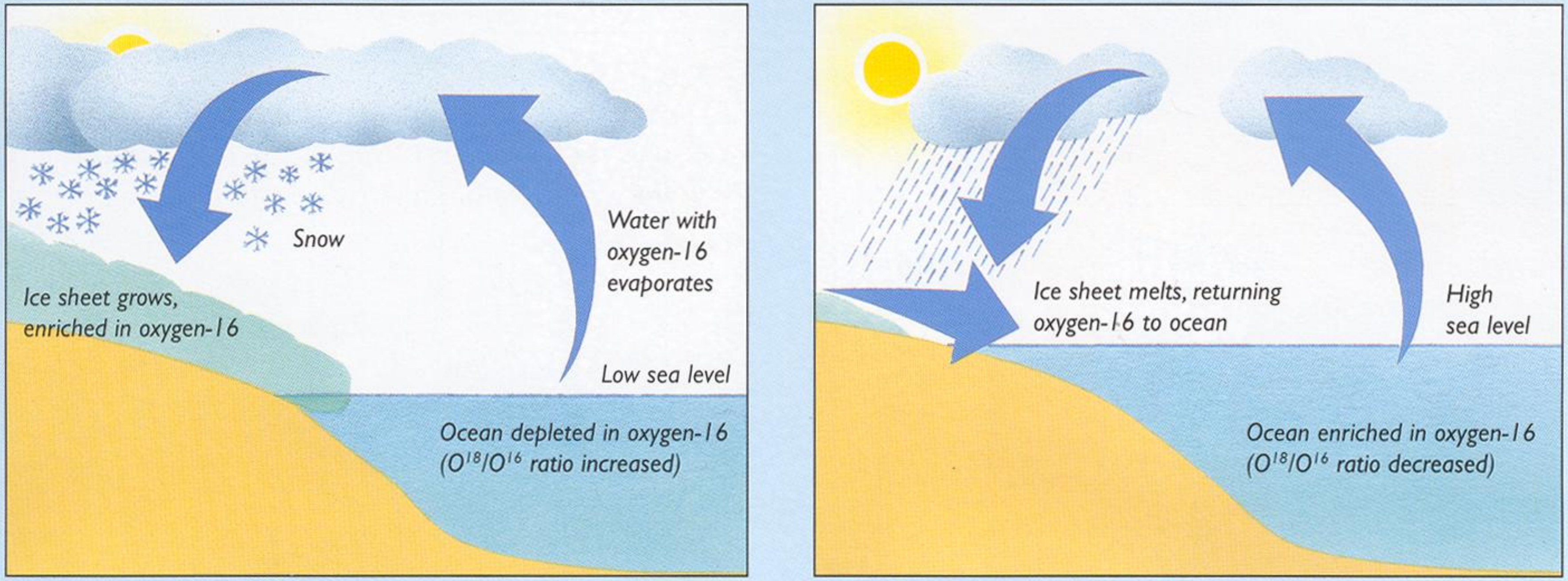
ICE AGES AND CARBON DIOXIDE

Robert Berner, an American climatologist, has calculated the changes in the atmospheric concentration of the important greenhouse gas carbon dioxide through time. His work suggests that the level of carbon dioxide is high during warm periods in the Earth's history and low during Ice Ages, supporting the notion that long-term changes in the planet's climate are strongly influenced by fluctuations in the level of atmospheric greenhouse gases.



氧同位素,冰帽與海水面變化

冰河期 **間冰期**



(a) Glacial period **(b)** Interglacial period

The waxing and waning of large ice sheets on land can affect the ratio of the light and heavy isotopes of oxygen in sea water. Water with light oxygen (oxygen-16) evaporates more readily from the oceans. Some of this water vapour will eventually freeze as snow and accumulate on ice sheets during the winter months. During a glacial period, the snow does not melt much during the summer and the ice sheets grow, taking water out of the oceans and lowering the sea level **(a)**. This way, the water in the ice is enriched in light oxygen, but the oceans are depleted (i.e. the ratio of heavy to light oxygen in oceans increases). During an interglacial period the ice sheets melt. The melt water raises the sea level and enriches the oceans again with oxygen-16 **(b)**.

海水中的O^{18}/O^{16}比值增加

海水中的O^{18}/O^{16}比值減小

改變地球日照量與古代海水溫度測量

Changes in Earth's orbital parameters
(Milankovich orbital-climate cycles, fourth- and fifth-order cycles)

地球公轉與自轉的軌道與參數變化

改變地球日照量造成氣候改變

Climate

Ice volume
glacial, interglacial

$\delta^{18}O$ ↗ +	$\delta^{18}O$ ↘ -
ice grow	ice decay
glacial	interglacial
sea-level fall	sea-level rise

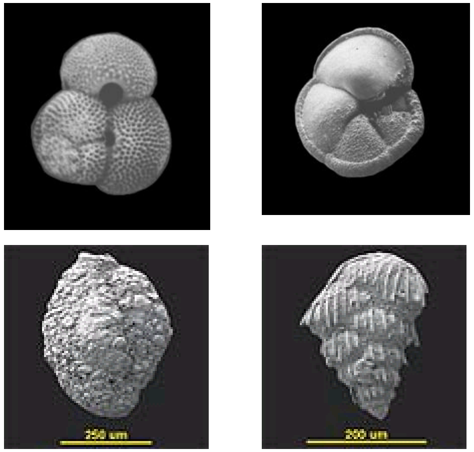
若地球表面平均溫度低，南北兩極形成冰川；平均溫度較高，南北極沒有冰川

Temperature

$\delta^{18}O$ ↗ +	$\delta^{18}O$ ↘ -
Temp. drop	Temp. rise

$\delta^{18}O$
sea water

測量有孔蟲殼體的氧同位素得知以前海水的溫度



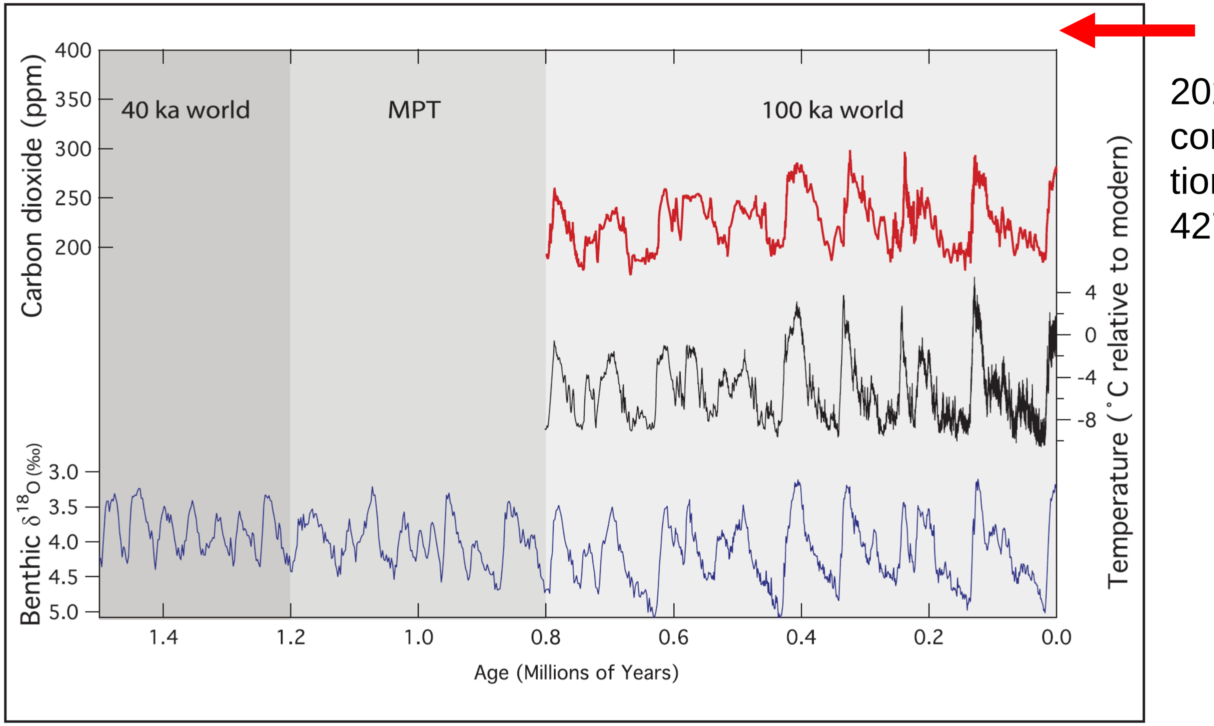
$\delta^{18}O$
marine carbonate

$$\delta^{18}O = \frac{[(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}]}{(^{18}O/^{16}O)_{standard}} \times 1000$$

Oxygen isotopes and their controlling factors

Variations of oxygen isotope, carbon dioxide and temperature for past 1.5 m.y.

Severinghaus et al. (2010) EOS 91(40)



2026 CO2 concentra-tion: 427 ppm

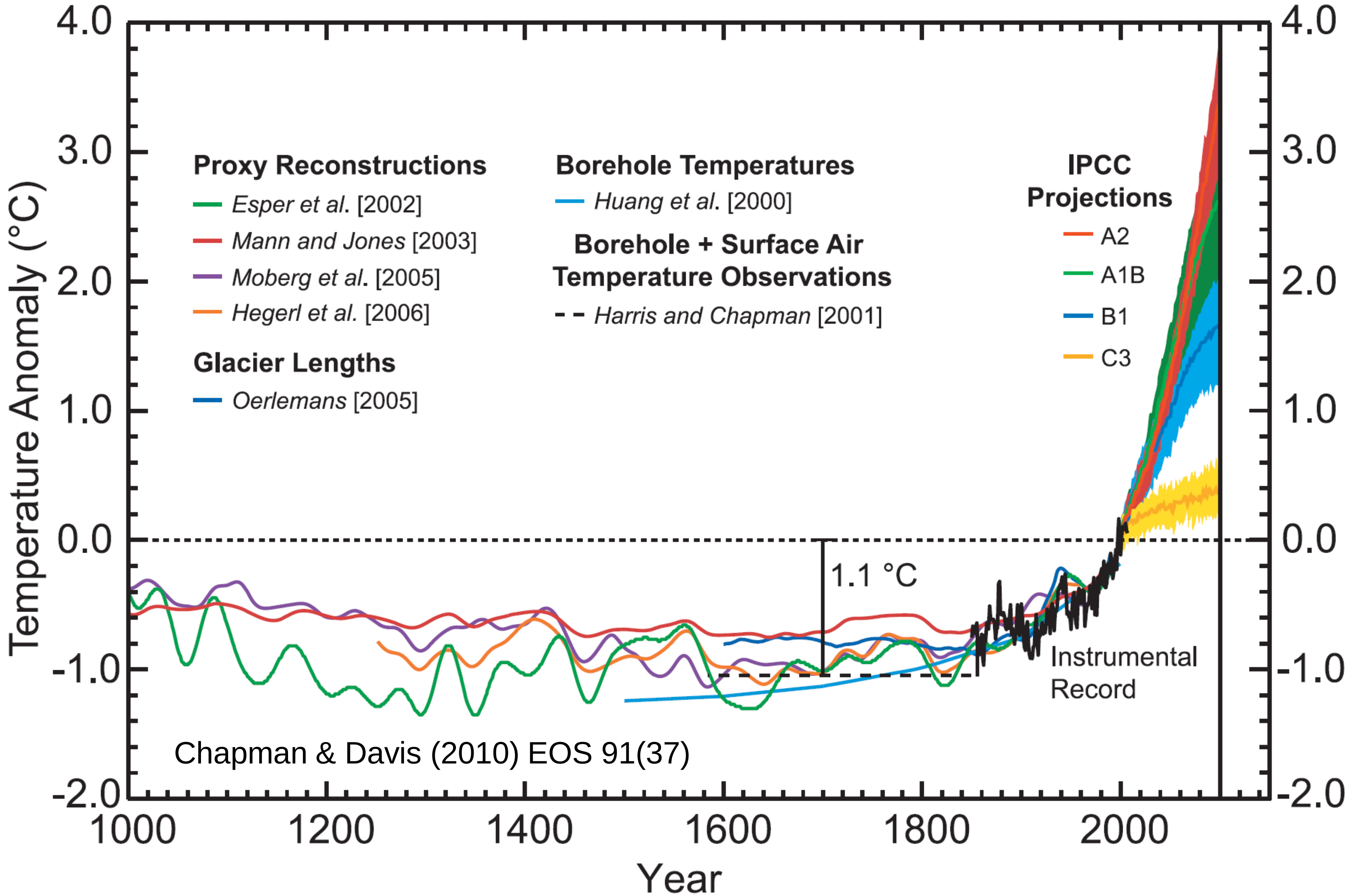
*The record of past temperature and carbon dioxide from the European Project for Ice Coring in Antarctica (EPICA) Dome C core [*Luthi et al., *2008], the oldest such records yet obtained, and the oxygen isotope record from benthic foraminifera, a proxy for global ice volume and therefore global climate conditions [*Lisiecki and Raymo, *2005]. Lower values of oxygen isotope ratios (delta18O) in calcium carbonate of benthic foraminifera correspond to times of lower global ice volume, warmer temperatures in Antarctica, and higher levels of carbon dioxide. The switch from predominantly 41,000-year cycles to 100,000-year cycles in the isotope record at the mid-Pleistocene transition (MPT) took place during the period from about 1.2 million to 800,000 years ago.*

1 Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally distributed benthic delta18O records, *Paleoceanography, 20,* PA1003, doi:10.1029/2004PA001071.

2. Luthi, D., et al. (2008), High-resolution carbon dioxide concentration record 650,000–800,000 years before present, *Nature, 453*(7193), 379–382, doi:10.1038/nature06949.

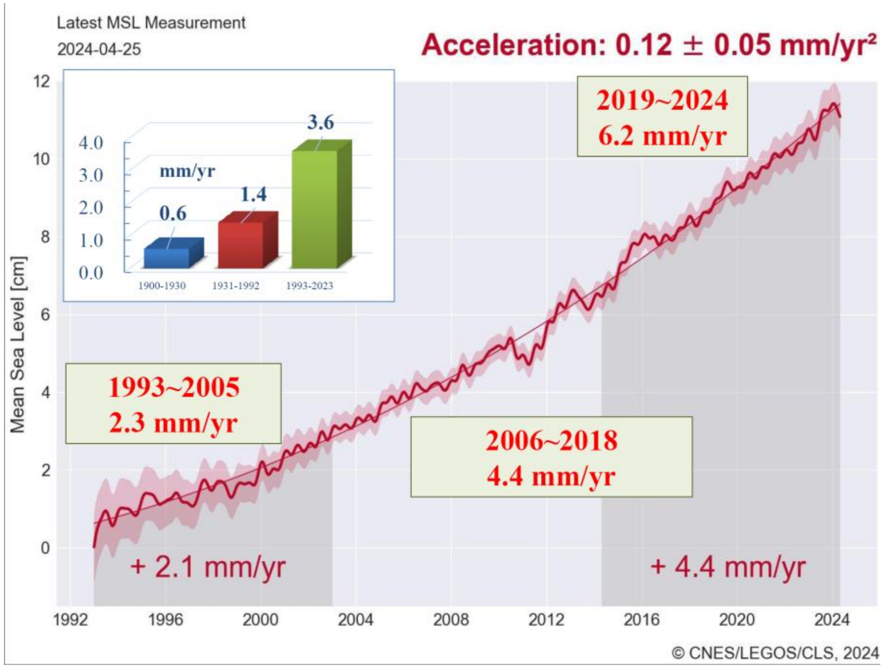
3. Raymo, M. E., L. E. Lisiecki, and K. H. Nisancioglu (2006), Plio-Pleistocene ice volume, Antarctic climate, and the global 18O record, *Science,313*(5786), 492–495, doi:10.1126/science.1123296.

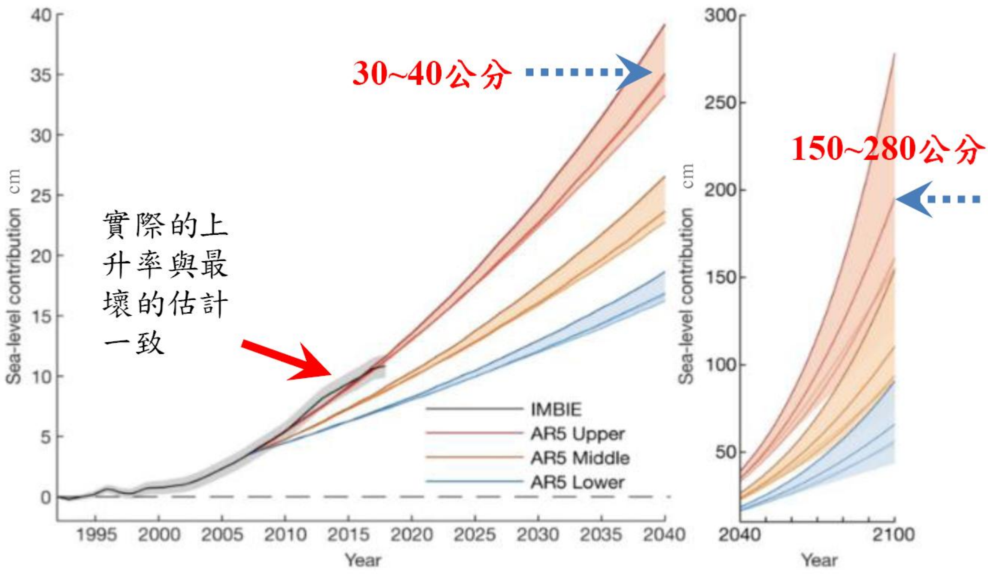
全球暖化已不可避免
人類應將暖化程度降至最低



全球1000年至2000年大氣溫度以及IPCC預測2006-2100年的可能溫度趨勢

於2100年，依最壞情境，預估海平面上升約2公尺，上升趨勢會再延續數百年。





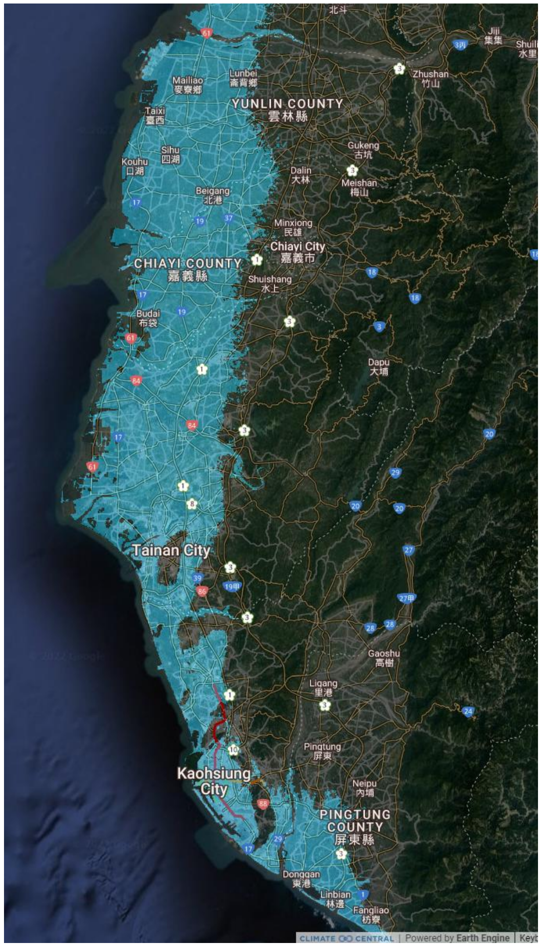
Rate of global sea-level rise:
Recent rate: 6.2 mm/yr
Forecasted rate at 2100: 10-20 mm/yr
(IPCC, 2019)

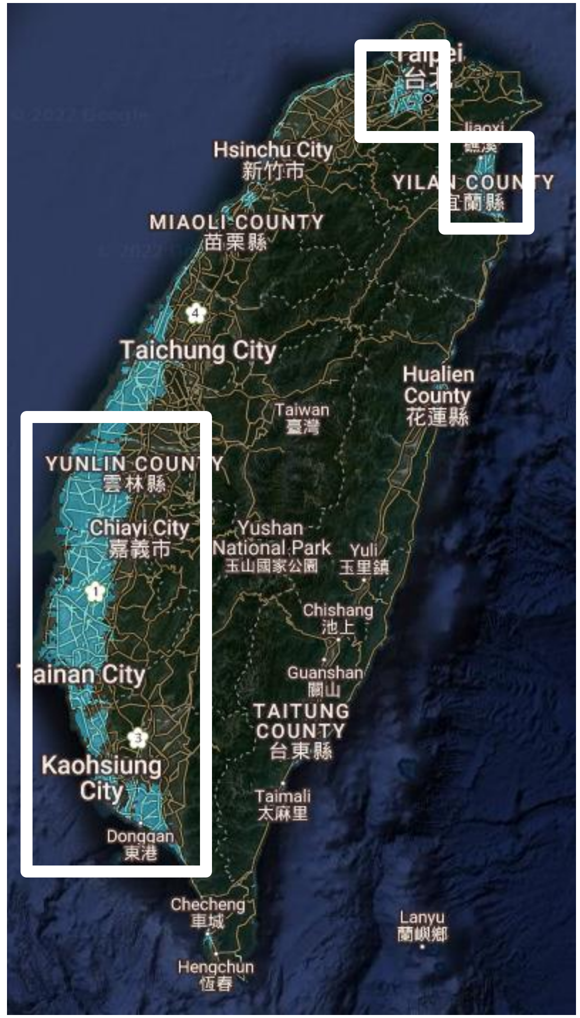
海平面上升的速率的觀測結果，與氣候模式最壞的變
化情境十分吻合。到2050年，全球海平面上升約40~50 公分可能是無法避免的；到2100年海平面上升約2公尺！

幾百年後的海平面上升，反映現在的二氧化碳濃度所造成的升溫！

未來海平面上升12公尺情境
(約未來300-600年後發生)

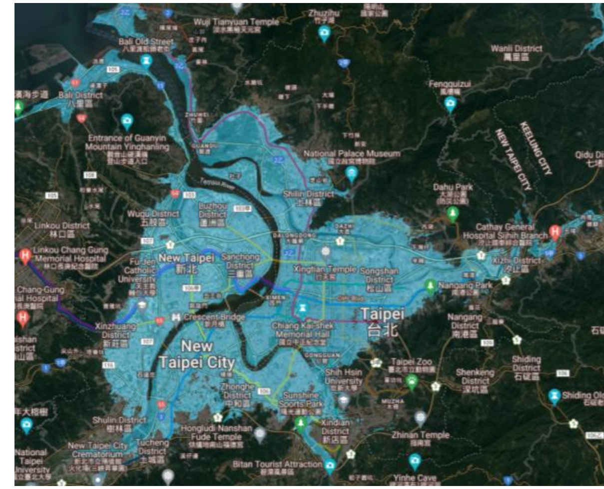
西部城市全部消失

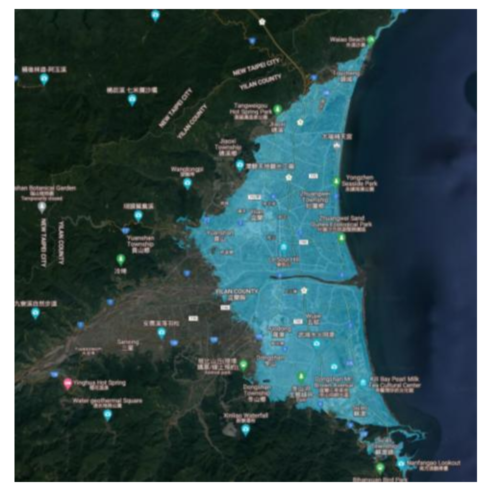




https://coastal.climatecentral.org/map

台北市變成台北湖!





宜蘭平原剩下一半！

但是，現在的二氧化碳濃度仍持續快速增加中！

影響地球表面溫度的因素

表 7-2　影響石質行星表面溫度的因素

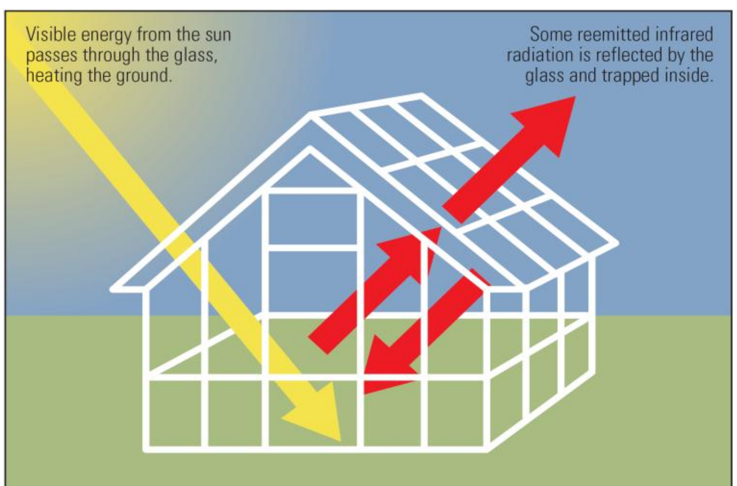
日照量　　溫室效應

	大氣壓（公斤／平方公分）	和太陽的距離（10^6公里）	接收到的太陽能量（10^6耳格／平方公分・秒）	黑體溫度 C°	太陽光被反射的比例	因反射陽光造成的降溫 C°	溫室效應造成的增溫 C°	表面實際溫度 C°
水星	0	58	9.2	+175	.06	-5	0	–
金星	115*	108	2.6	+55	.71	-84	+460	+430
地球	1.03★	150	1.4	5	.33	-25	+35	+15
火星	0.016*	228	0.6	-50	.17	-10	+15	-45

* 大氣以二氧化碳爲主

★ 大氣主要是氮和氧

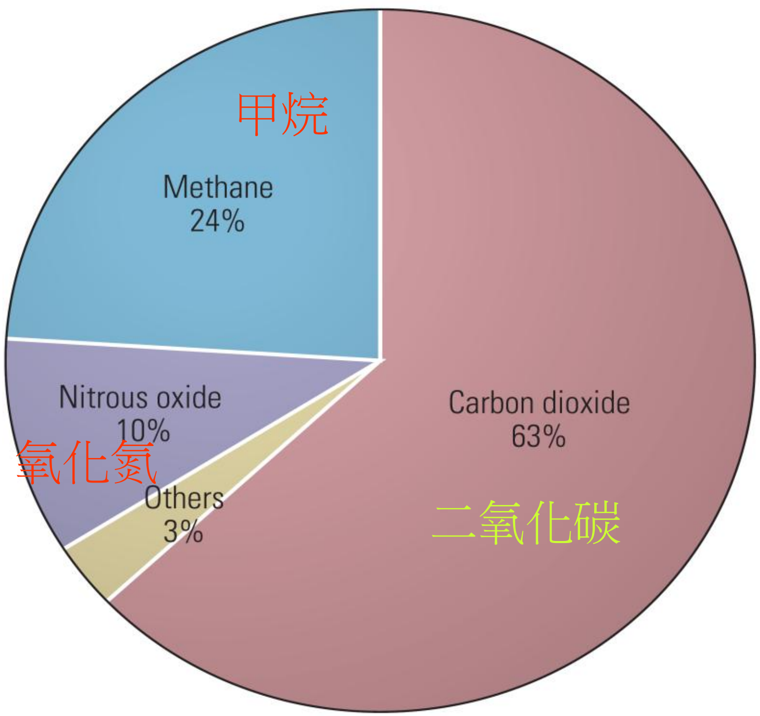
溫室效應



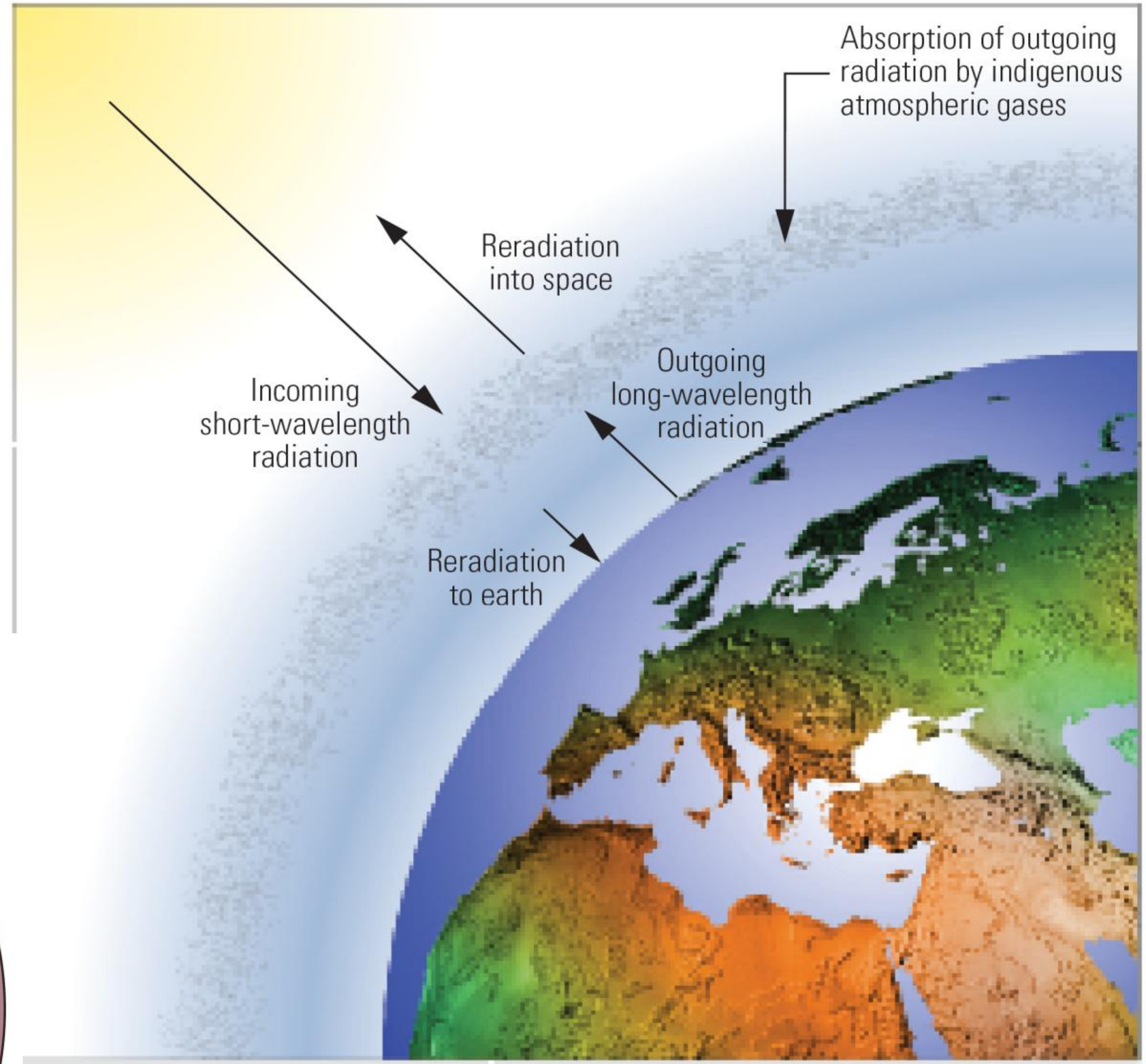
如果大氣內溫室氣體含量改變或日照量改變，則地球表面溫度會改變

溫室效應

溫室氣體：由三個以上的原子所構成的大氣分子。這些分子可以擋住由地球表面往外太空散射的紅外光，使地球表面保持溫暖。重要的溫室氣體如：水蒸氣(H_2O)、二氧化碳(CO_2)、甲烷(CH_4)、氧化氮(N_2O)



Natural Greenhouse Effect

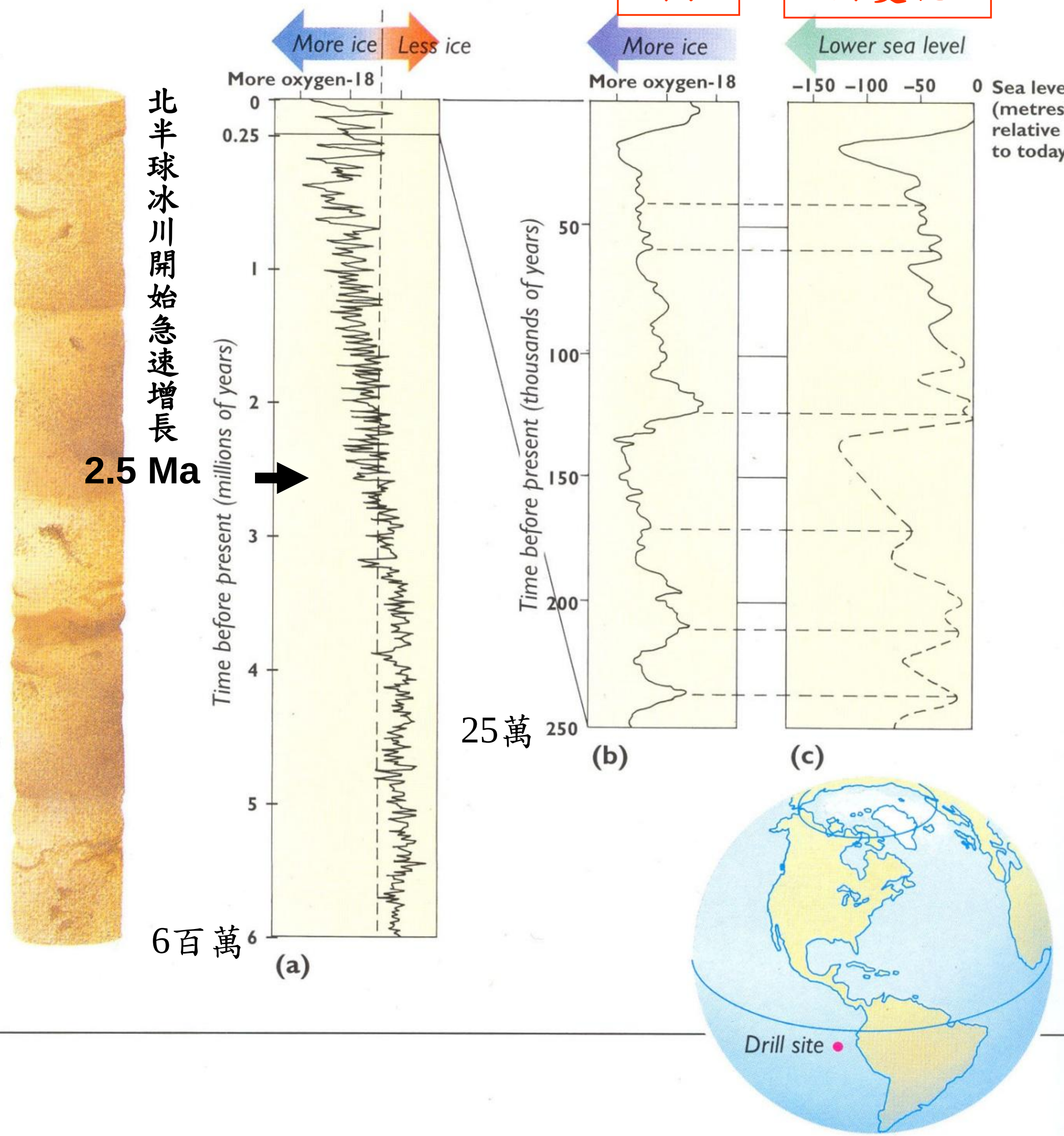


六百萬年來的氧同位素變化

冰川消長 = 全球海水面變化

OXYGEN ISOTOPE RECORD IN DEEP SEA CORES

Fossil shells, buried beneath the sea floor, contain a record of past conditions in the oceans. By measuring the relative amounts of the light and heavy isotopes of oxygen locked up in the shells, it is possible to calculate both the temperature of the ocean water in which the fossil creature lived and the volume of ice sheets on land. The record in deep sea cores from the Pacific suggests that about 2.5 million years ago the climate began to cool markedly and ice sheets became extensive in the northern hemisphere **(a)**. The record for the last 250,000 years shows that there have been numerous advances and retreats of the ice sheets which correlate with changes in sea level **(b–c)**.

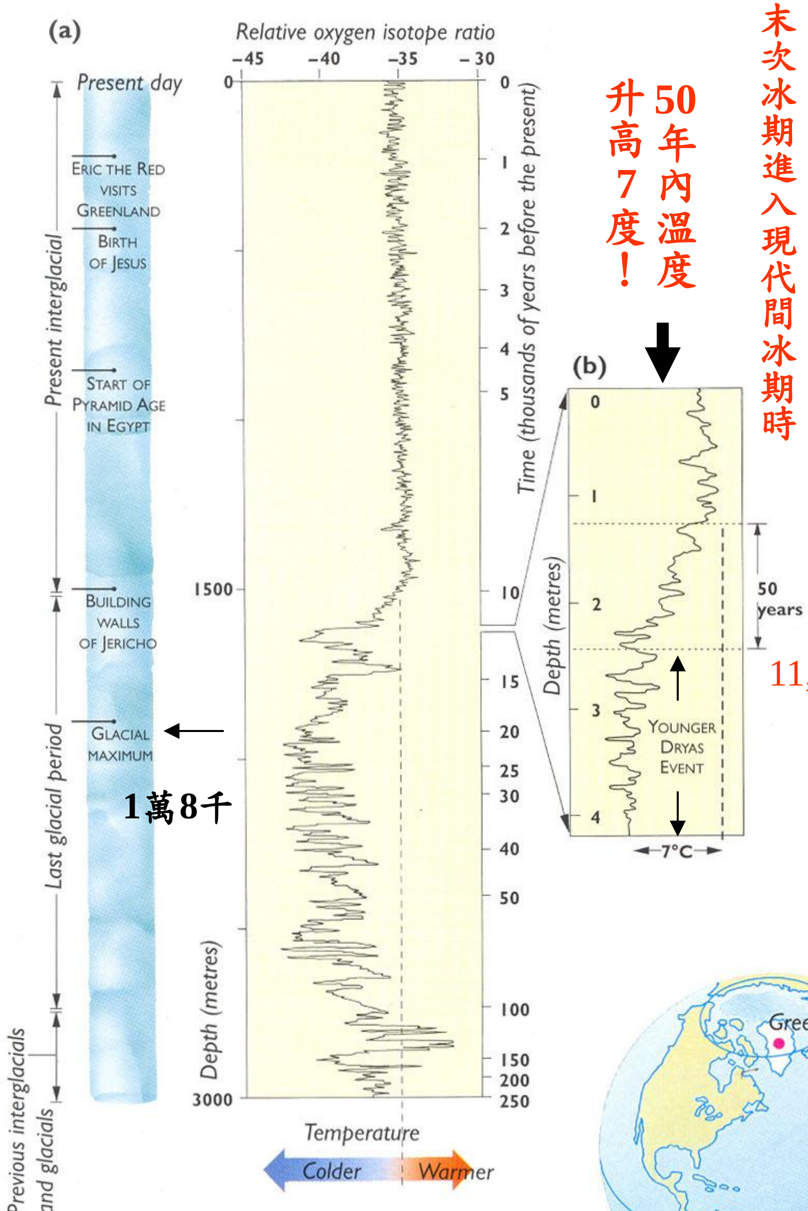


二十五萬年來的氧同位素變化

現代間冰期

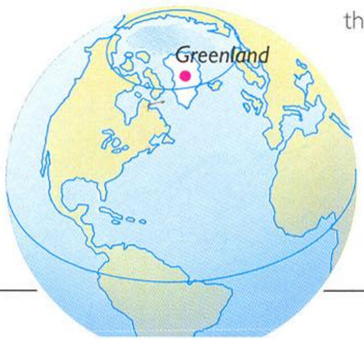
末次冰期

OXYGEN ISOTOPES IN GREENLAND



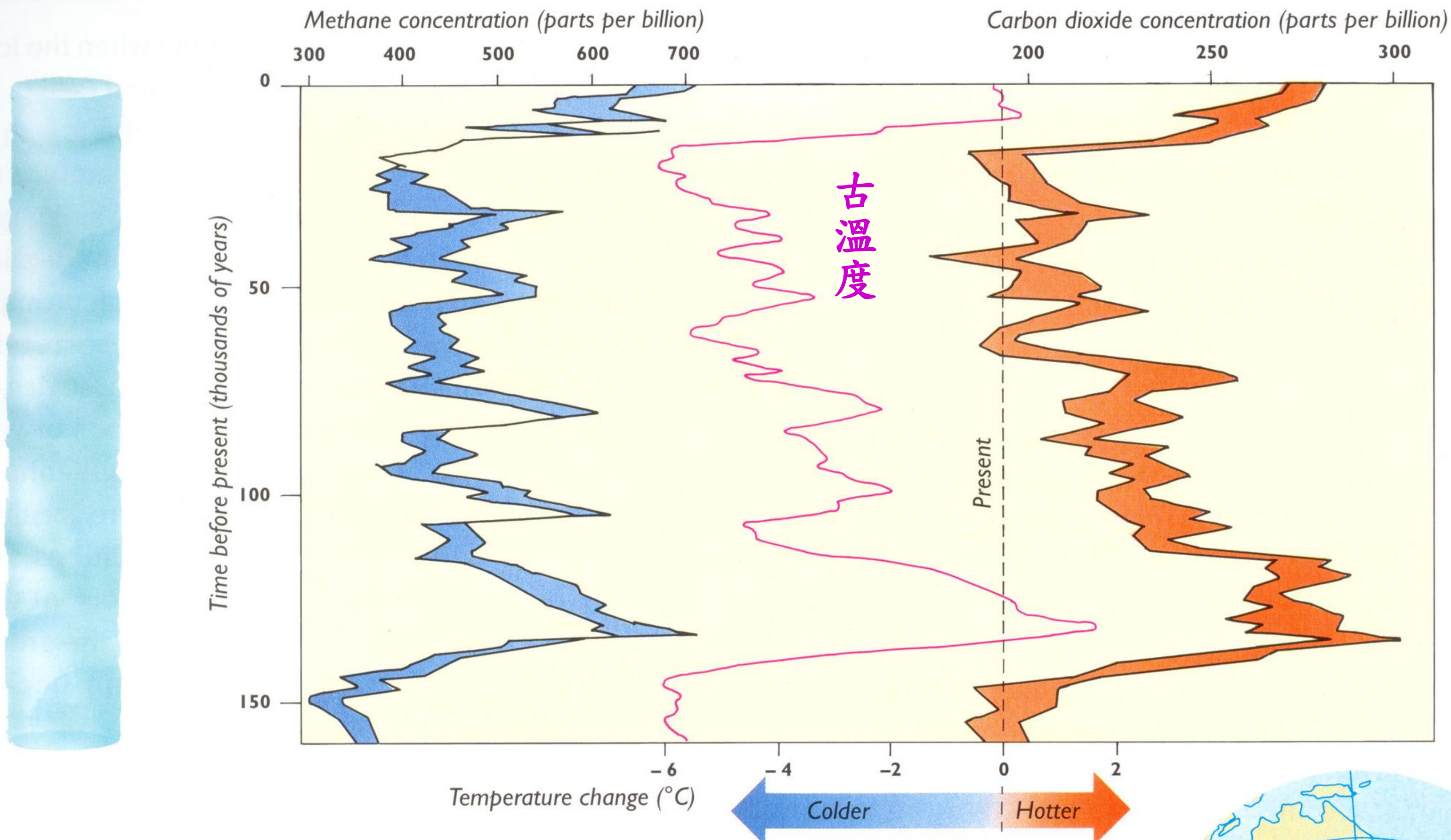
The ice in Antarctica and Greenland accumulates year by year. Scientists can study the Earth's climate in the last few hundred thousand years by analysing the annual layers of ice. To do this, they must drill into the ice sheets and extract long cylinders (cores) of ice.

Cores of ice, extracted from the Greenland ice sheet, contain a record of the climate over the last 250,000 years **(a)**. Over time, the ice has accumulated. By measuring the relative amounts of the light and heavy isotopes of oxygen in the ice at particular levels in the core, it is possible to calculate the atmospheric temperature when the ice at this level formed. During the present interglacial period, in the last 10,000 years, the temperature has been fairly constant, but in the period before that, in the last glacial period, the temperatures have been generally colder, swinging rapidly back and forth. For example, about 11,500 years ago, the temperature increased extremely rapidly at the end of the so-called Younger Dryas Event **(b)**.

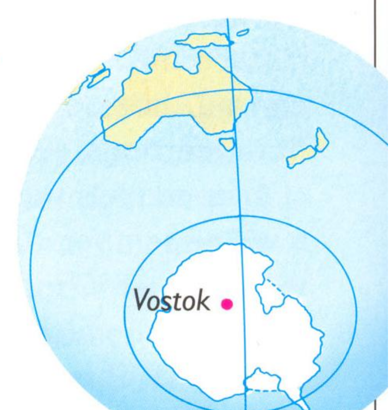


南極冰心揭示15萬年來大氣中二氧化碳與甲烷的成分

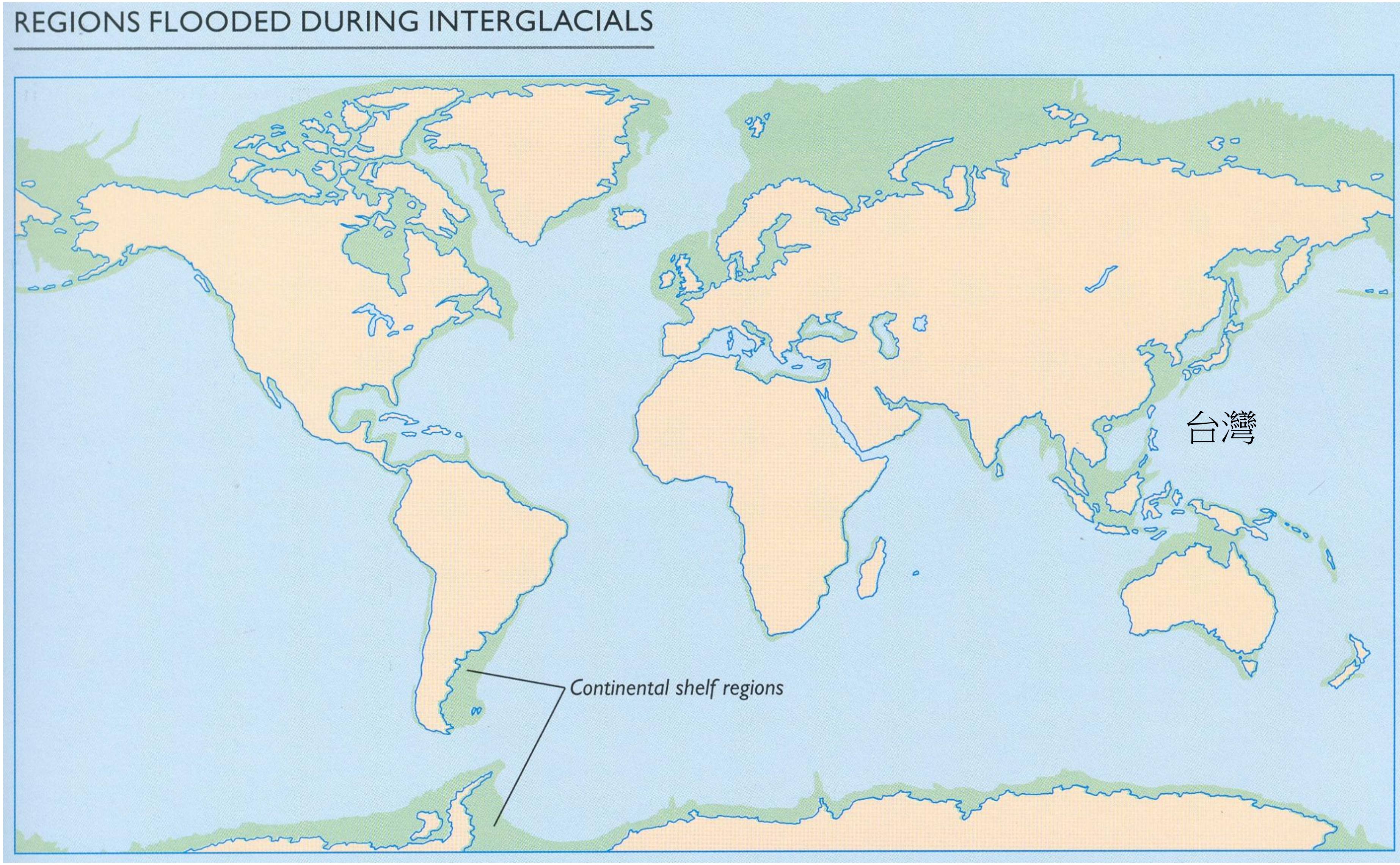
VOSTOK ICE CORE, ANTARCTICA



An ice core extracted by Russian scientists from Vostok in Antarctica contains a detailed record of the climate during the last 150,000 years. Tiny bubbles, trapped in the ice, contain samples of gases that were in the atmosphere when the ice formed. These show that the levels of greenhouse gases such as methane and carbon dioxide have fluctuated through time – the fluctuations correlate with changes in the atmospheric temperature, calculated from the proportion of light and heavy oxygen in the ice. This may suggest that past climate change has been influenced by variations in the concentration of these greenhouse gases.

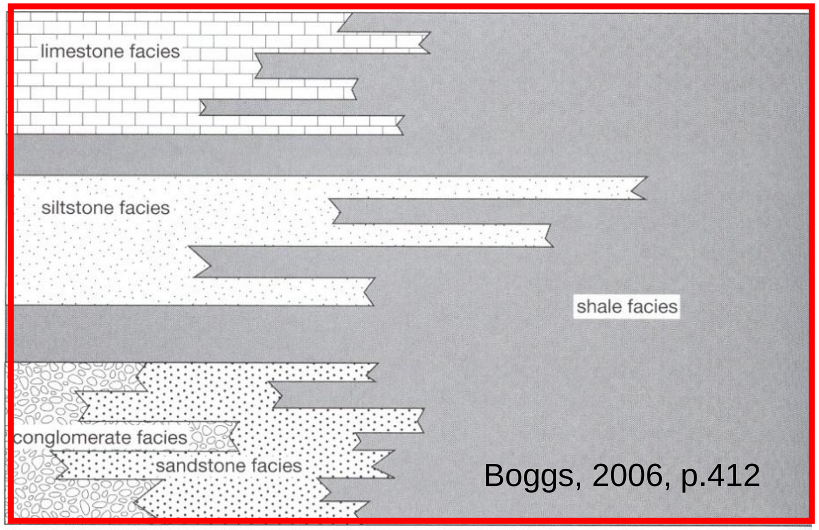


現代間冰期海水面升高約130公尺， 形成現在的大陸棚。
末次冰期時，現在的大陸棚沒有海水覆蓋(如台灣海峽) 。



Sedimentary Facies

A facies is a body of rock characterized by a particular combination of lithology, physical and biological structures that bestow an aspect ("facies") different from the bodies of rock above and below and laterally adjacent. A facies may be a single bed, or a group of multiple beds. A facies that is identified on the basis of lithologic characteristics as **lithofacies** (for example, thick cross-bedded sandstone facies) and facies distinguished by paleontologic characteristics (fossil content) without regard to lithologic character as **biofacies.** Where definition depends on features seen in thin section, as is often the case with carbonates, the term **microfacies** (for example, ooid grainstone microfacies) is used. An important objective of facies studies is to ultimately make environmental interpretations from the facies.



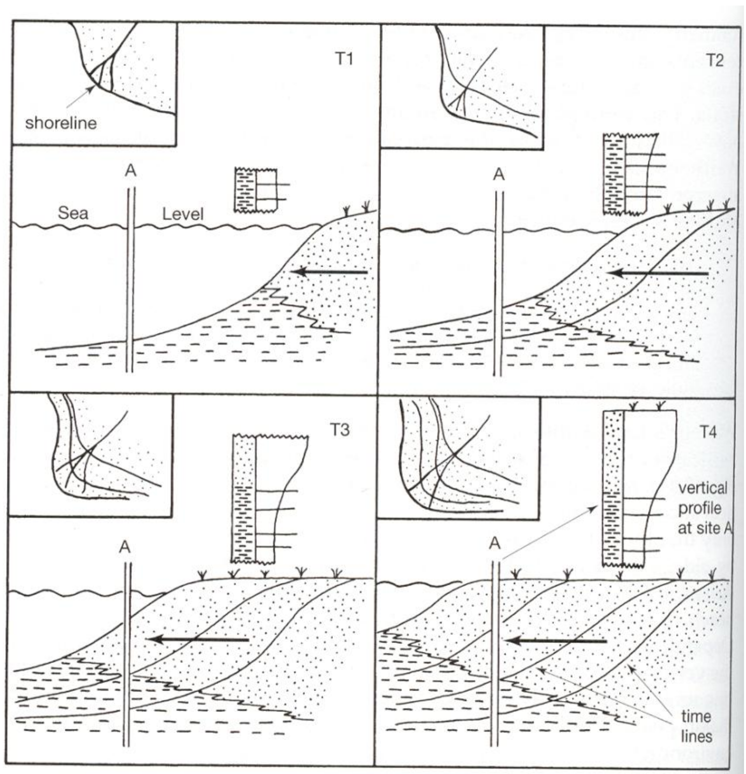
Graphic illustration of facies

Walther's law of succession of facies

Walther's law: "The various deposits of the same facies-area and similarly the sum of the rocks of different facies-areas are formed beside each other in space, though in a cross-section we see them lying on top of each other (Walther, 1894)". Walther's law is thus interpreted to mean that facies that occur in conformable vertical successions of strata also occurred in laterally adjacent environments. This principle has long been used, for example, to explain how a prograding delta yields a coarsening-upward sequence.

Progradational successions

Retrogradational successions



Boggs, 2006, p.414

Figure 13.12
Walther's Law illustrated by the growth of a delta through time. Note the successive outbuilding of the delta at four different time periods (T1-T4). With time, the shoreline progrades from right to left, so that at a single location depicting a vertical succession (A), a gradual transition from prodelta mud to coarser-grained delta deposits takes place, generating a coarsening-upward succession. [After Pirrie, D., 1998, Interpreting the record: Facies analysis, *in* Doyle, P., and M. R. Bennett (eds.), Unlocking the stratigraphical record: Advances in modern stratigraphy, John Wiley and Sons, Ltd., Chichester, reproduced by permission.]

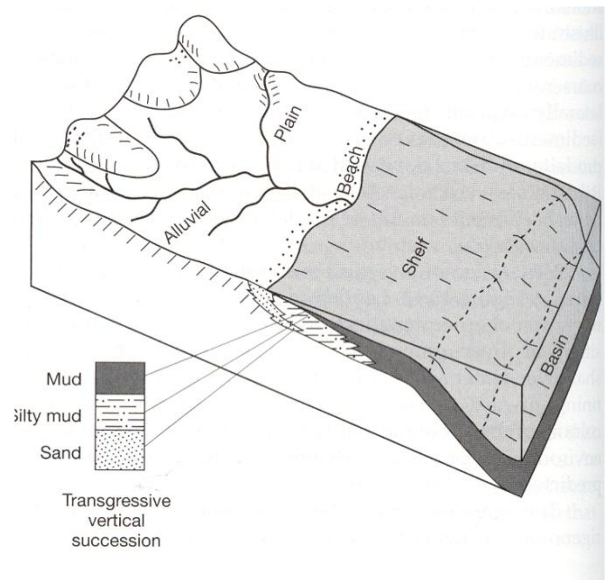


Figure 13.13
Schematic representation of Walther's Law applied to transgressive deposits. Transgression results in lateral shifts of environments and corresponding facies, producing the fining-upward vertical succession of facies shown in the column.

Practical application of Walther's law

Transgression: Transgression is a movement of a shoreline in a landward direction, also called a **retrogradation**.

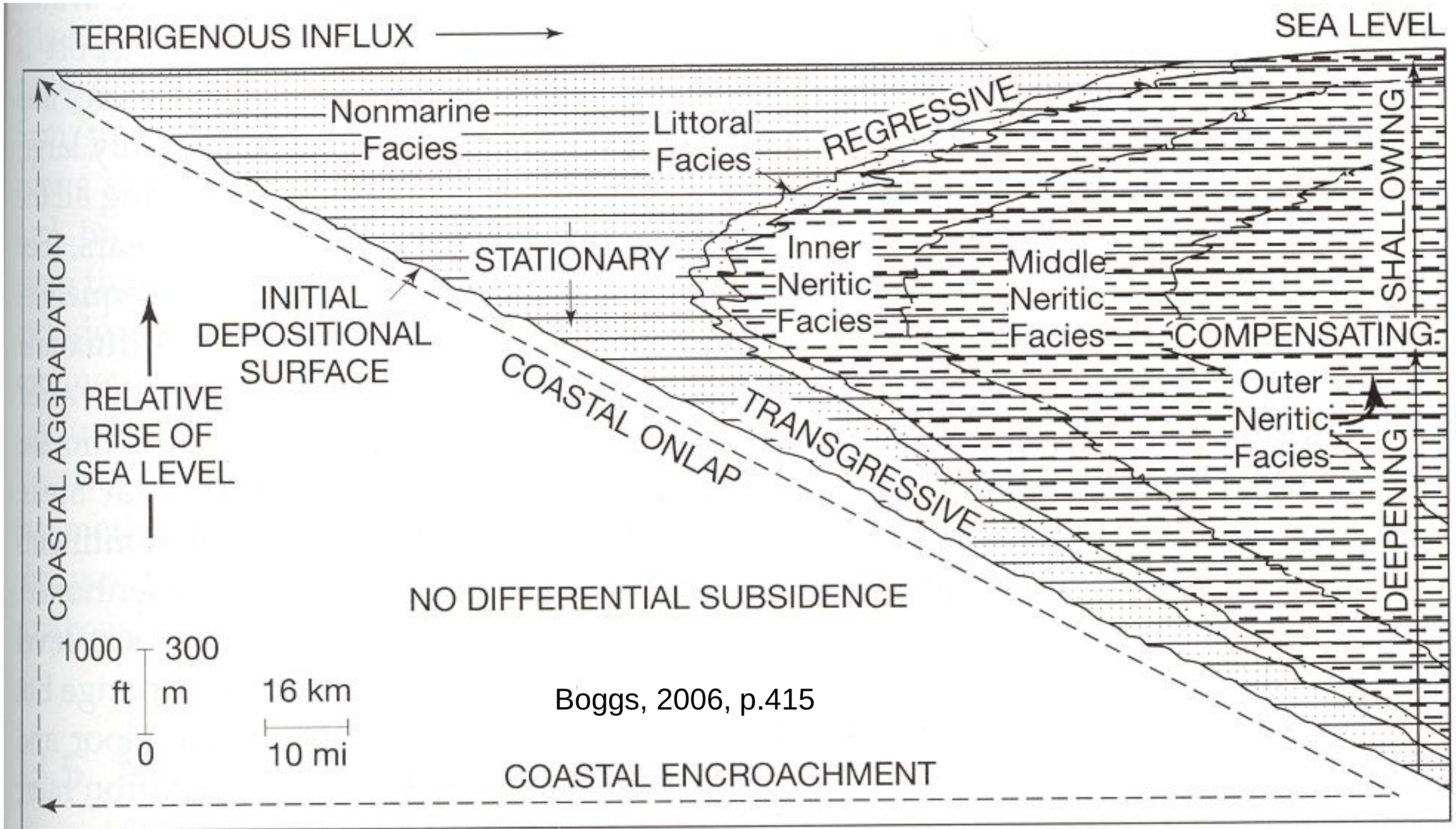
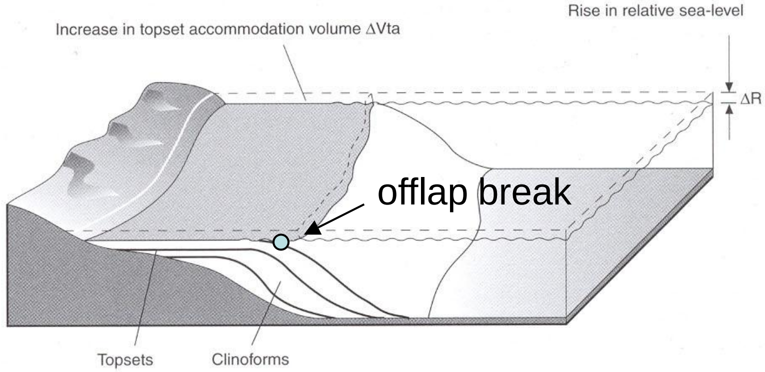


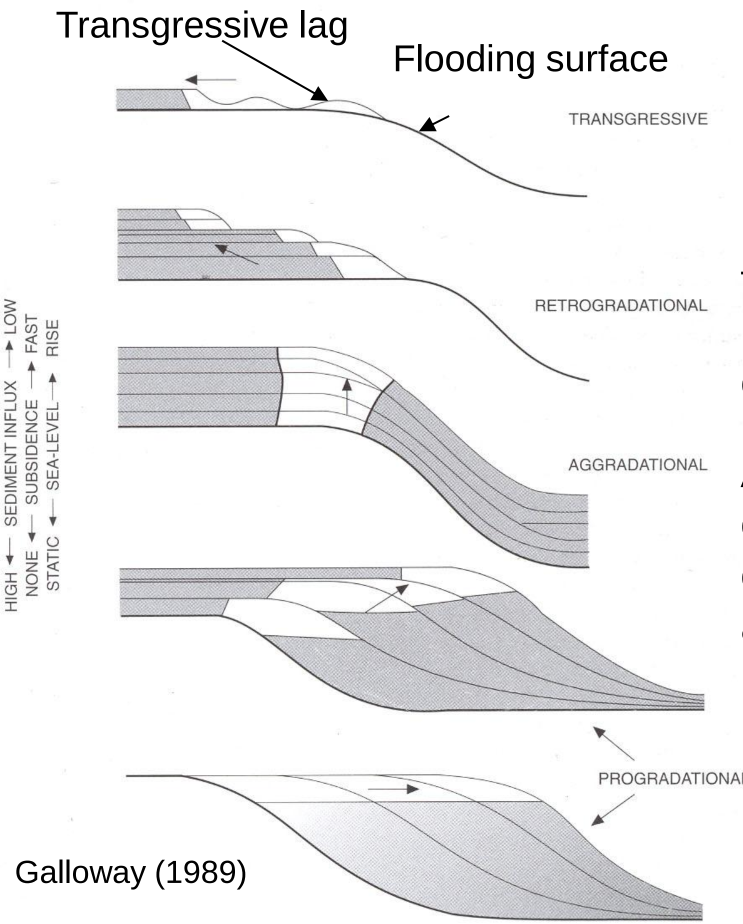
Figure 13.14
Coastal onlap owing to marine transgression and regression. During relative rise in sea level, littoral facies may be transgressive, stationary, or regressive. Neritic (shallow shelf) facies may be deepening, shallowing, or compensating (maintaining a given depth). Note the wedge of sediment formed during a cycle of transgression-regression. [From

Regression: Regression refers to movement of a shoreline in a seaward direction, also called a **progradation**.

Regression and transgression used in referring to the movement of shorelines; progradation and retrogradation used to refer movement of sediment facies.



The increment of topset accommodation volume ΔVta caused by a rise in relative sea-level ΔR is equal to the product of ΔR and the topset area



Galloway (1989)

Depositional architecture as a function of accommodation volume and sediment supply

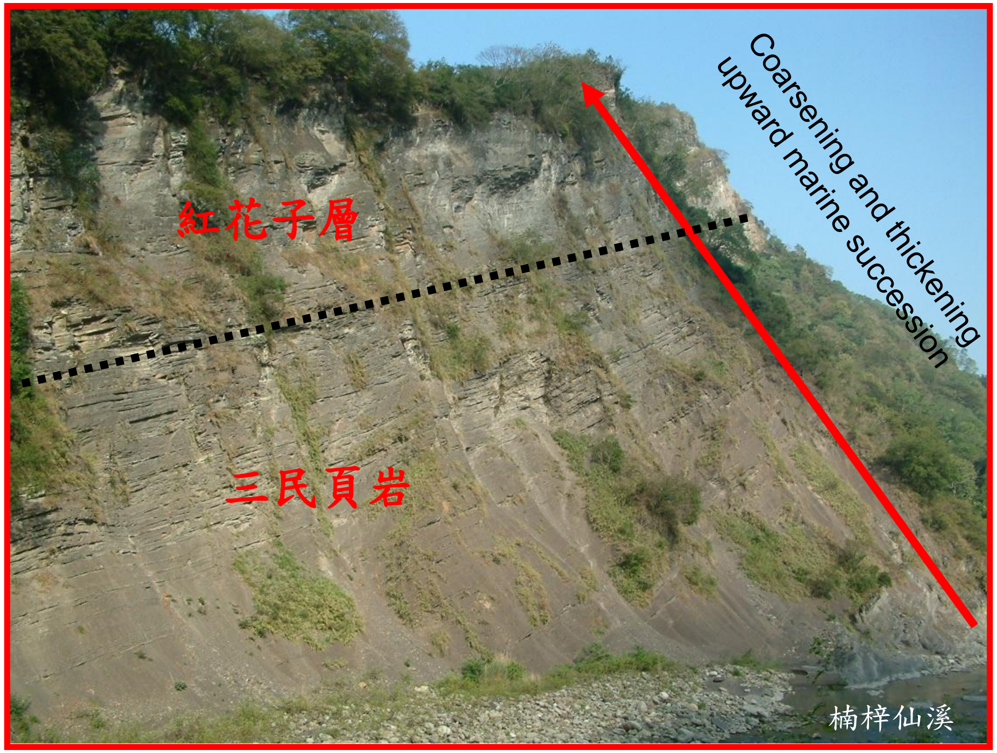
Transgression: landward movement of the shoreline. During the transgressive process, it may or may not deposit a thin bed called “transgressive lag”. This surface is called a “flooding surface”.

Retrogradational: Facies belts migrate landward and the former depositional offlap break becomes a relict feature. It occurs when sediment supply is less than the rate of creation of accommodation volume.

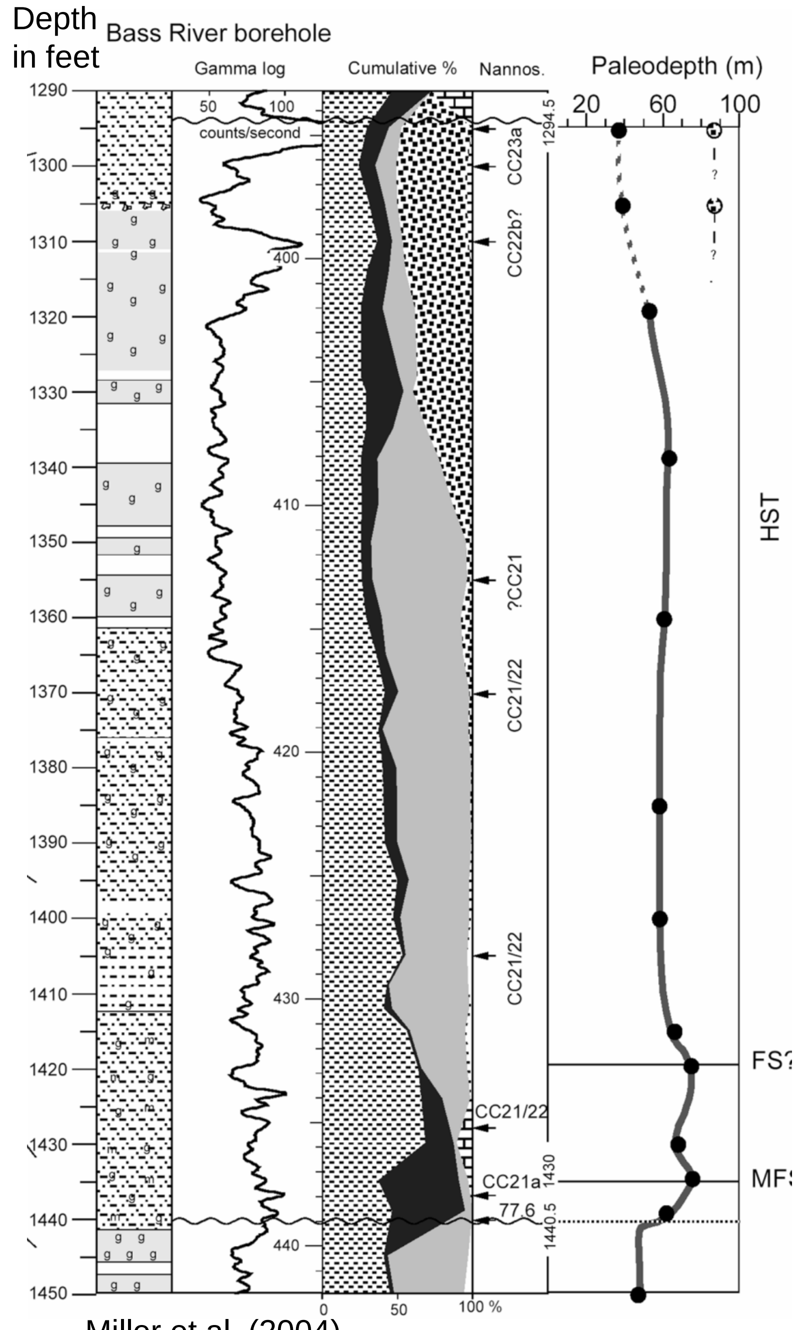
Aggradational: Facies belts stack vertically and the offlap break does not migrate landward or basinward. It occurs when sediment supply and rate of creation of accommodation volume are roughly balanced.

Progradational: Facies belt migrate basinward. This occurs when sediment supply exceeds the rate of creation of accommodation space.

Regression examples



New Jersey, Cretaceous, USA



Miller et al. (2004)

Transgression examples

Retrogradational succession, Jurassic, UK.

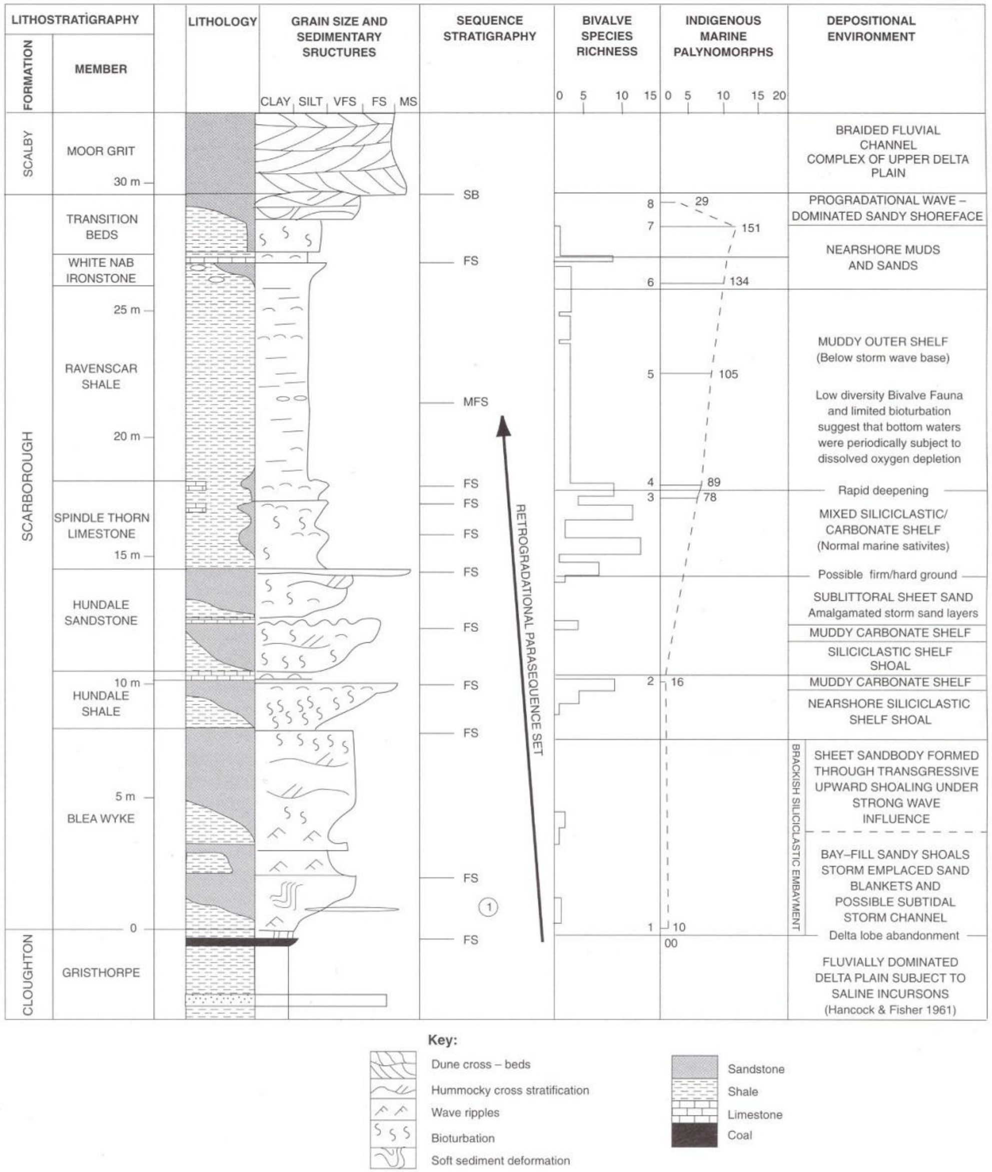
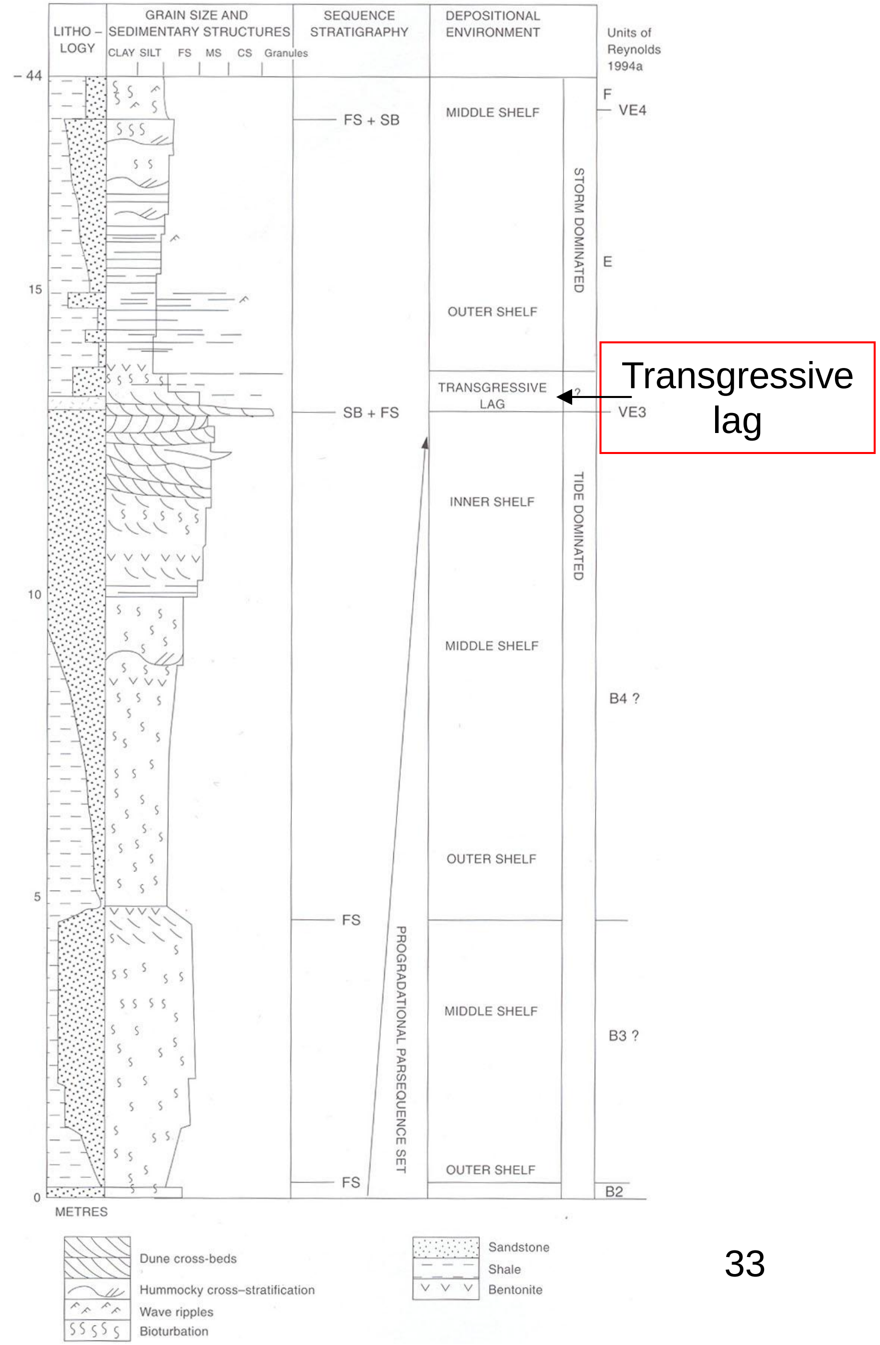


Fig. 4.3 Retrogradational parasequence architecture from the Middle Jurassic of the Yorkshire coast. See text for details (after Gowland and Riding, 1991). FS, flooding surface; MFS, maximum flooding surface; SB, sequence boundary

Viking Formation, Canada



Effects of climate and sea level on sedimentation patterns

Table 13.2 Postulated Mechanisms of Sea-level Change

Mechanisms	Time scale (yr)	Order of magnitude
1. Ocean steric (thermohaline) volume changes		
Shallow (0–500 m)	0.1–100	0–1 m
Deep (500–4000 m)	10–10,000	0.01–10 m
2. Glacial accretion and wastage		
Mountain glaciers	10–100	0.1–1 m
Greenland Ice Sheet	100–100,000	0.1–10 m
East Antarctic Ice Sheet	1,000–100,000	10–100 m
West Antarctic Ice Sheet	100–10,000	1–10 m
3. Liquid water on land		
Groundwater aquifers	100–100,000	0.1–10 m
Lakes and reservoirs	100–100,000	0.01–0.1 m
4. Crustal deformation		
Lithosphere formation and subduction	$100{,}000–10^8$	1–100 m
Glacial isostatic rebound	100–10,000	0.1–10 m
Continental collision	$100{,}000–10^8$	10–100 m
Seafloor and continental epirogeny	$100{,}000–10^8$	10–100 m
Sedimentation	$10{,}000–10^8$	1–100 m

Source: Revelle, 1990.

Boggs, 2006, p.416

2.3 Nomenclature and classification of lithostratigraphic units

Development of the stratigraphic code

US code

1933 Committee on Stratigraphic Nomenclature
1961 American Commission on Stratigraphic Nomenclature
1983 North American Commission on Stratigraphic Nomenclature

North American Commission on Stratigraphic Nomenclature (1983) North American Stratigraphic Code, American Association of Petroleum Geologists Bulletin, v.67 (5), 841-875. see Appendix C In Boggs (2006).

International code

Salvador, A. (ed.) (1994) International Stratigraphic Guide: A guide to stratigraphic classification, terminology, and procedure. International Union of Geological Sciences and Geological Society of America, Inc., Trondheim, Norway, 214 p.

Whittaker, A. et al. (1991) A guide to stratigraphical procedure. Journal Geological Society, London, v.148, 813-824.

Rawson, P.F. and 17 others (2002) Stratigraphical procedure: Geological Society of London Professional Handbook, 57 p.

袁彼得、林殿順(2009)簡介『中華民國地層命名原則』草案。經濟部中央地質調查所特刊，第22號，1-11頁。
(http://140.115.21.141/publications/papers/Yuan&Lin_2009_CGSSpecialPub_ROC_stratigraphic code-an introduction.pdf)

☆ Major types of stratigraphic units

Table 13.3 Categories of Stratigraphic Units Defined by the 1983 North American Stratigraphic Code

Boggs, 2006, p.419

Material categories based on content or physical limits (composition, texture, fabric, structure, color, fossil content)
- **Lithostratigraphic units**—conform to the law of superposition and are distinguished on the basis of lithic characteristics and lithostratigraphic position
- **Lithodemic units**—consist of predominantly intrusive, highly metamorphosed, or intensely deformed rock that generally does not conform to the law of superposition
- **Magnetopolarity units**—bodies of rock identified by remnant magnetic polarity
- **Biostratigraphic units**—bodies of rock defined and characterized by their fossil content
- **Pedostratigraphic units**—consist of one or more pedologic (soil) horizons developed in one or more lithic units now buried by a formally defined lithostratigraphic or allostratigraphic unit or units
- **Allostratigraphic units**—mappable stratiform (in the form of a layer) bodies defined and identified on the basis of bounding discontinuities

Categories expressing or related to geologic age
- **Material categories to define temporal spans** (stratigraphic units that serve as standards for recognizing and isolating materials of a particular age)
  - **Chronostratigraphic units**—bodies of rock established to serve as the material reference for all rocks formed during the same spans of time
  - **Polarity-chronostratigraphic units**—divisions of geologic time distinguished on the basis of the record of magnetopolarity as embodied in polarity-chronostratigraphic units
- **Temporal (nonmaterial) categories**—(not material units but conceptual units, i.e., divisions of time)
  - **Geochronologic units**—divisions of time distinguished on the basis of the rock record as expressed by chronostratigraphic units
  - **Polarity-chronologic units**—divisions of geologic time distinguished on the basis of the record of magnetopolarity as embodied in polarity-chronostratigraphic units
  - **Diachronic units**—comprise the unequal spans of time represented by one or more specific diachronous rock bodies, which are bodies with one or two bounding surfaces that are not time synchronous and thus "transgress" time
  - **Geochronometric units**—isochronous units (units having equal time duration) that are direct divisions of geologic time expressed in years

Source: North American Commission on Stratigraphic Nomenclature, 1983, North American Stratigraphic Code: *Am. Assoc. Petroleum Geologists Bull.*, v. 67.

The various categories of stratigraphic units recognized by the North American Stratigraphic Code (1983) are listed on the left.

Table 12.4 Categories and ranks of stratigraphic units as defined in North American Commission on Stratigraphic Nomenclature Note 63

I. Material categories based on content or physical limits

Lithostratigraphic	Lithodemic	Magnetopolarity	Biostratigraphic	Pedostratigraphic	Allostratigraphic
Supergroup	Supersuite				
Group	Suite Complex	Polarity Superzone			Allogroup
Formation	*Lithodeme*	*Polarity Zone*	*Biozone* (Interval, Assemblage or Abundance)	*Geosol*	*Alloformation*
Member (or Lens, or Tongue)		Polarity Subzone	Subbiozone		Allomember
Bed(s) or Flow(s)					

IIA. Material categories used to define temporal spans

Chronostratigraphic	Polarity Chronostratigraphic
Eonothem	Polarity Superchronozone
Erathem (Supersystem)	
System (Subsystem)	*Polarity Chronozone*
Series	
Stage (Substage)	Polarity Subchronozone
Chronozone	

IIB. Nonmaterial categories related to geologic age

Boggs, 2006, p.420

Geochronologic	Polarity Chronologic	Diachronic	Geochronometric
Eon	Polarity Superchron		Eon
Era (Superperiod)			Era (Superperiod)
Period (Subperiod)	*Polarity Chron*	*Episode*	*Period* (Subperiod)
Epoch		Diachron Phase	Epoch
Age (Subage)	Polarity Subchron	Span	Age (Subage)
Chron		Cline	Chron

*Fundamental units are italicized.

Source: Ferrusquia-Villafranca et al., 2001.

Lithodemic units: A lithodemic unit is a defined body of predominantly intrusive, highly deformed, and/or highly metamorphosed rock, distinguished and delimited on the basis of rock characteristics. In contrast to lithostratigraphic units, a lithodemic unit generally does not conform to the Law of Superposition. Its contacts with other rock units may be sedimentary, extrusive, intrusive, tectonic, or metamorphic.

Boggs, 2006, p.604

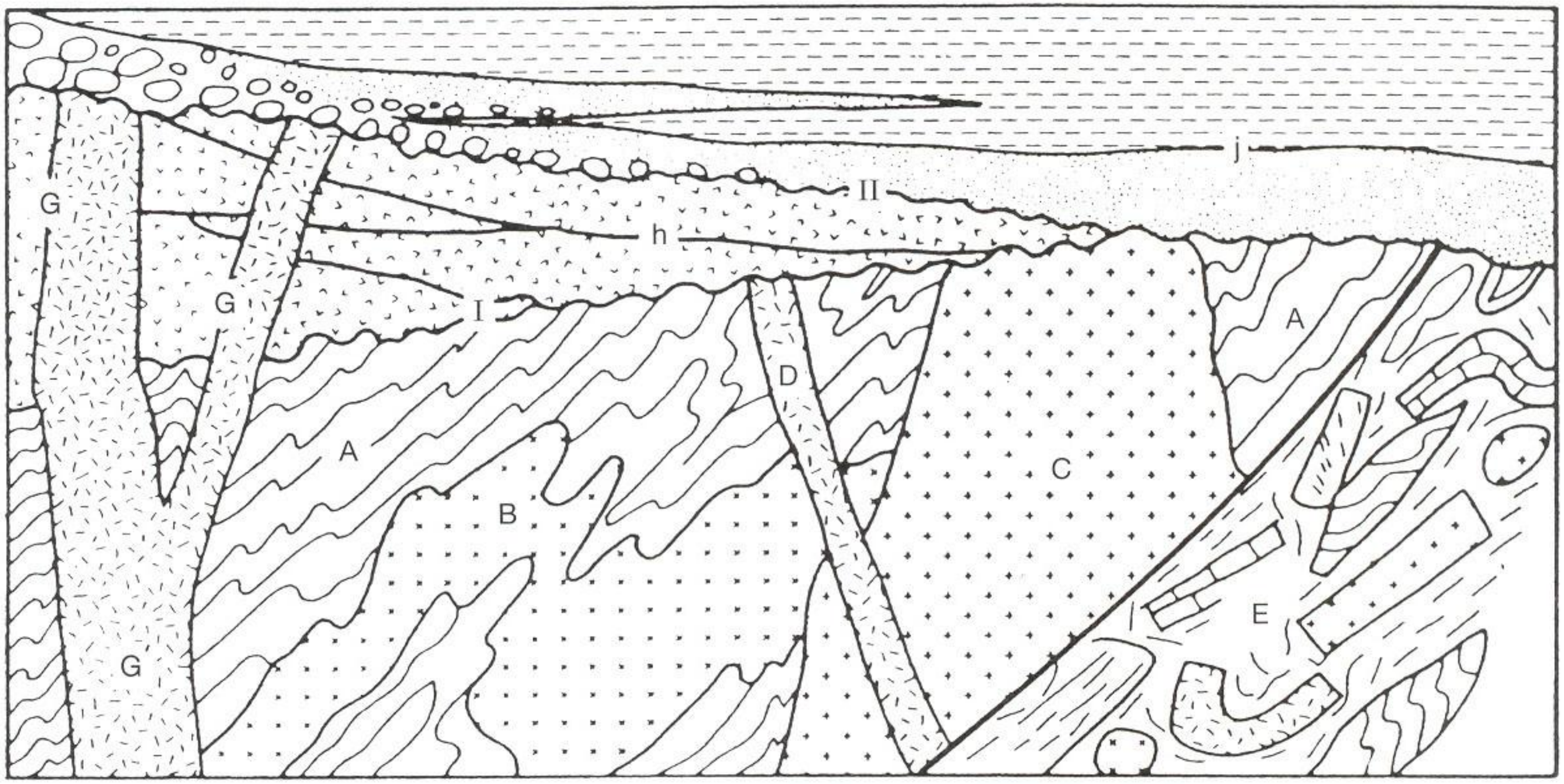


FIG. 3.–Lithodemic (upper case) and lithostratigraphic (lower case) units. A *lithodeme* of *gneiss* (A) contains an *intrusion* of diorite (B) that was deformed with the gneiss. A and B may be treated jointly as a *complex*. A younger *granite* (C) is cut by a dike of *syenite* (D), that is cut in turn by unconformity I. All the foregoing are in fault contact with a *structural complex* (E). A *volcanic complex* (G) is built upon unconformity I, and its feeder dikes cut the unconformity. Laterally equivalent volcanic strata in orderly, mappable succession (h) are treated as lithostratigraphic units. A *gabbro* feeder (G′), to the volcanic complex, where surrounded by gneiss is readily distinguished as a separate lithodeme and named as a *gabbro* or an *intrusion*. All the foregoing are overlain, at unconformity II, by sedimentary rocks (j) divided into formations and members.

Table 13.5 Hierarchy of Lithostratigraphic Units

Supergroup—a formal assemblage of related or superposed groups or of groups and formations.

- **Group**—Consists of assemblages of formations, but groups need not be composed entirely of named formations.
  - **Formation**—a body of rock, identified by lithic characteristics and stratigraphic position, that is prevailingly but not necessarily tabular and is mappable at Earth's surface and traceable in the subsurface. Must be of sufficient areal extent to be mappable at the scale of mapping commonly used in the region where it occurs. **The fundamental lithostratigraphic unit**—formations are grouped to form higher-rank lithostratigraphic units and are divided to form lower-rank
    - **Member**—the formal lithostratigraphic unit next in rank below a formation and always part of some formation. A formation need not be divided entirely into members. A member may extend laterally from one formation to another.
    - **Lens** (or lentil)—a geographically restricted member that terminates on all sides within a formation.
    - **Tongue**—a wedge-shaped member that extends beyond the main boundary of a formation or that wedges or pinches out within another formation.
      - **Bed**—distinctive subdivisions of a member; the smallest formal lithostratigraphic unit of sedimentary rock. Members commonly are not divided entirely into beds.
      - **Flow**—the smallest formal lithostratigraphic unit of volcanic rock.

Boggs, 2006, p.421

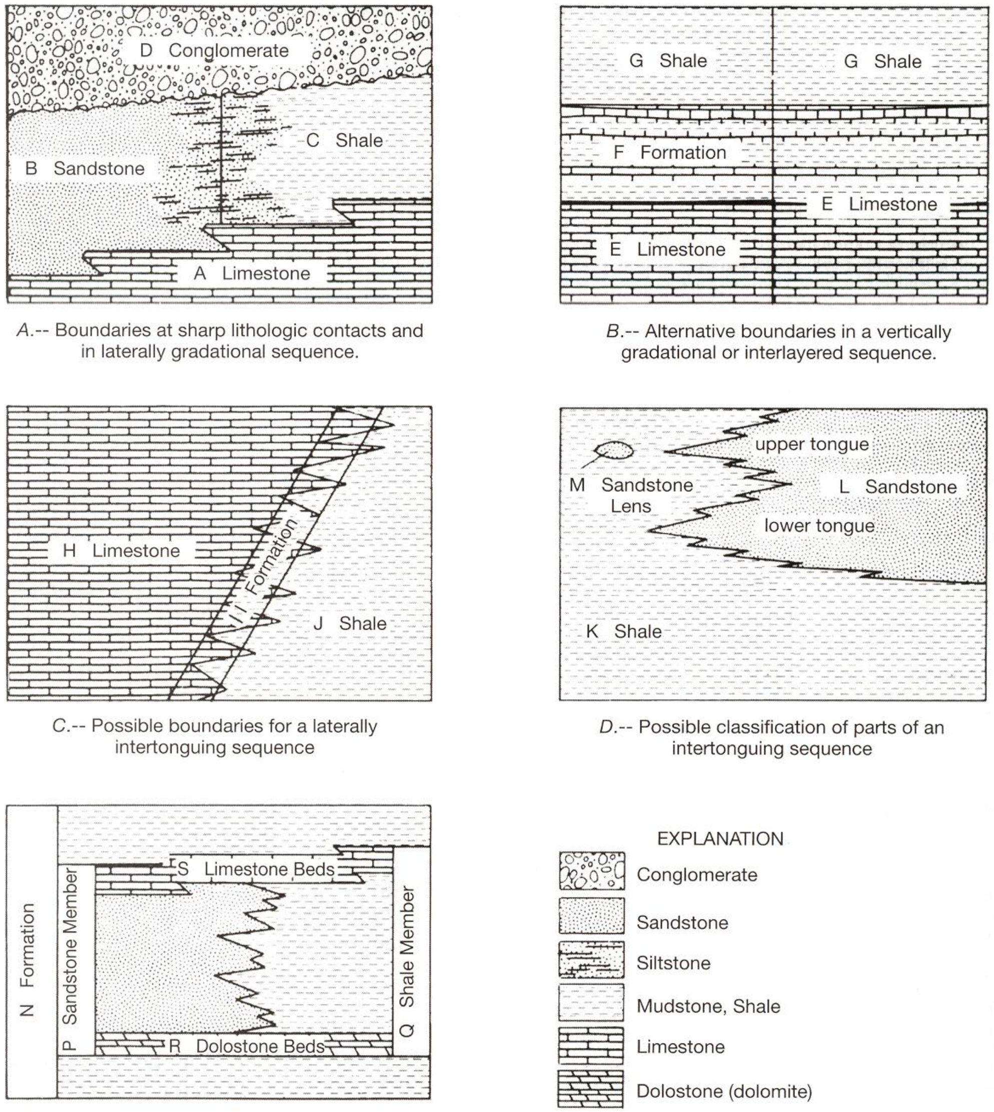
Source: North American Commission on Stratigraphic Nomenclature, 1983, North American Stratigraphic Code: *Am. Assoc. Petroleum Geologists Bull.*, v. 67.

Formation is the fundamental unit of lithostratigraphic classification. All other lithostratigraphic units are defined as either assemblages or subdivisions of formations. Formation may be defined on the basis of:

◎ a single lithic type (e.g. conglomerate, sandstone, shale, limestone, volcanic rocks. Such as林口礫岩、觀音山砂岩、錦水頁岩、港口石灰岩、公館凝灰岩)

◎ repetitions of two or more lithic types (e.g. intercalated sandstone and shale, such as卓蘭層)

◎ extreme lithic heterogeneity (where such heterogeneity constitutes a form of unity when compared to adjacent units). (For example, 利吉層、墾丁層)



E-- Key beds, here designated the R Dolostone Beds and the S Limestone Beds, are used as boundaries to distinguish the Q Shale Member from the other parts of the N Formation. A lateral change in composition between the key beds requires that another name, P Sandstone Member, be applied. The key beds are part of each member.

Boggs, 2006, p.601

FIG. 2.–Diagrammatic examples of lithostratigraphic boundaries and classification.

Definition of lithostratigraphic units is based on a stratotype (a designated type unit, 標準剖面), or type section, consisting of readily accessible rocks, where possible, in natural outcrops, excavations, mines, or boreholes.

A stratotype is the standard for a named geologic unit or boundary and constitutes the basis for definition or recognition of that unit or boundary; therefore, it must be illustrative and representative of the concept of the unit or boundary being defined.

2.4 Correlation of lithostratigraphic units

Stratigraphic correlation is the demonstration of equivalency of stratigraphic units. Three categories of correlation:

1. Lithocorrelation, which links units of similar lithology and stratigraphic position;
2. Biocorrelation, which expresses similarity of fossil content and biostratigraphic position; and
3. Chronocorrelation, which expresses correspondence in age and chronostratigraphic position.

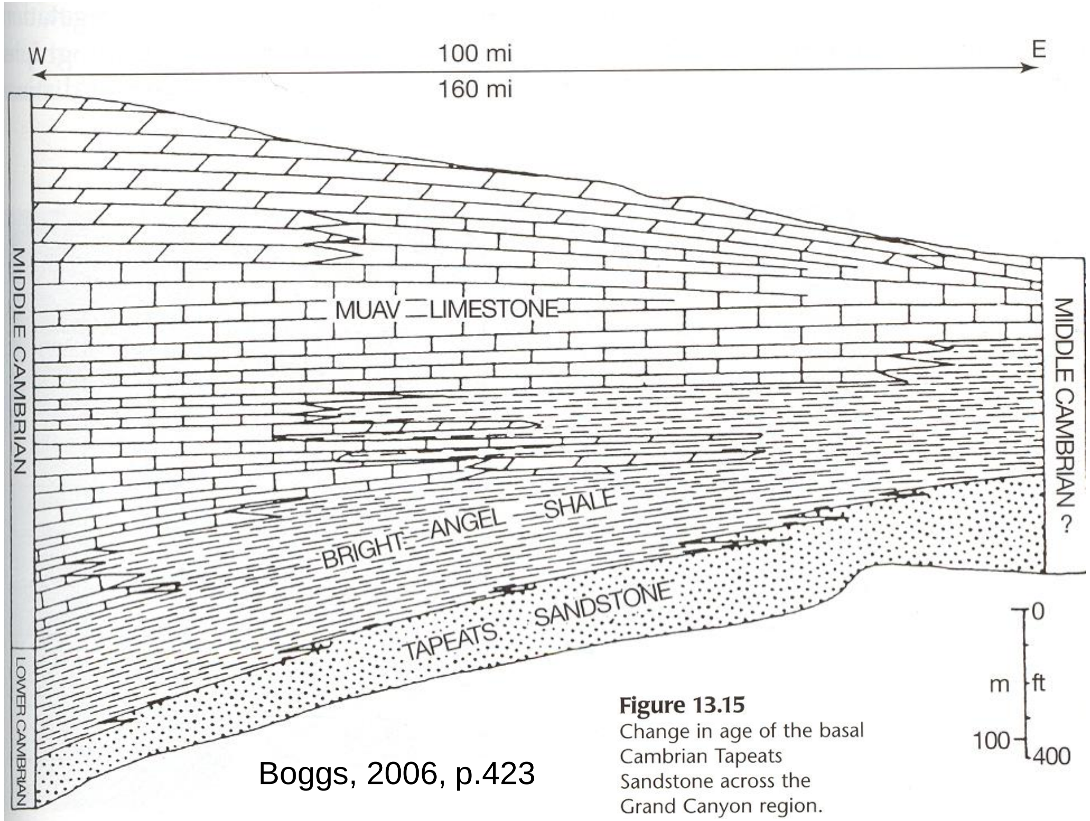


Figure 13.15
Change in age of the basal Cambrian Tapeats Sandstone across the Grand Canyon region.

Boggs, 2006, p.423

Difference in lithocorrelation and chronocorrelation

◎ Correlation of units defined by lithology may also yield chronostratigraphic correlation on a local scale, but when traced regionally many lithostratigraphic units transgress time boundaries. Stratigraphic units deposited during major transgressions and regressions are notably time-transgressive.

Lithocorrelation

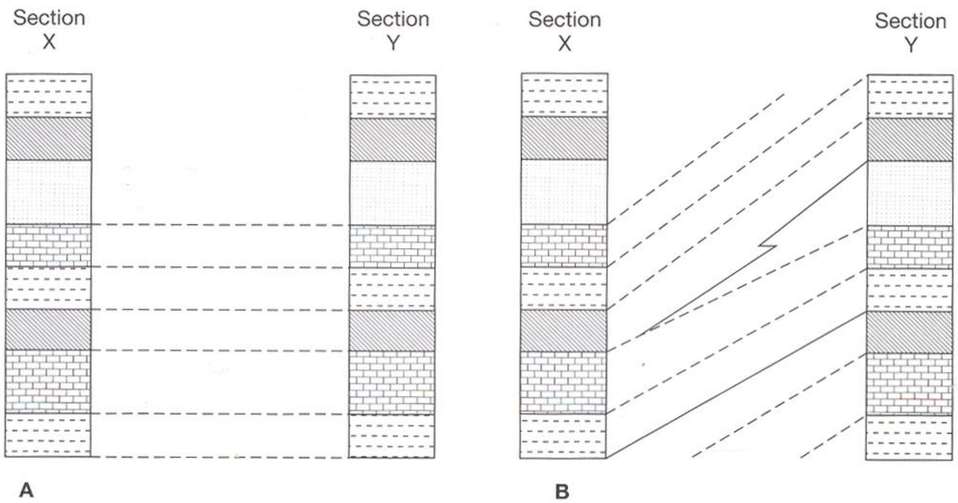
Direct correlation: Continuous lateral tracing of lithostratigraphic units (applicable only in widely- and well-exposed strata); e.g., walking out the beds; following the beds on aerial photographs.

Matching and correlation: Direction correlation is a “correlation; indirect correlation is a “matching”.

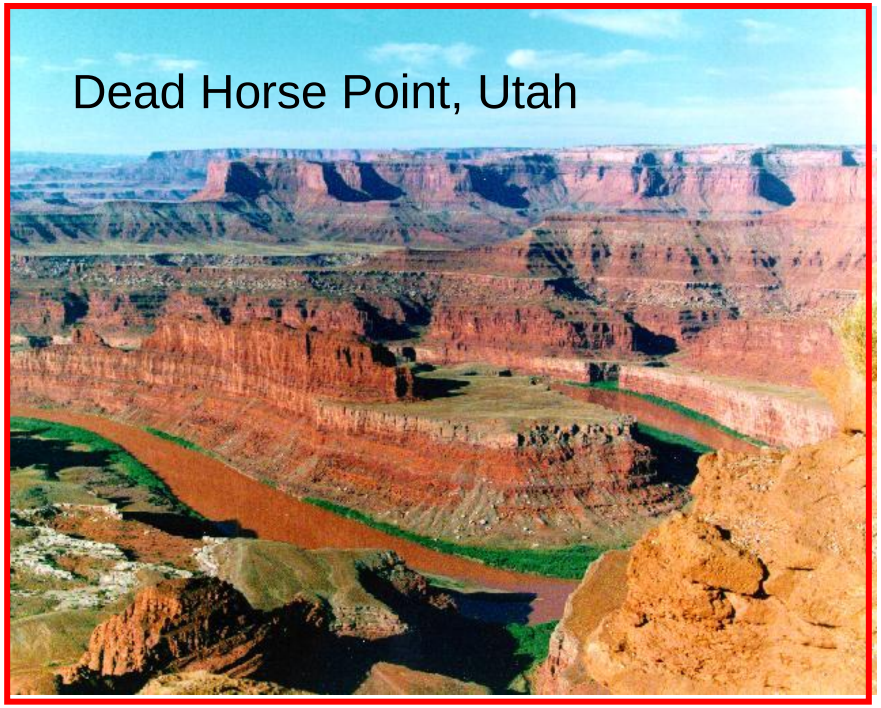
Direct correlation: tracing beds along outcrops

Apparent correlation (matching)

Actual lithocorrelation



Boggs, 2006, p.424

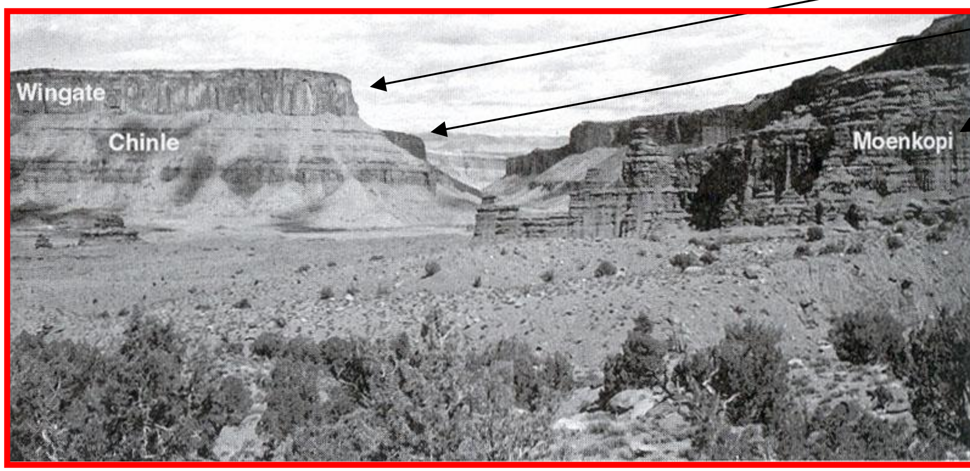


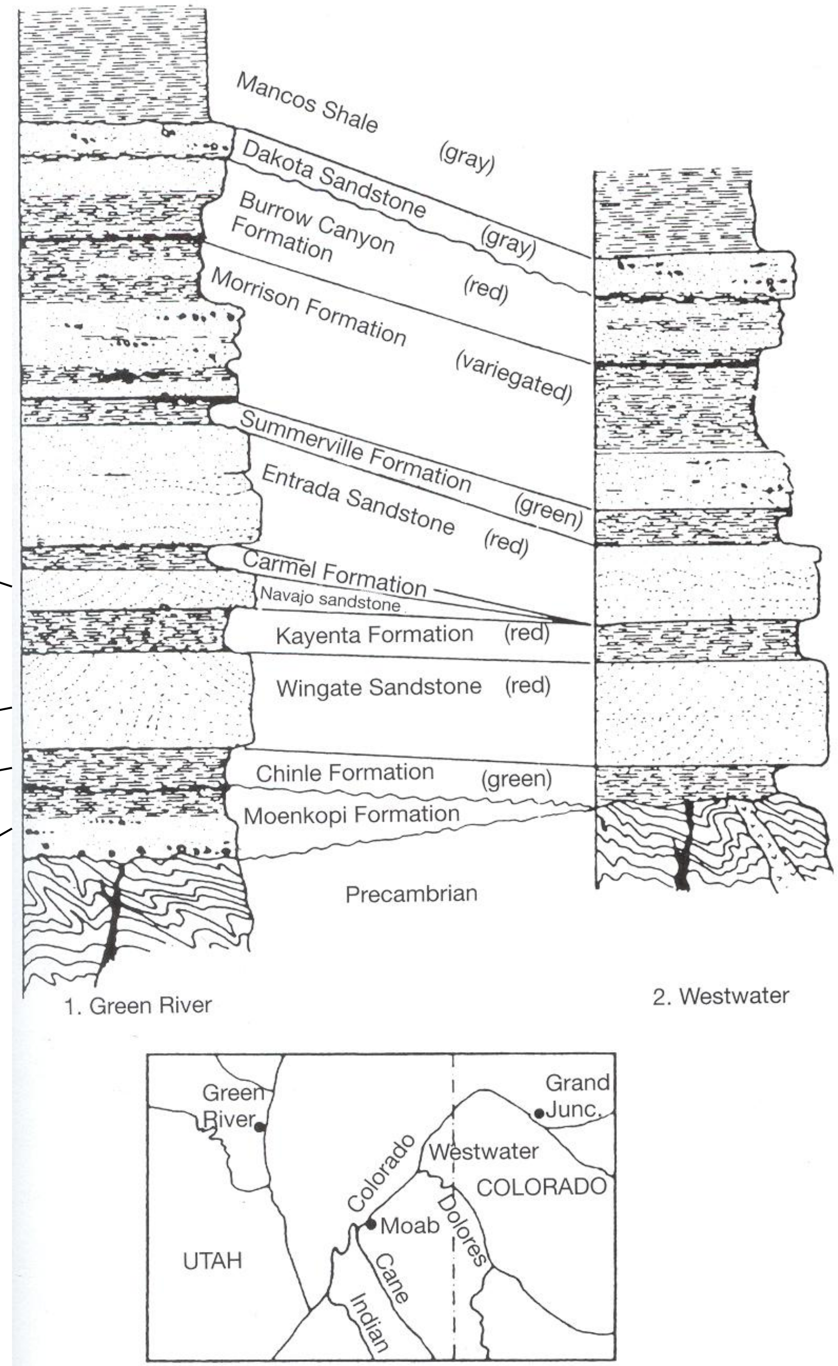
Lithologic similarity and stratigraphic position (indirect correlation)

Lithologic similarity based on: gross lithology (e.g., sandstone, shale, limestone), color, mineral assemblages, primary sedimentary structures, thickness and weathering characteristics etc. A single properties may change laterally within a given stratigraphic unit, but a suite of distinctive lithologic properties is less likely to change. It is therefore better in using **a succession of several distinctive units** to match (correlate) stratigraphic columns.

Marker bed (key bed, 指準層): A thin bed of distinctive rock that is widely distributed. For examples, a thin, ash-fall unit or bentonite bed, transgressive lag, extensive coal bed etc.

Correlation of strata between two localities on the Colorado Plateau on the basis of similar lithology of distinctive stratigraphic units.





Boggs, 2006, p.426-427