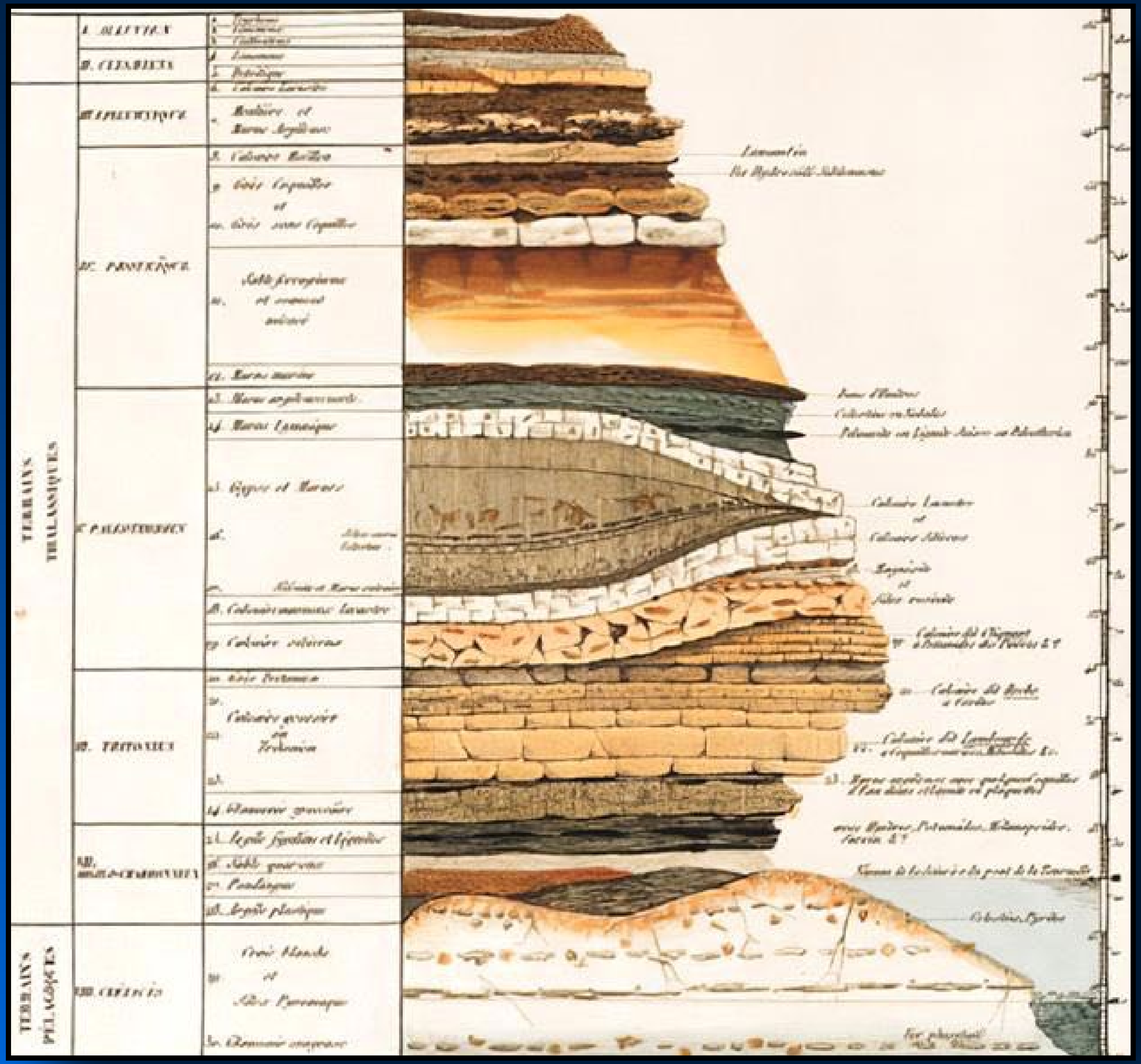
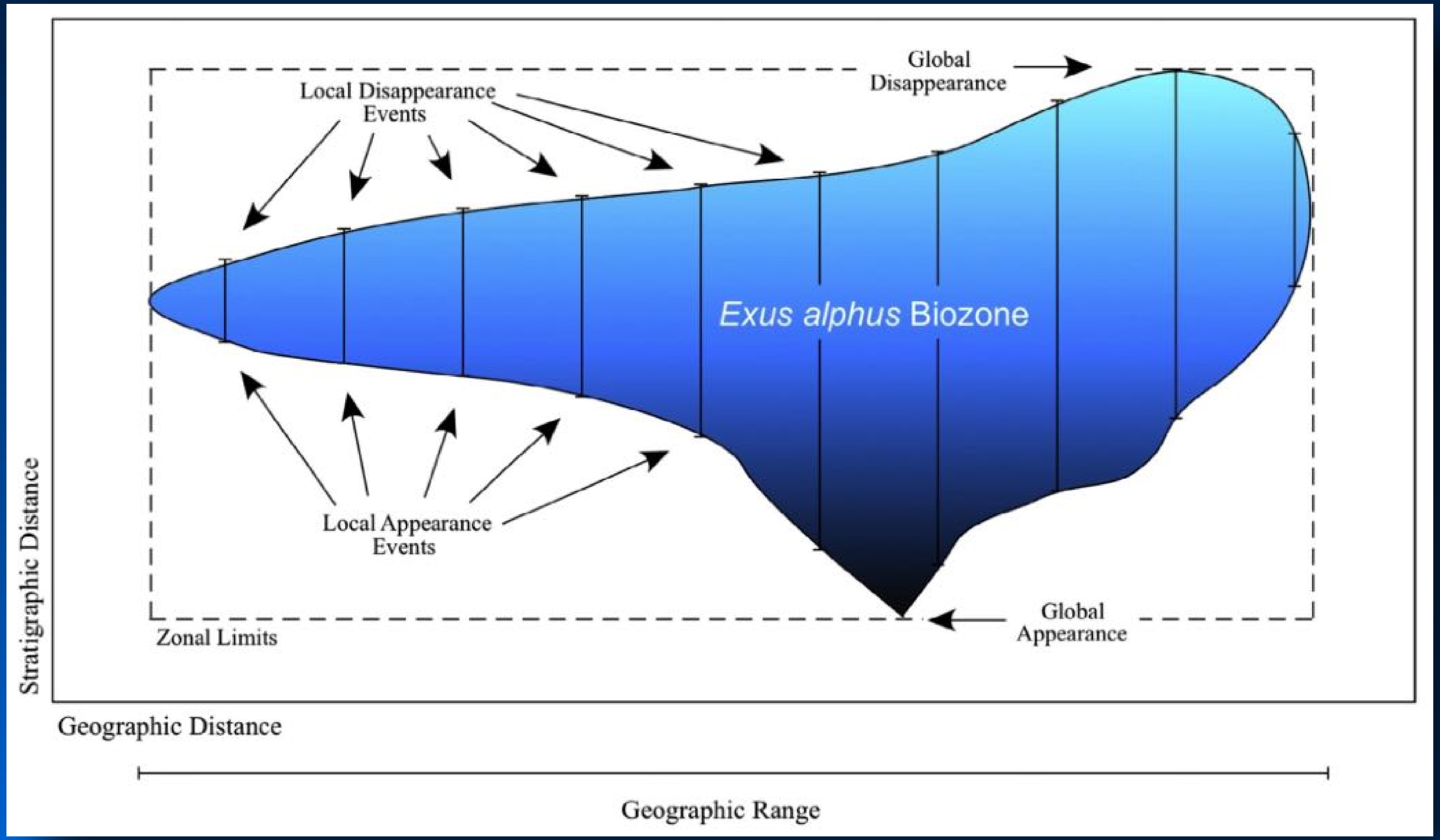
NJU Course

Principles of Paleobiology

Stratigraphy: Zonation & Correlation

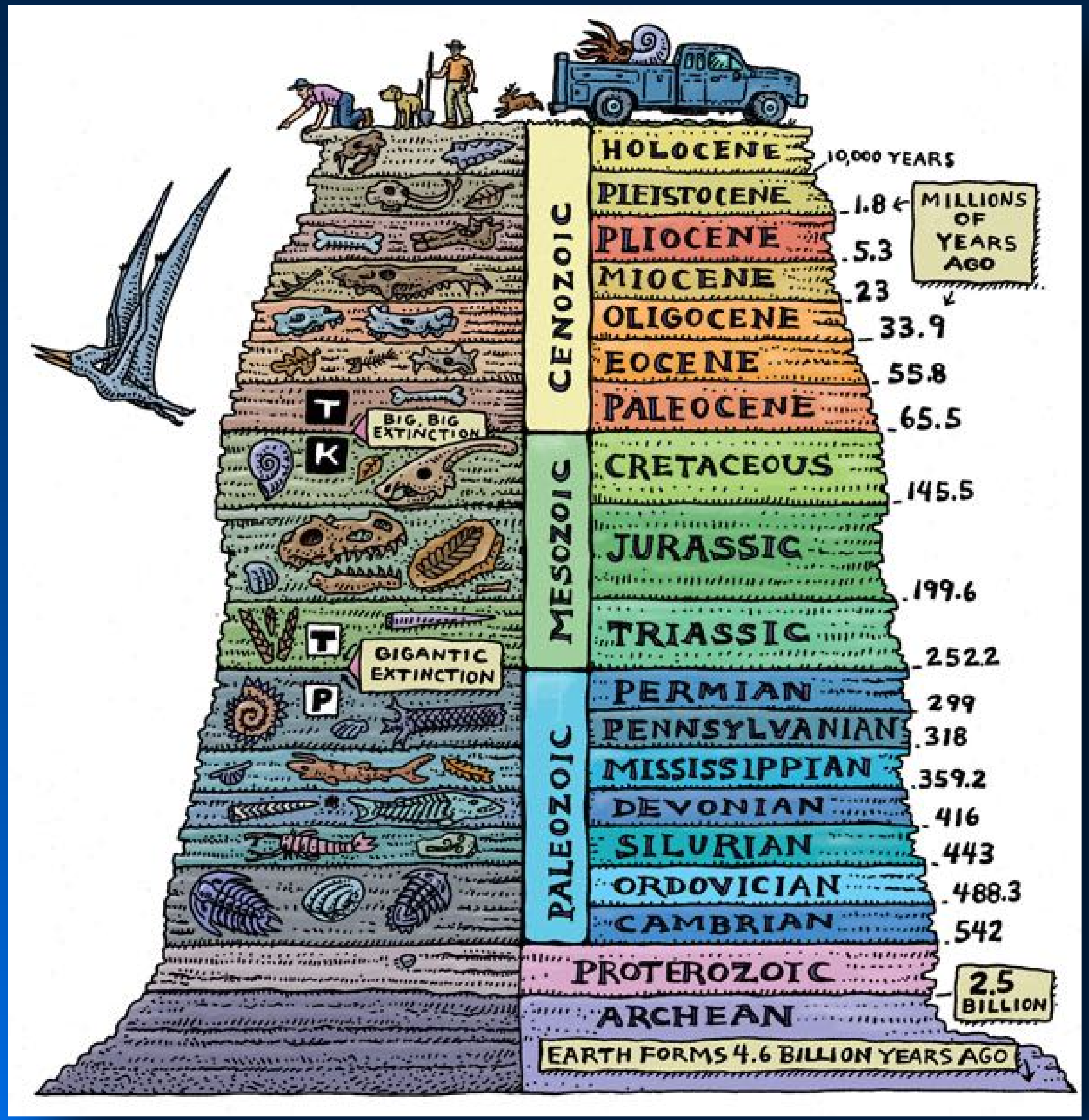




Stratigraphy: Zonation & Correlation

Stratigraphy

Stratigraphy - The branch of geology that studies rock layers.



Stratigraphy: Zonation & Correlation

Stratigraphy

Stratigraphy - The branch of paleobiology that establishes the temporal context of paleobiological data.

- Owing to the laws of superposition, original horizontality, and crosscutting relations stratigraphic relations can be used to infer relative time sequences.
- Fossils are typically used to assign relative ages to rock layers, though other sources of information may also be helpful in this respect.
- In some cases rock layers may contain materials that can be used to assess the absolute time of formation of the layer.

Stratigraphy: Zonation & Correlation

What is Time?

Time is …

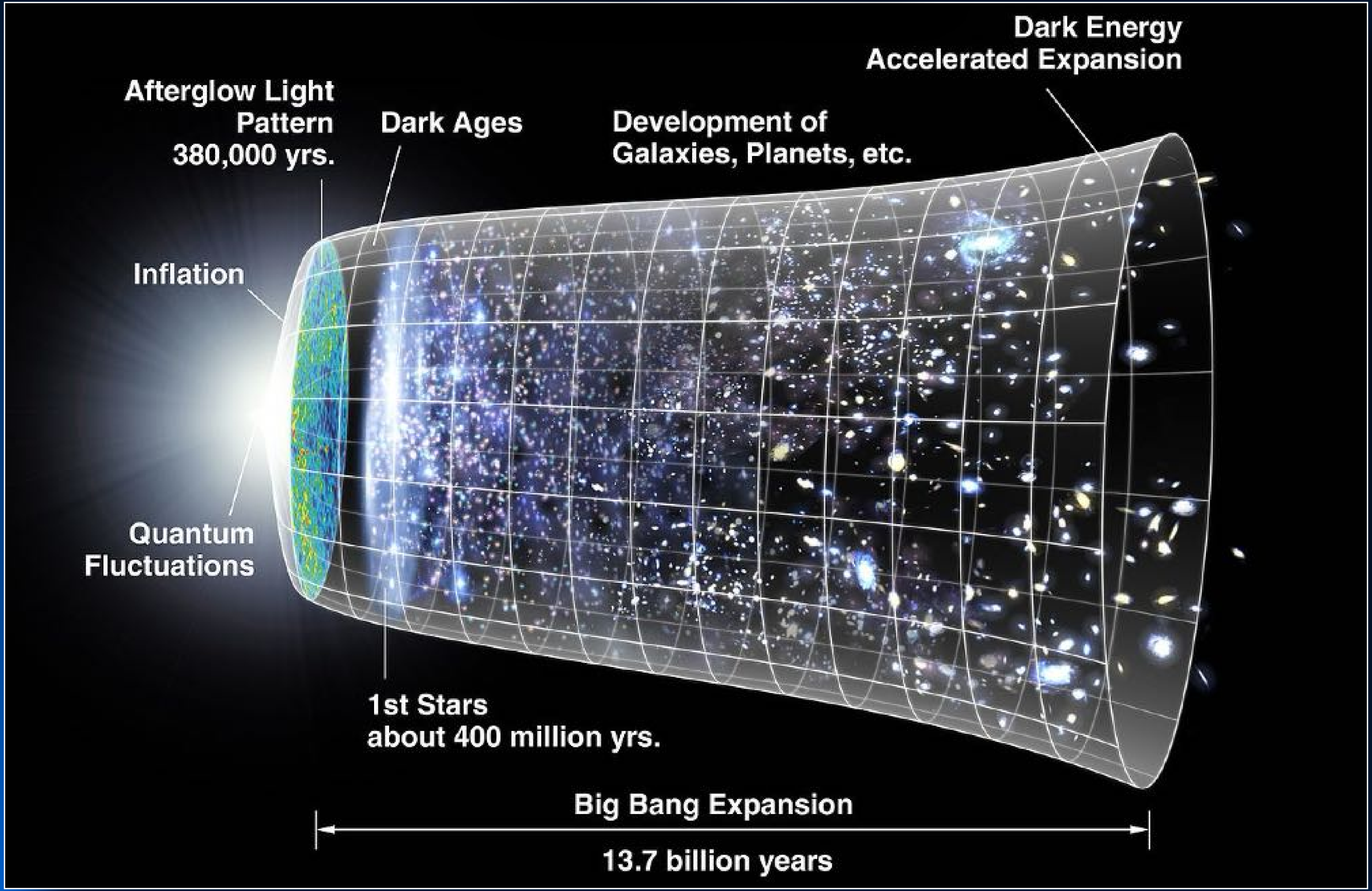
- … the scale against which observable events can be ordered into a sequence.
- … the scale against which the durations of events, and/or the intervals between them can be measured.

But what kind of scale does time represent? Is it constant or variable? Directional or cyclic? Finite or infinite? Is it a “thing” or merely a convenient concept?

Philosophers, theologians, and scientists as diverse as Socrates, St. Agustine, Newton, Kant, and Einstein have all expressed fundamentally differing views regarding the precise nature of time.

Stratigraphy: Zonation & Correlation

What is Time?



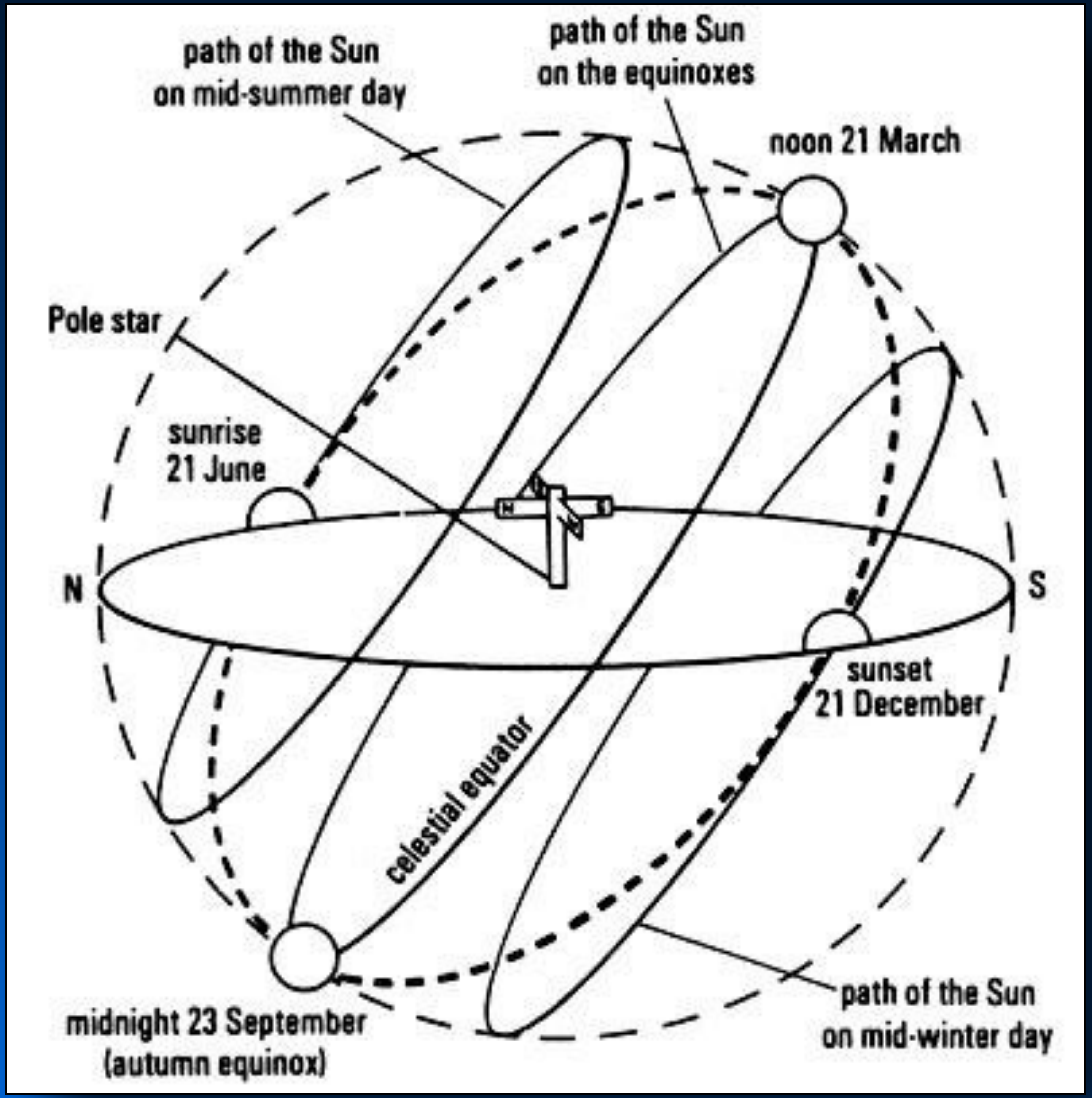
By convention we measure time via reference to the motion of objects. For example, the age of the universe is estimated to be 13.7 billion years based on the distance to the furthest galaxies and the speed at which they are moving away from the Earth.

Stratigraphy: Zonation & Correlation

What is Time?

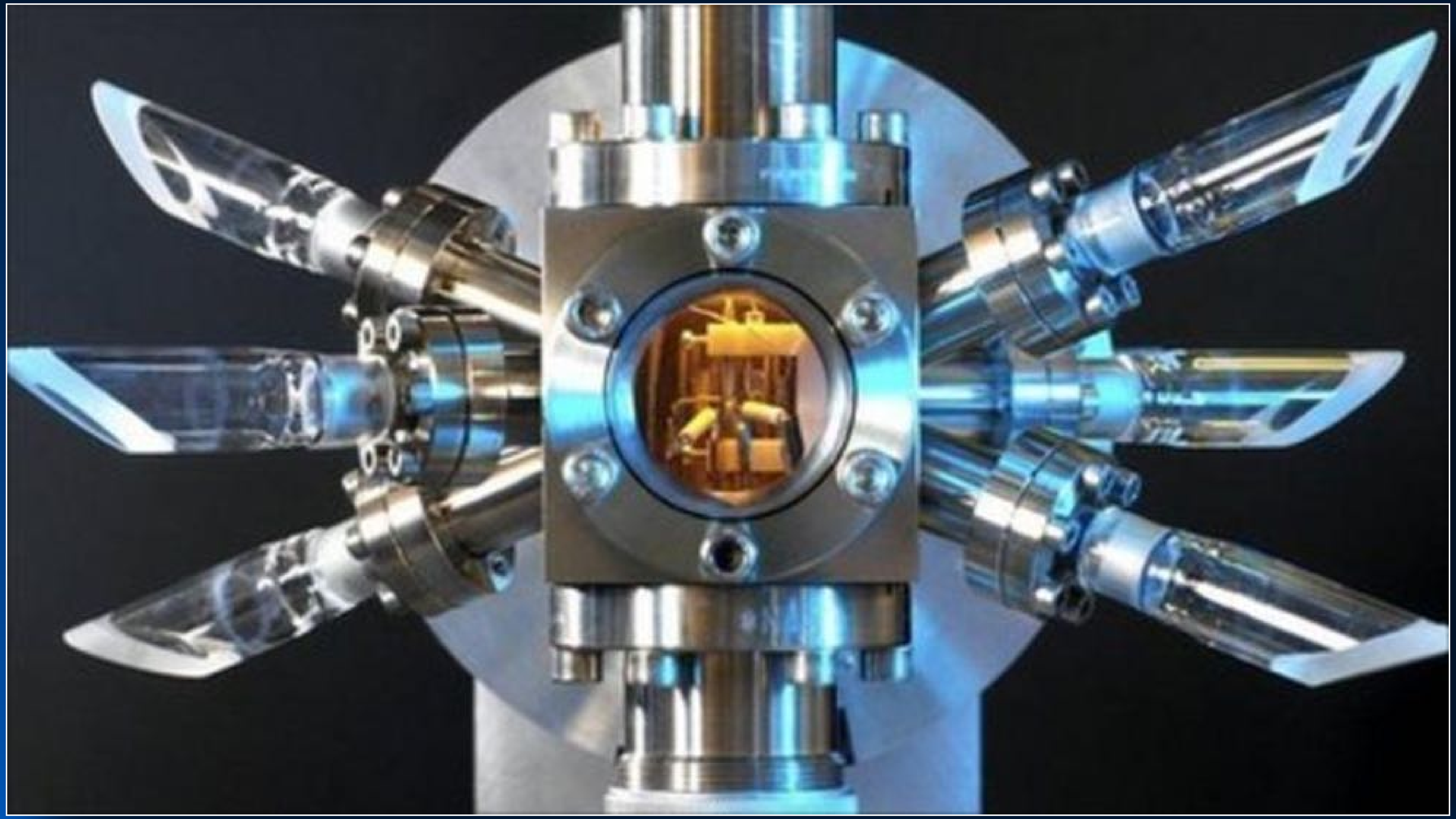
In ancient times a year was defined as the time interval between Sol (the sun) reaching its absolute maximum height above the horizon and the day as the time interval between the sun reaching successive maximum heights above the horizon.

Later it was discovered these variations were the result of the Earth turning on its rotational axis (day) and that axis being inclined to the plane of the Earth's orbit around the sun at 23.5°.



Stratigraphy: Zonation & Correlation

What is Time?

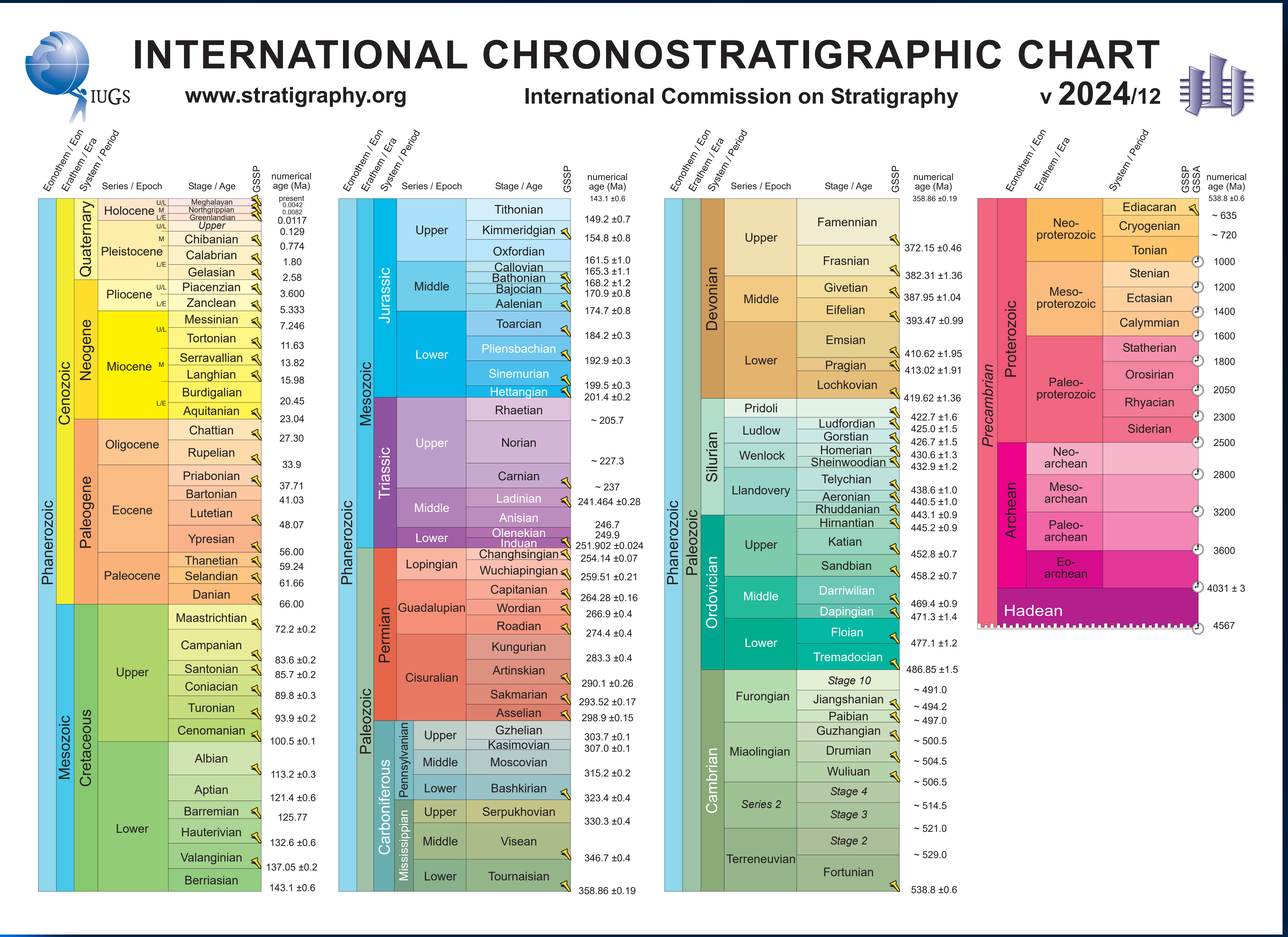


We still reference time to the motion of objects. Watches count minutes and hours as the time required for the second and hour hands to complete one cycle of the watch face. Atomic clocks — currently the world's most accurate — measure the intervals of time required by electrons as they oscillate between energy levels. Here 1 sec. is defined as 9,192,631,770 oscillations of the Cs^{133} atom.

Stratigraphy: Zonation & Correlation

Stratigraphy

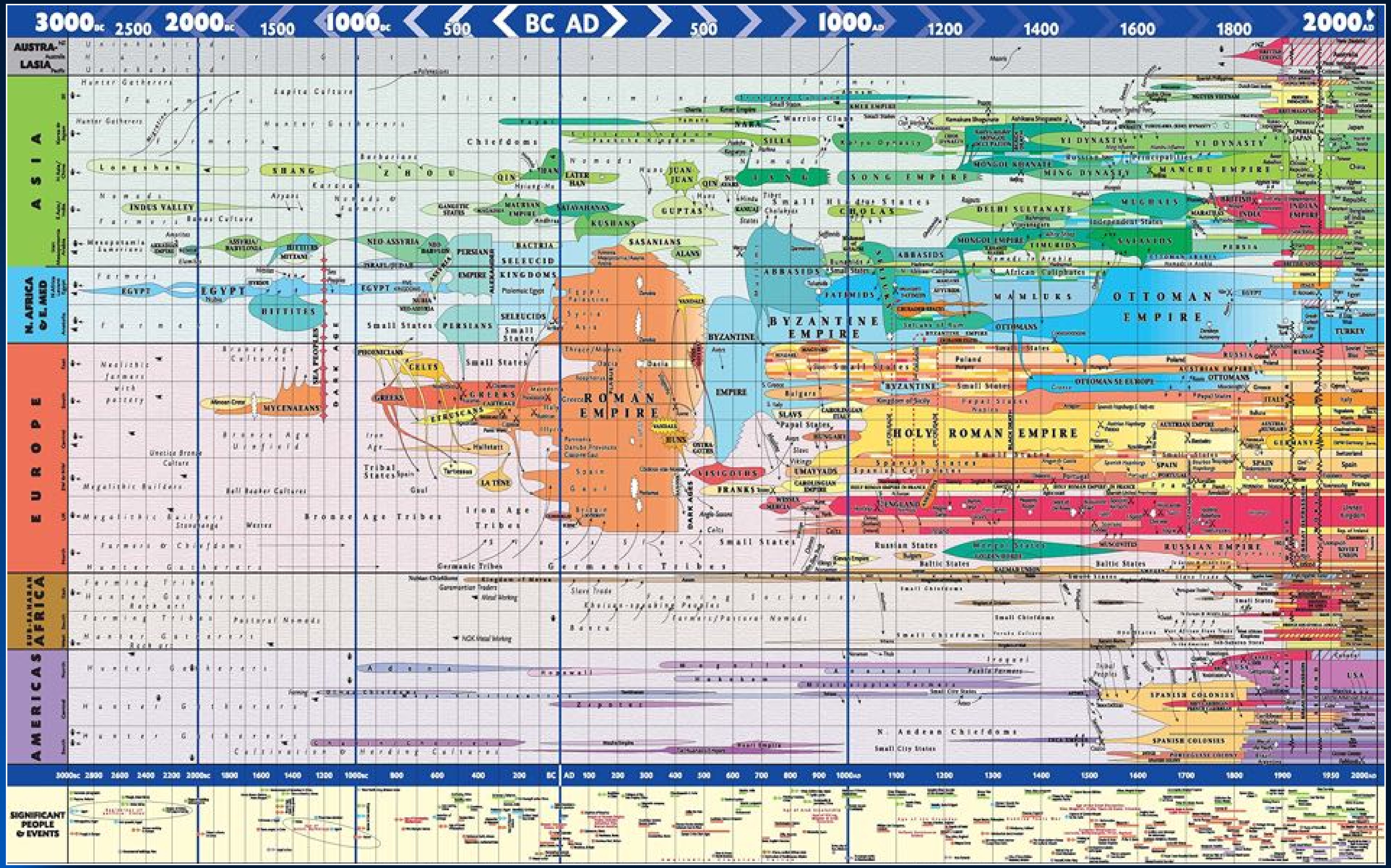
How Do We Tell Time in the Stratigraphic Record?



Stratigraphy: Zonation & Correlation

Historical Time?

1. 4000 BC Origins of Civilization
2. 3000 BC The Ancient Middle East
3. 2700 BC ______________
4. 2600 BC Ancient India
5. 2000 BC Ancient China
6. 2000 BC ______________
7. 1600 BC Native Americans
8. 800 BC-476 AD Ancient Rome
9. 500-1050 ______________
10. 610 The Origins of Islam
11. 1096-1291 ______________
12. 1050-1350 The Late Middle Ages
13. 1300 ______________
14. 1517 The Protestant Reformation
15. 1534 Henry VIII
16. 1543 ______________
17. 1492 Europeans Explore Overseas
18. 1625 Parliament
19. 1651 ______________
20. 1789 The French Revolution
21. 1804 ______________
22. 1800-1914 The Age of Imperialism
23. 1914-1918 ______________
24. 1917 The Russion Revolution
25. 1939-1945 ______________
26. 1945-1991 The Cold War New



Historians work with two time scales, the first is the scale of absolute time which is determined by physics, but the second is the scale of relative time in which time major time intervals are defined by major cultural transitions (e.g., political changes, technological innovations). This relative time scale is produced by a process termed “periodization”.

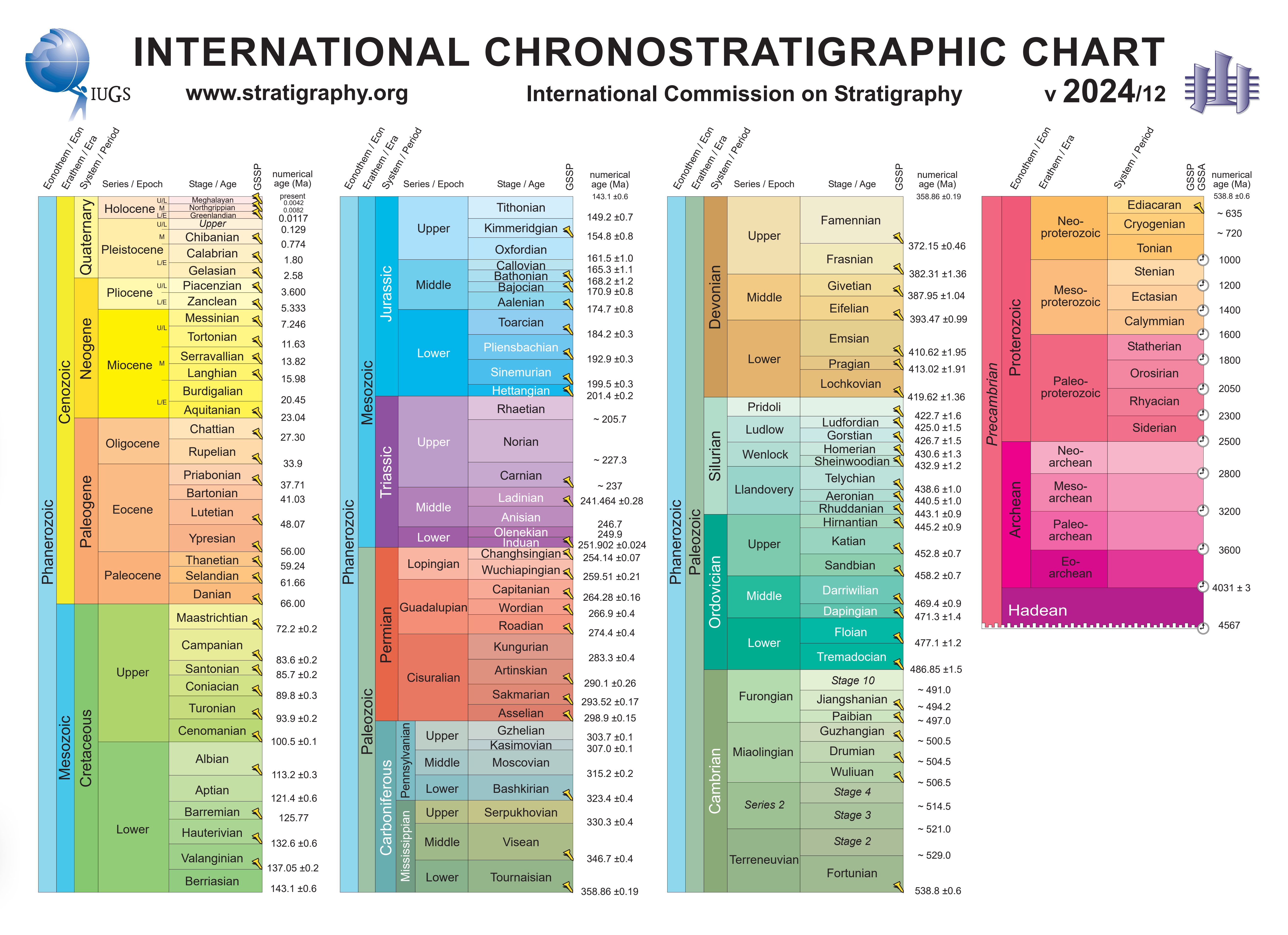
Stratigraphy: Zonation & Correlation

Geological Time Scale

Like historians geologists and stratigraphers work with both numerical (geochronologic) and relative chronostratigraphic – or periodized – time scales.

Both these scales can be found in all modern representations of the geologic time scale. It's important to understand the difference between the two.

For day-to-day stratigraphic work, the relative (chronostratigraphic) time scale is the more useful because it is by far the more stable.



Stratigraphy: Zonation & Correlation

Types of Stratigraphy

Lithostratigraphy

- The branch of stratigraphy that characterizes rock layers by their lithological (= physical) content.
  - Formation - the smallest mappable rock unit possessing a distinctive suite of lithological characteristics.
  - Superior (e.g., groups) and inferior (e.g., members, beds) can be recognized.
  - Many ways to define a lithostratigraphic unit.
  - No necessary time (= chronostratigraphic) implication.

Stratigraphy: Zonation & Correlation

Types of Stratigraphy

Biostratigraphy

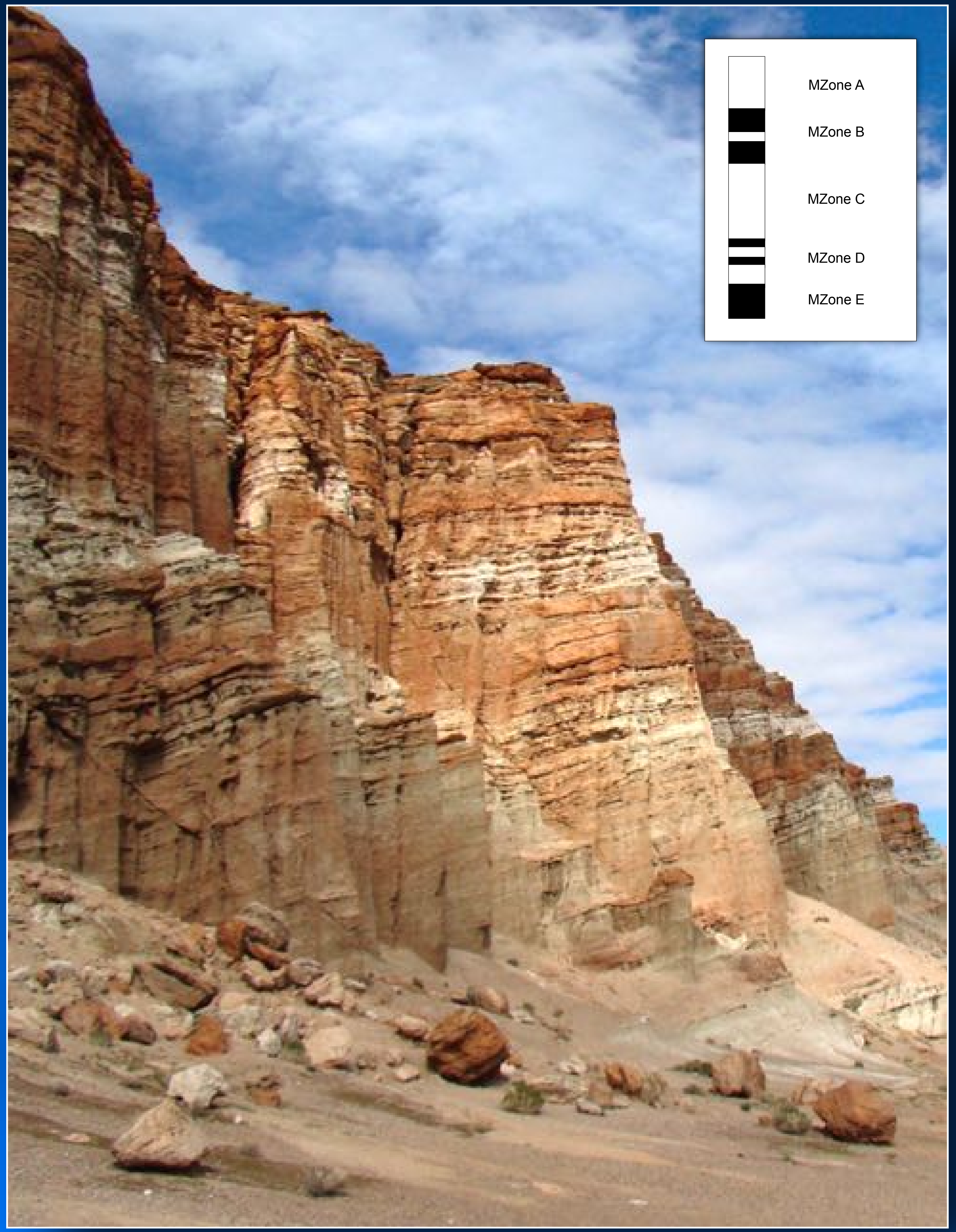
- The branch of stratigraphy that characterizes rock layers by their fossil (= biotic) content.
  - Zone - any rock unit distinguishable from other rock units by its fossil content.
  - Many ways of defining a zone.
  - No need for zones to be mappable.
  - No necessary time (= chronostratigraphic) implication.

Stratigraphy: Zonation & Correlation

Types of Stratigraphy

Magnetostratigraphy

- The branch of stratigraphy that characterizes rock layers by their remnant magnetic polarity.
  - Magnetozone - any rock unit distinguishable from other rock units by minerals possessing a characteristic magnetic polarity.
  - No need for magnetozones to be mappable.
  - Magnetozones not unique (must use other criteria to be identified).
  - Practically speaking magnetozone boundaries cannot be assumed to be isochronous, but magnetic polarity reversals are effectively isochronous.

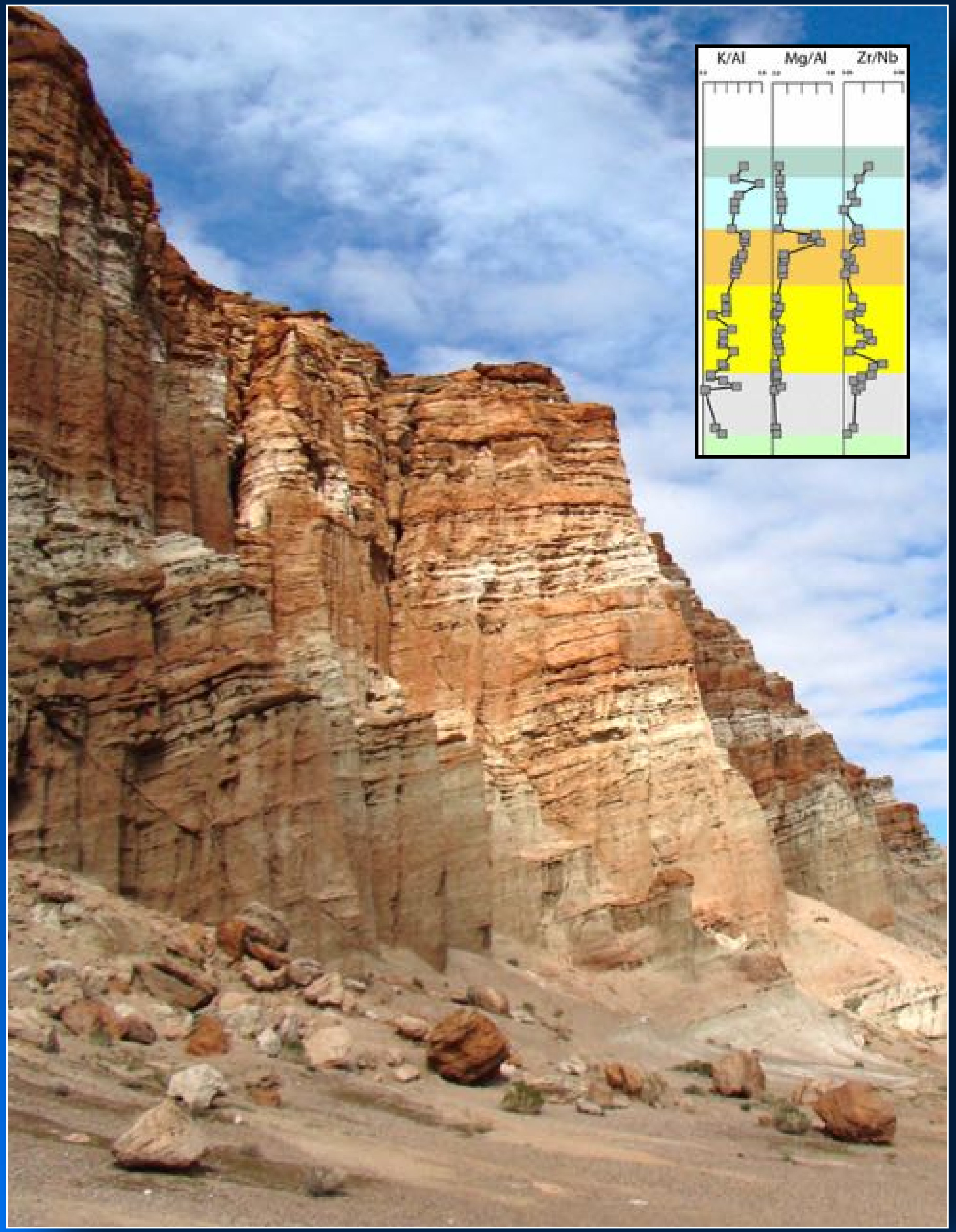


Stratigraphy: Zonation & Correlation

Types of Stratigraphy

Chemostratigraphy

- The branch of stratigraphy that characterizes rock layers by their chemical/isotopic content.
  - Chemozone - any rock unit distinguishable from other rock units by minerals possessing a characteristic chemical/isotopic content.
  - No need for chemozones to be mappable.
  - Chemozones not unique (must use other criteria to be identified).
  - Practically speaking chemozone boundaries cannot be assumed to be isochronous, but, when used in conjunction with other data can support an interpretation of isochrony.

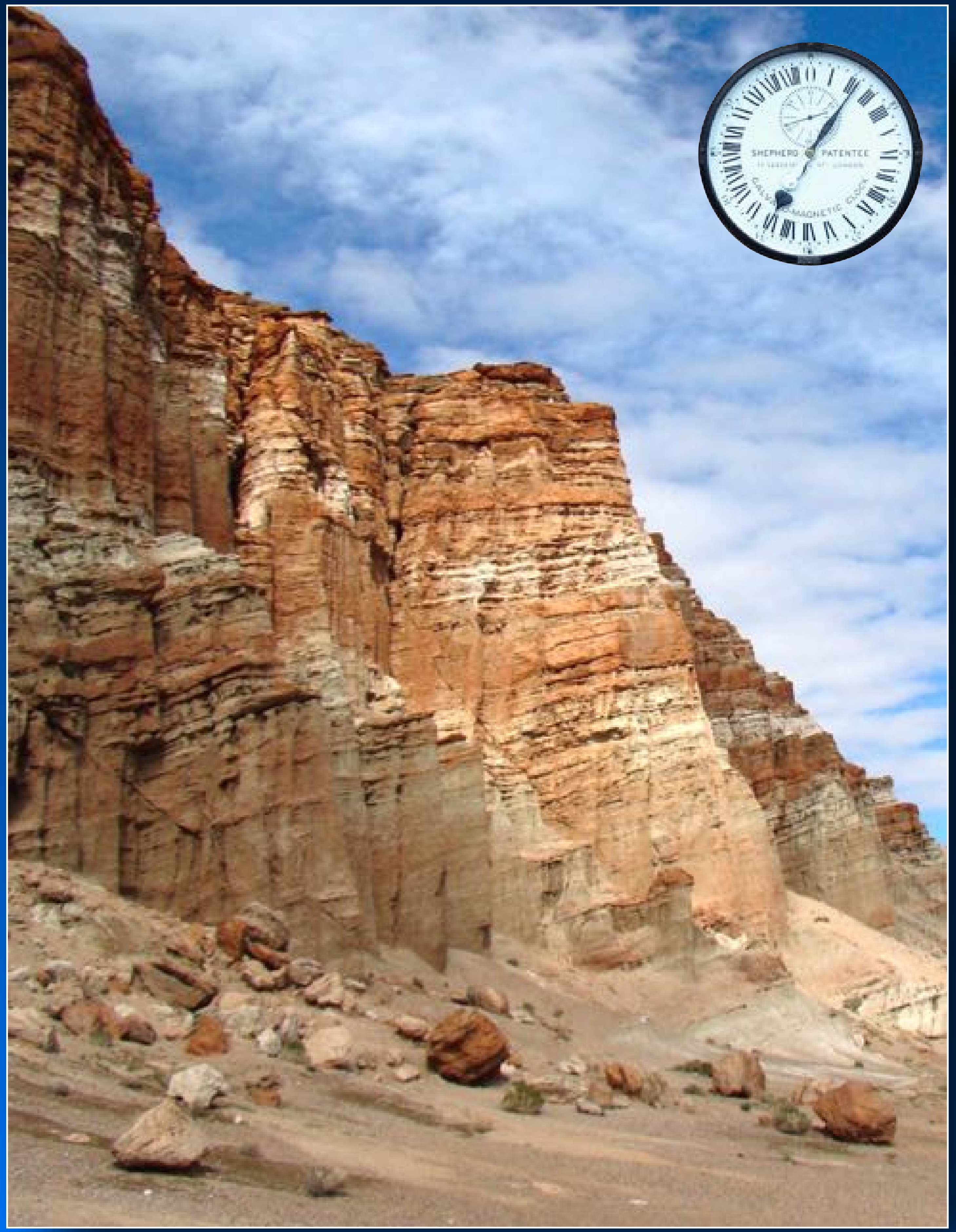


Stratigraphy: Zonation & Correlation

Types of Stratigraphy

Chronostratigraphy

- The branch of stratigraphy that characterizes rock layers by their relative time of origin/deposition.
  - Chronozone - any rock unit distinguishable from other rock units by different time relations.
  - No need for chronozones to be mappable.
  - Chronozones are unique but cannot be observed directly; they must be inferred based on other stratigraphic criteria.
  - Chronozone boundaries are isochronous.

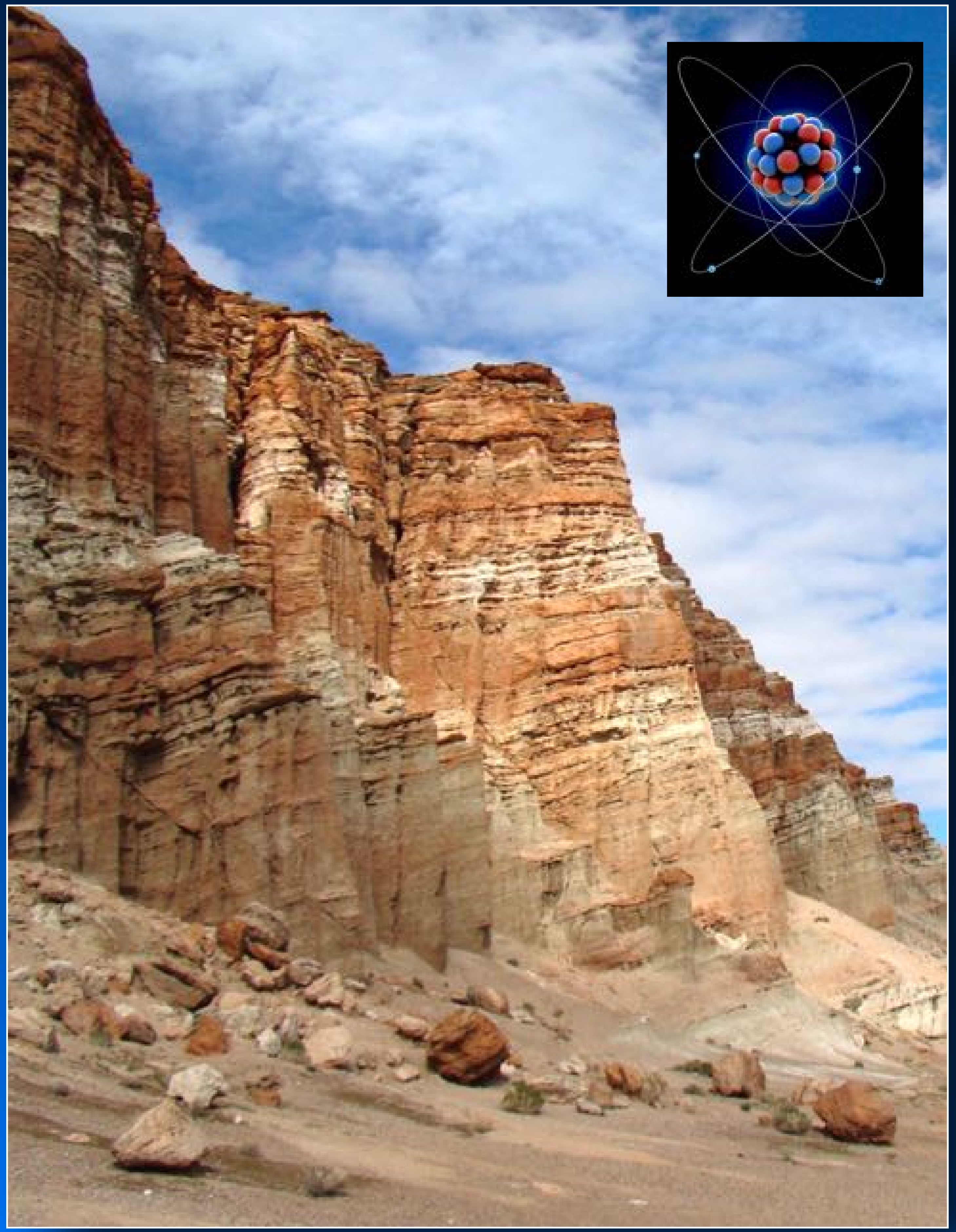


Stratigraphy: Zonation & Correlation

Types of Stratigraphy

Geochronology

- Methods
  - Radiometric (radioisotopic) dating
  - Fission-track dating
  - Cosmogenic nucleotide dating
  - Luminescence dating
  - Incremental dating
  - Dendrochronologic dating
  - Ice core dating
  - Varve dating



Stratigraphy: Zonation & Correlation

Geochronology versus Chronostratigraphy

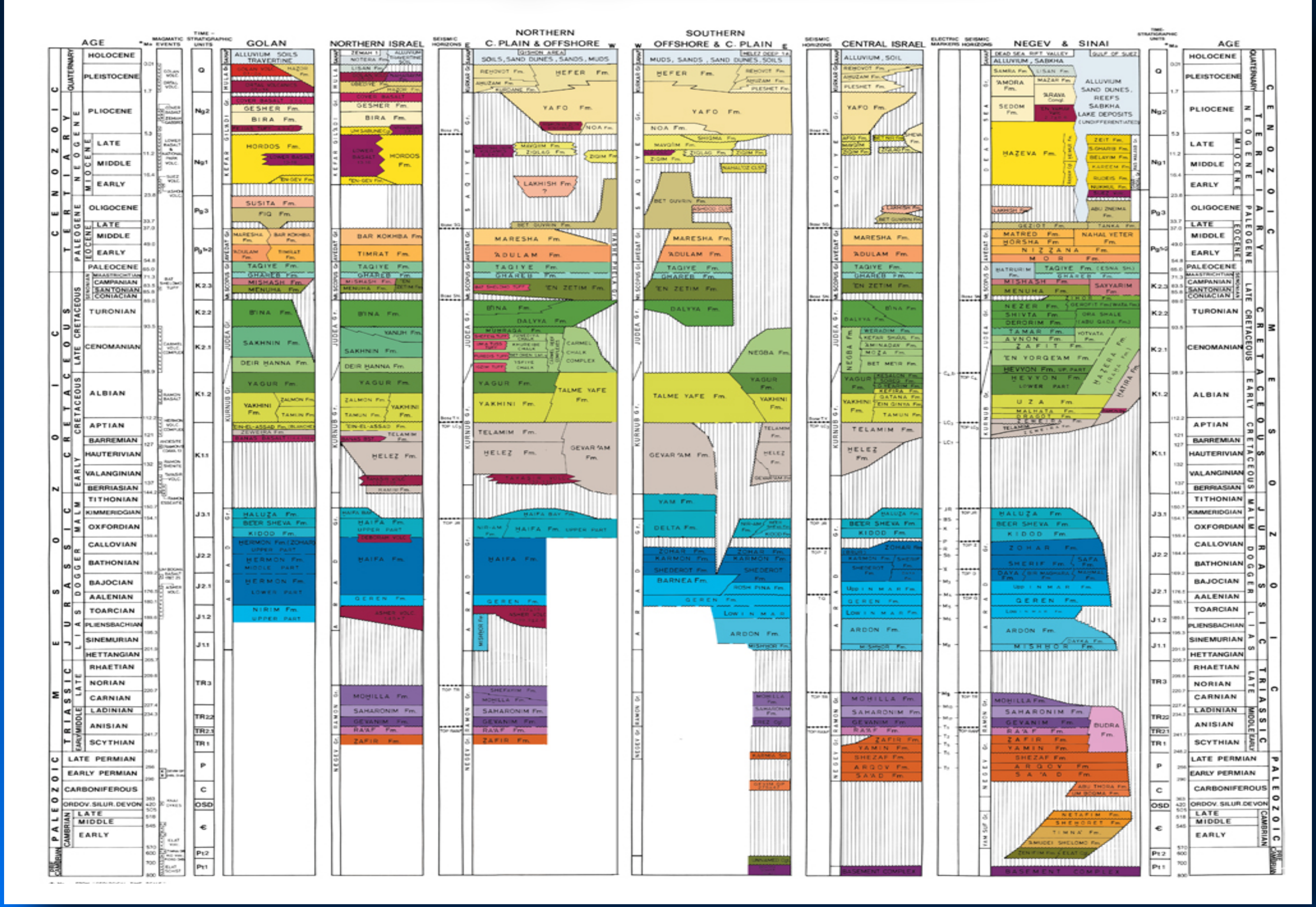
The difference between chronostratigraphy and time (= geochronology) is symbolized by the hourglass.

- Geochronology is the amount of time it took for the sand to fall from one reservoir to the other.
- Chronostratigraphy is the amount of sand that was deposited in the lower reservoir in that time interval.

Geological Time Systems		
Chronostratigraphy	Geochronology	Example
Eonothem	Eon	Phanerozoic
Erathem	Era	Mesozoic
System	Period	Cretaceous
Series	Epoch	Upper Cret.
Stage	Age	Maastrichtian
Chronozone	Chron	*B. occidentalis* Biozone

Stratigraphy: Zonation & Correlation

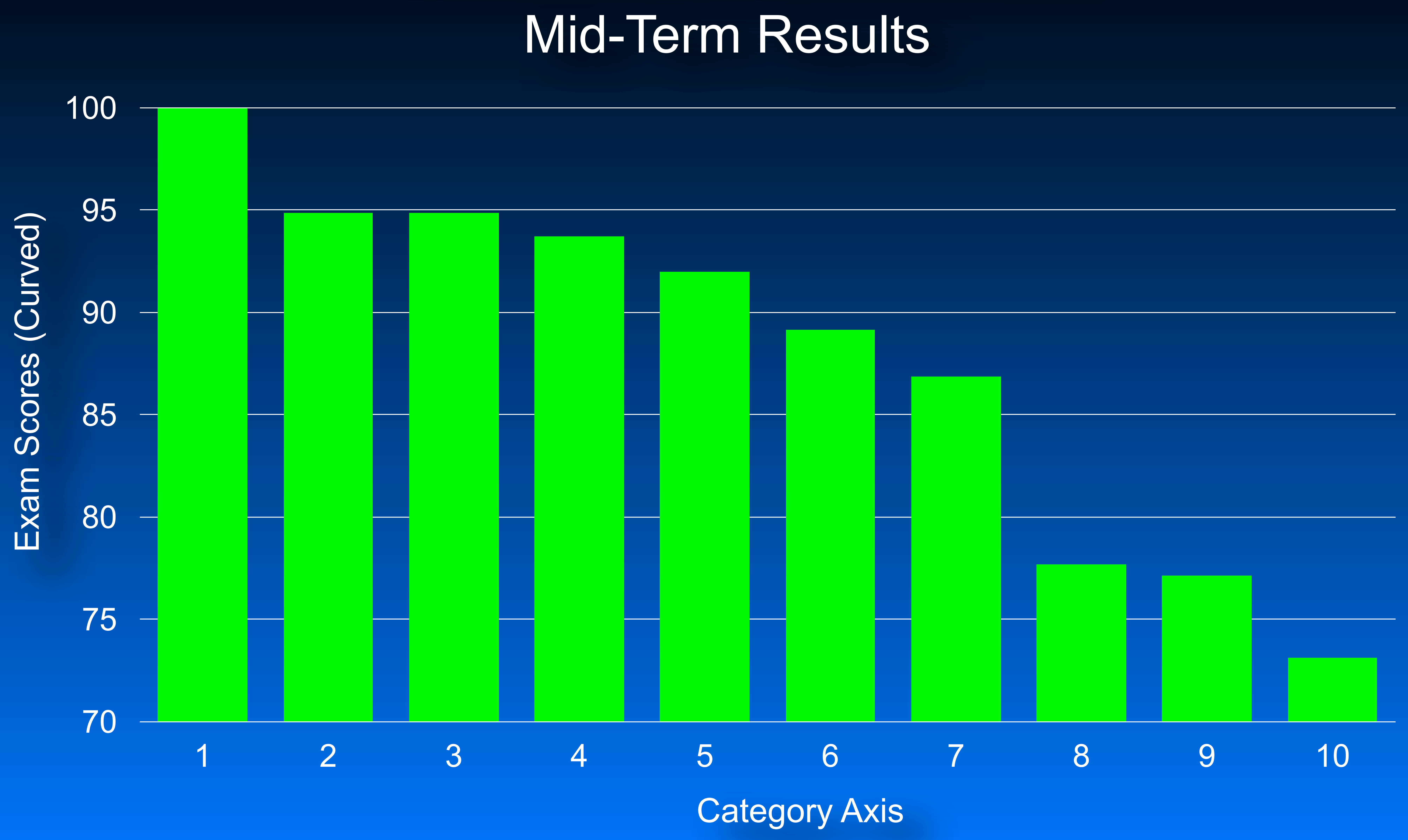
Stratigraphic Correlation



Principles of Palelobiology

Mid-Term Results

Principles of Palelobiology



Principles of Palelobiology

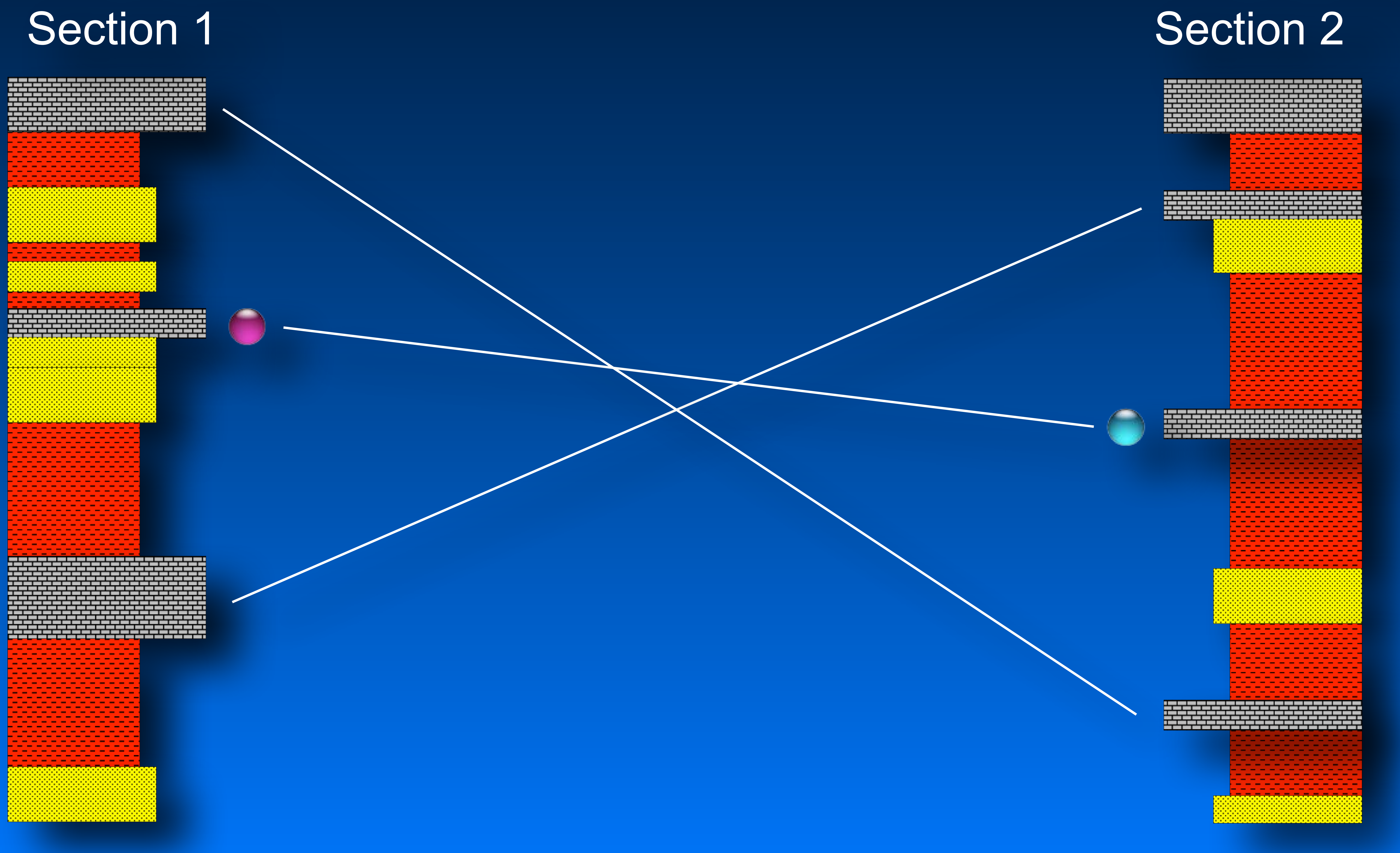
Mid-Term Results

- Questions w/ answers will be posted on course website.
- Add up your scores on each section to check the sum is correct.
- Divide the sum by 255, then multiply by 100 to check the raw percentage score is correct.
- Divide the raw score by 68.63, then multiply by 100 to check the curved percentage score is correct.
- Any questions about the answers or about your mid-term grade, make an appointment to come and see me.

Stratigraphy: Zonation & Correlation

Stratigraphic Correlation

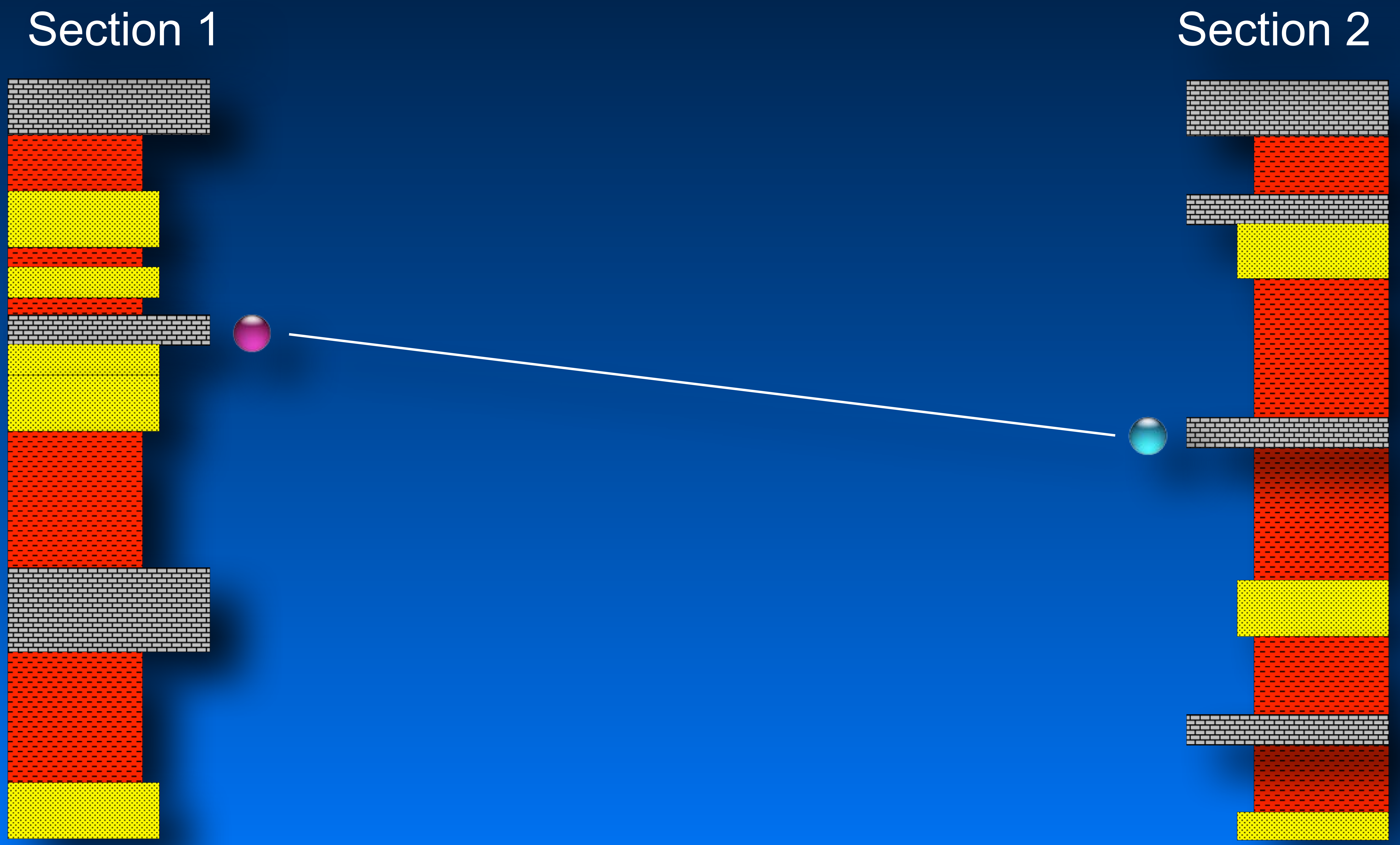
The determination of the contemporaneity of geological units or events in the histories of two or more locations.



Stratigraphy: Zonation & Correlation

Stratigraphic Correlation

Isochrony/Homochrony - The condition of being equivalent in absolute time.



Stratigraphy: Zonation & Correlation

Stratigraphic Correlation

Diachrony - The condition of being non-equivalent in absolute time.

Stratigraphy: Zonation & Correlation

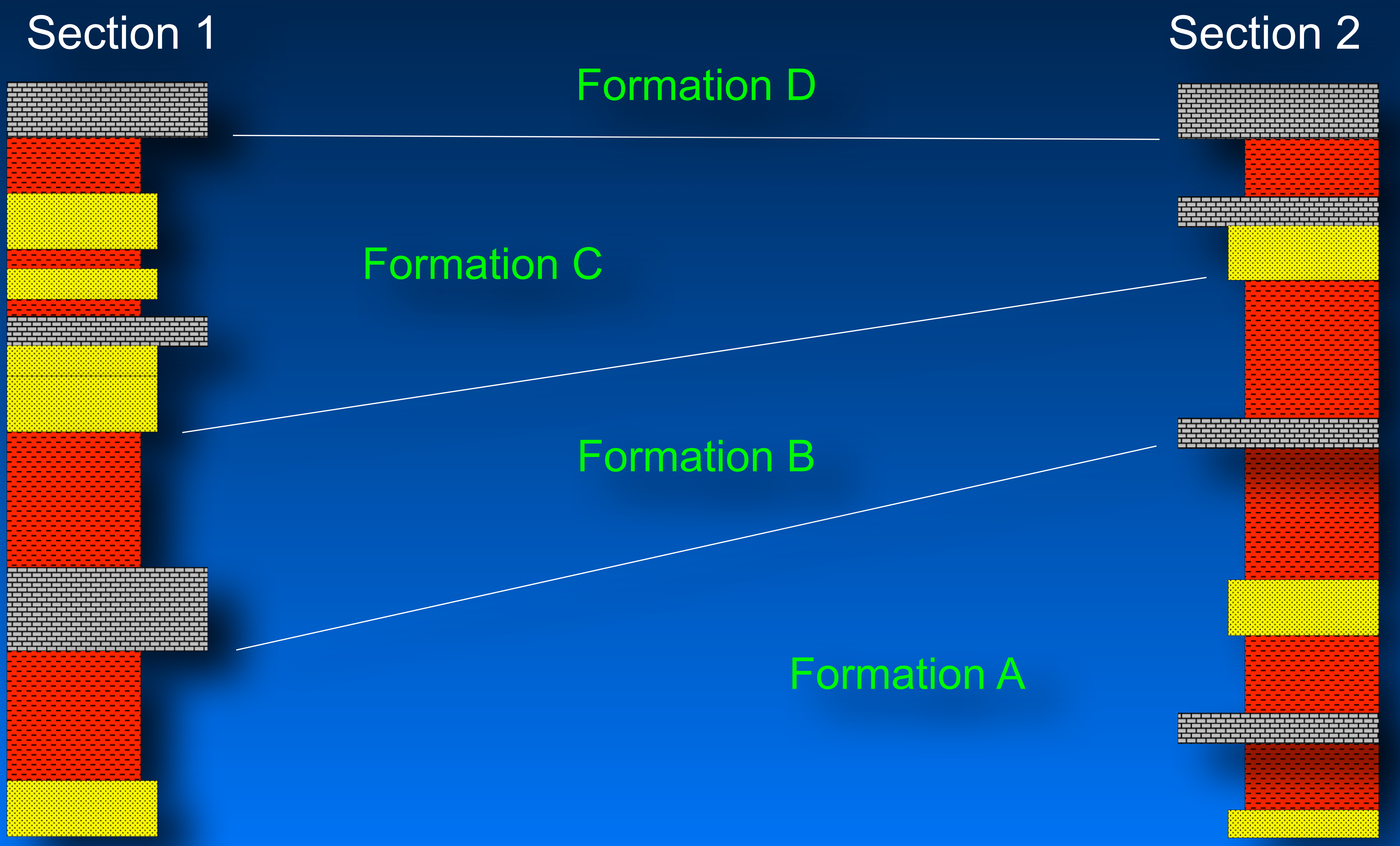
Lithostratigraphic Correlation

The branch of stratigraphy that characterizes rock layers by their lithological (= physical) content

Stratigraphy: Zonation & Correlation

Lithostratigraphic Correlation

The matching of lithozones in different stratigraphic sections or cores based on similarities or differences in their zone-defining lithologies.

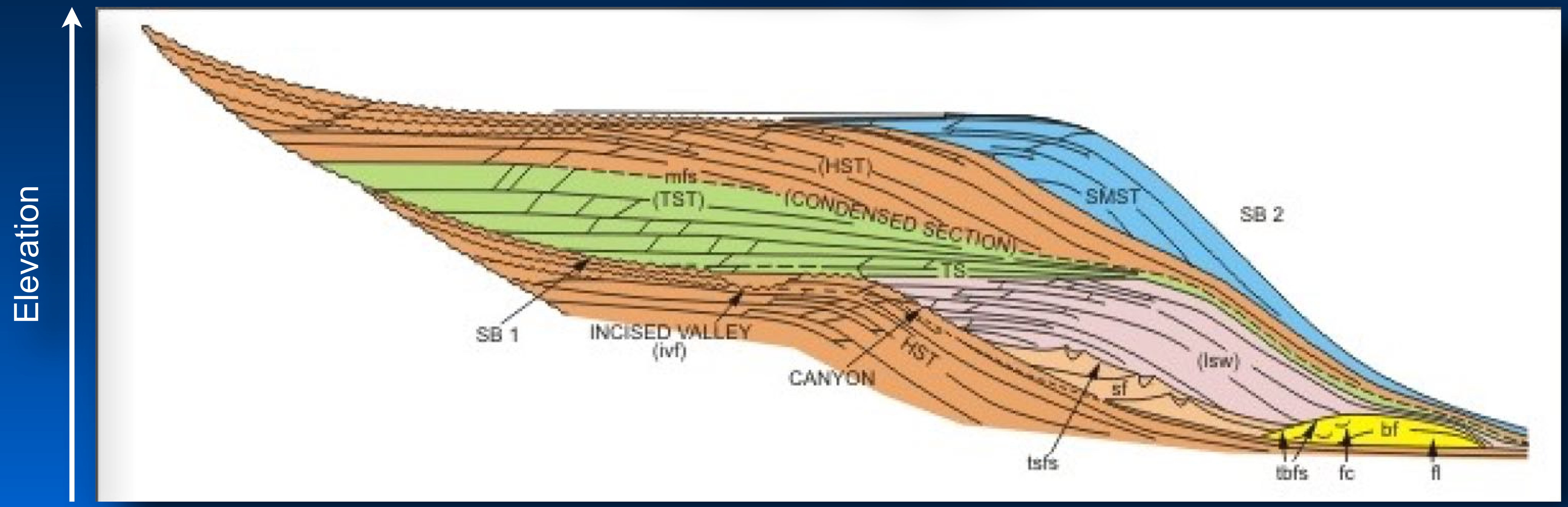


Stratigraphy: Zonation & Correlation

Sequence Stratigraphy

The analysis of sedimentary deposits in a time-stratigraphic context.

Wheeler Diagram



Abbreviations: SMST, Shelf Margin System Tract; HST, Highstand System Tract; SB1, Sequence Boundary 1; MFS, Maximum Flooding Surface; FSF, Falling stage Fan; LST, Lowstand System Tract; Unconformity, Subaerial hiatus; LSW, Low stand wedge; SB2, Sequence Boundary 2; TST, Transgressive System Tract; ivf, Incised Valley Fill.

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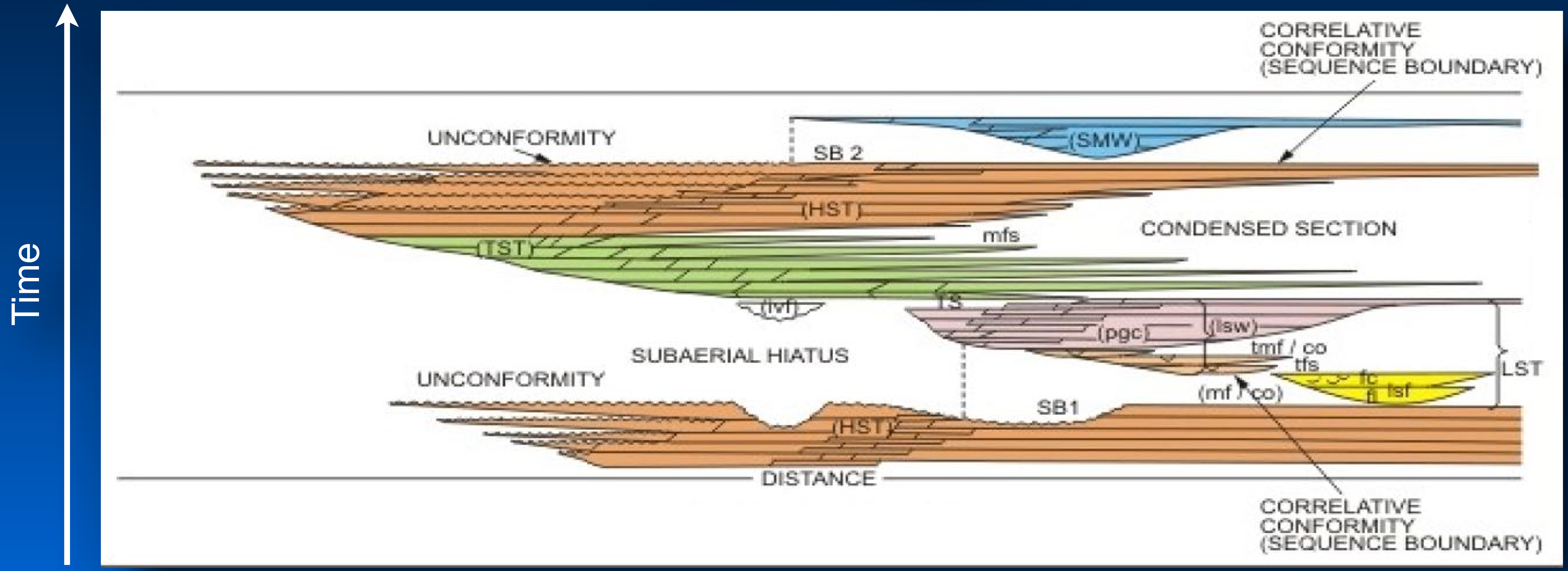

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Stratigraphy: Zonation & Correlation

Lithostratigraphic Correlation

Lithostratigraphic units per se have no chronostratigraphic significance. Some may have been deposited over a short time interval (e.g., tuffs, bentonite). But all must be assumed to be diachronous.

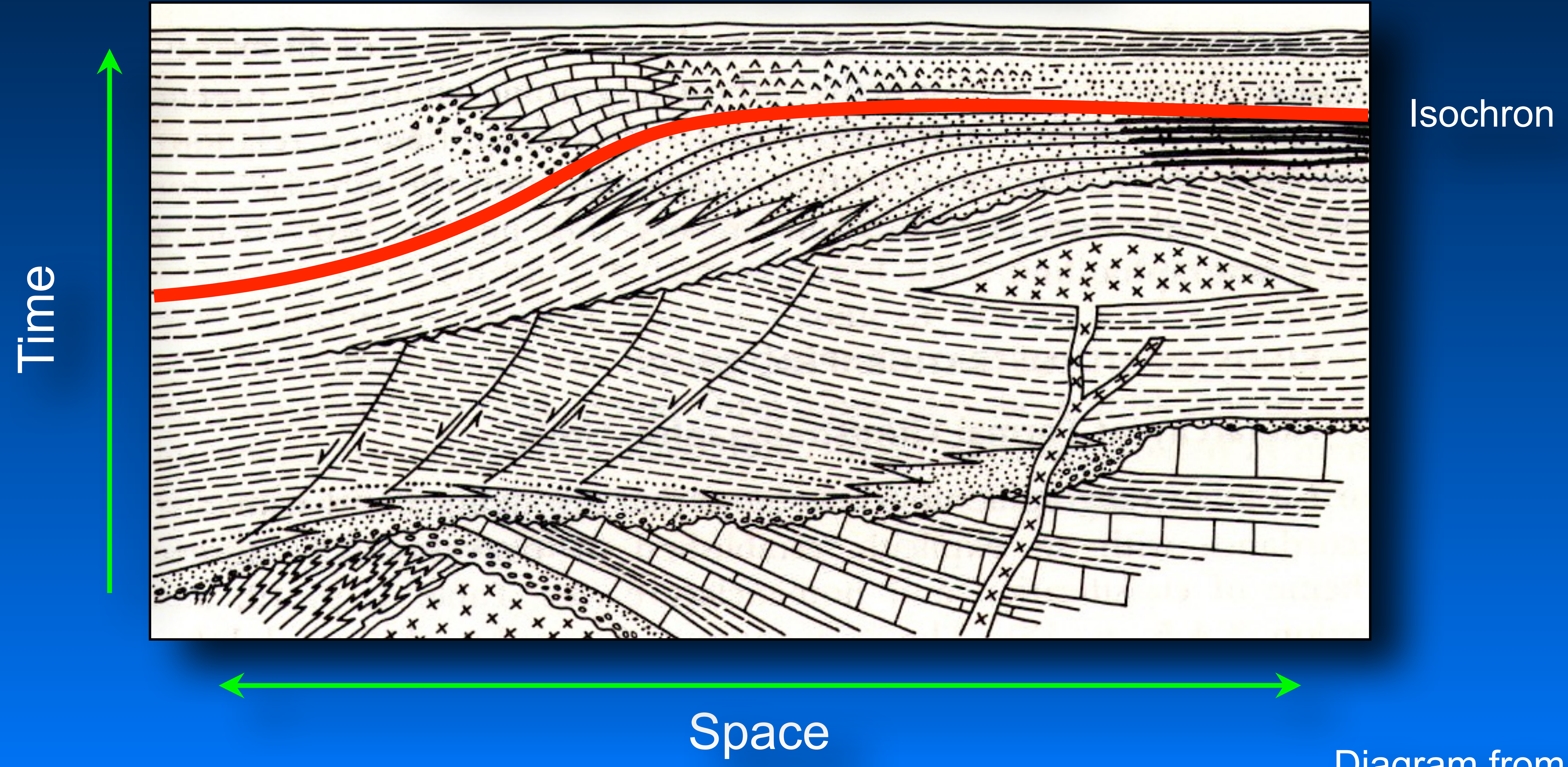

Diagram from Hedberg (1976)

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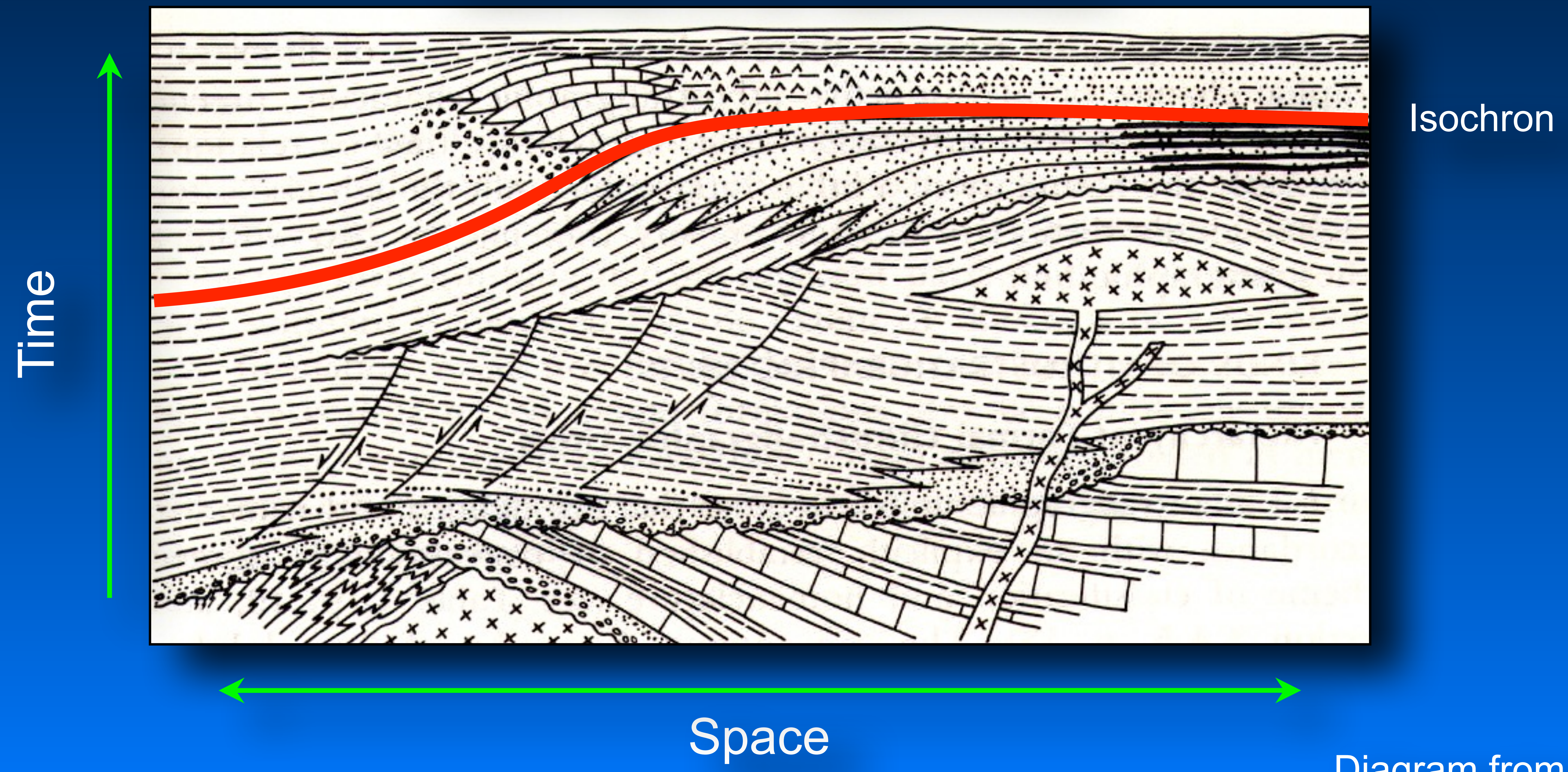
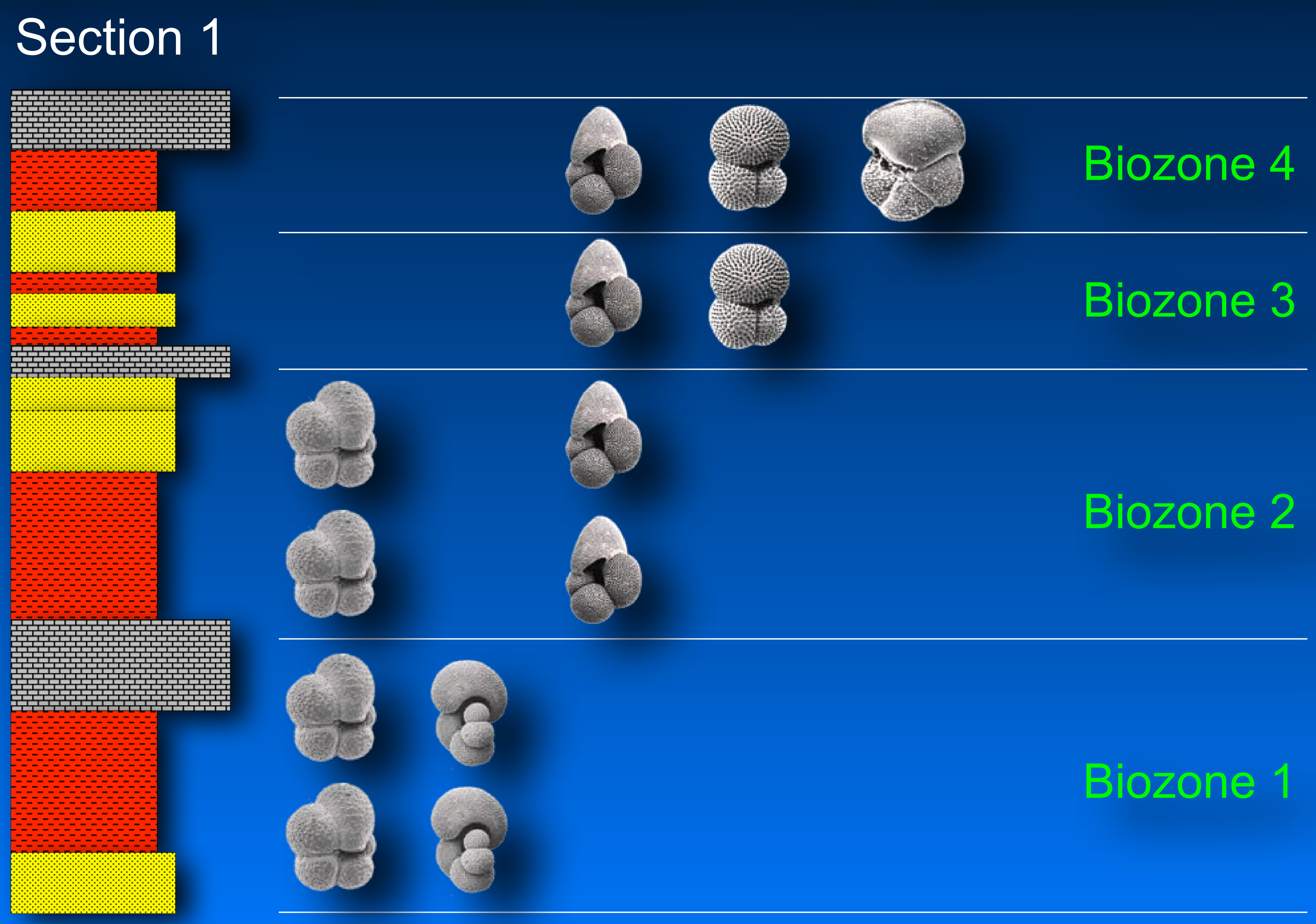


Diagram from Hedberg (1976)

Stratigraphy: Zonation & Correlation

Biostratigraphy

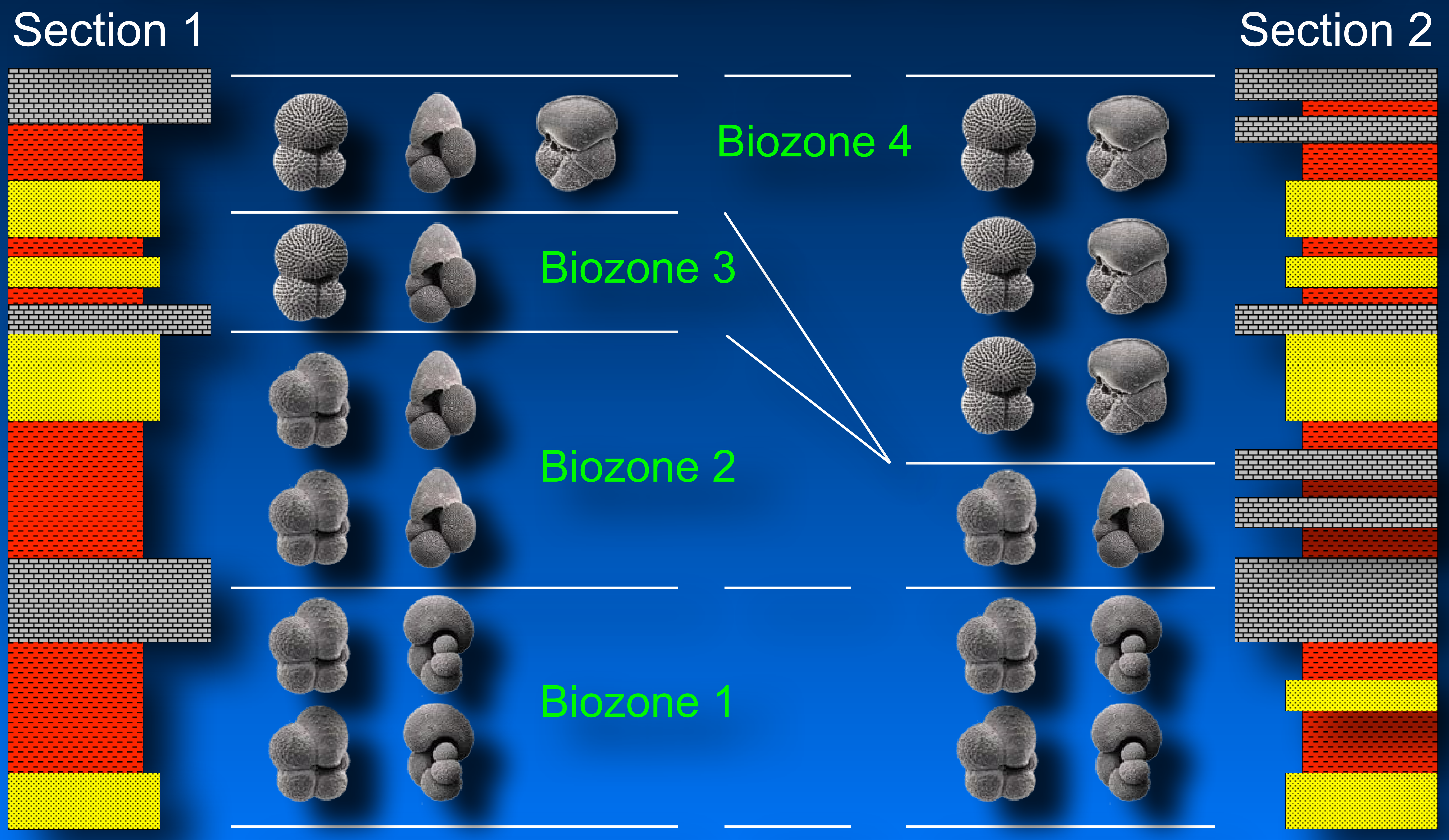
The branch of stratigraphy that deals with the fossil content of strata and with their organization into units based on the distribution of fossils.



Stratigraphy: Zonation & Correlation

Biostratigraphic Correlation

The matching of biozones in different stratigraphic sections or cores based on similarities or differences in their zone-defining taxa.



Stratigraphy: Zonation & Correlation

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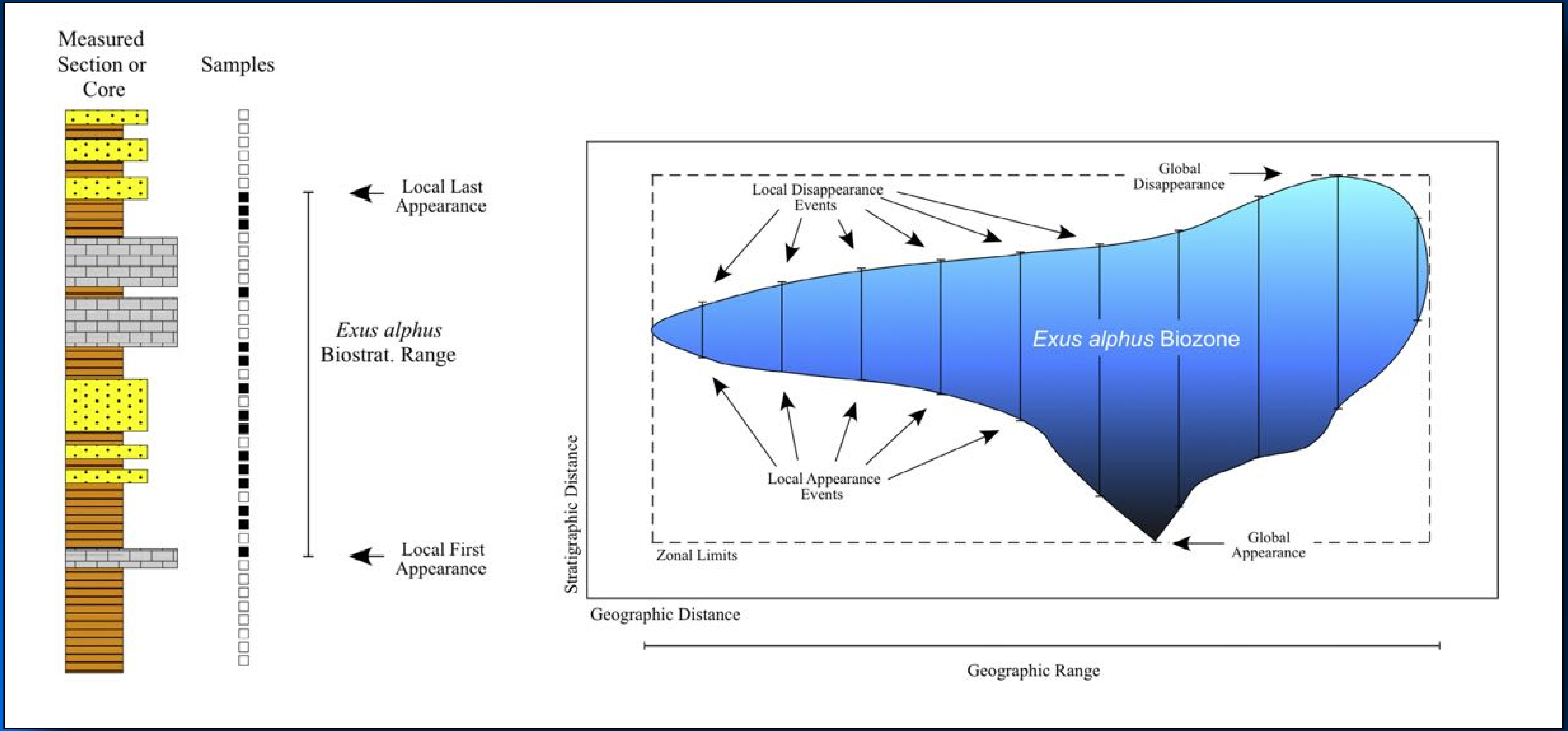

Diagram from MacLeod (2021)

Stratigraphy: Zonation & Correlation

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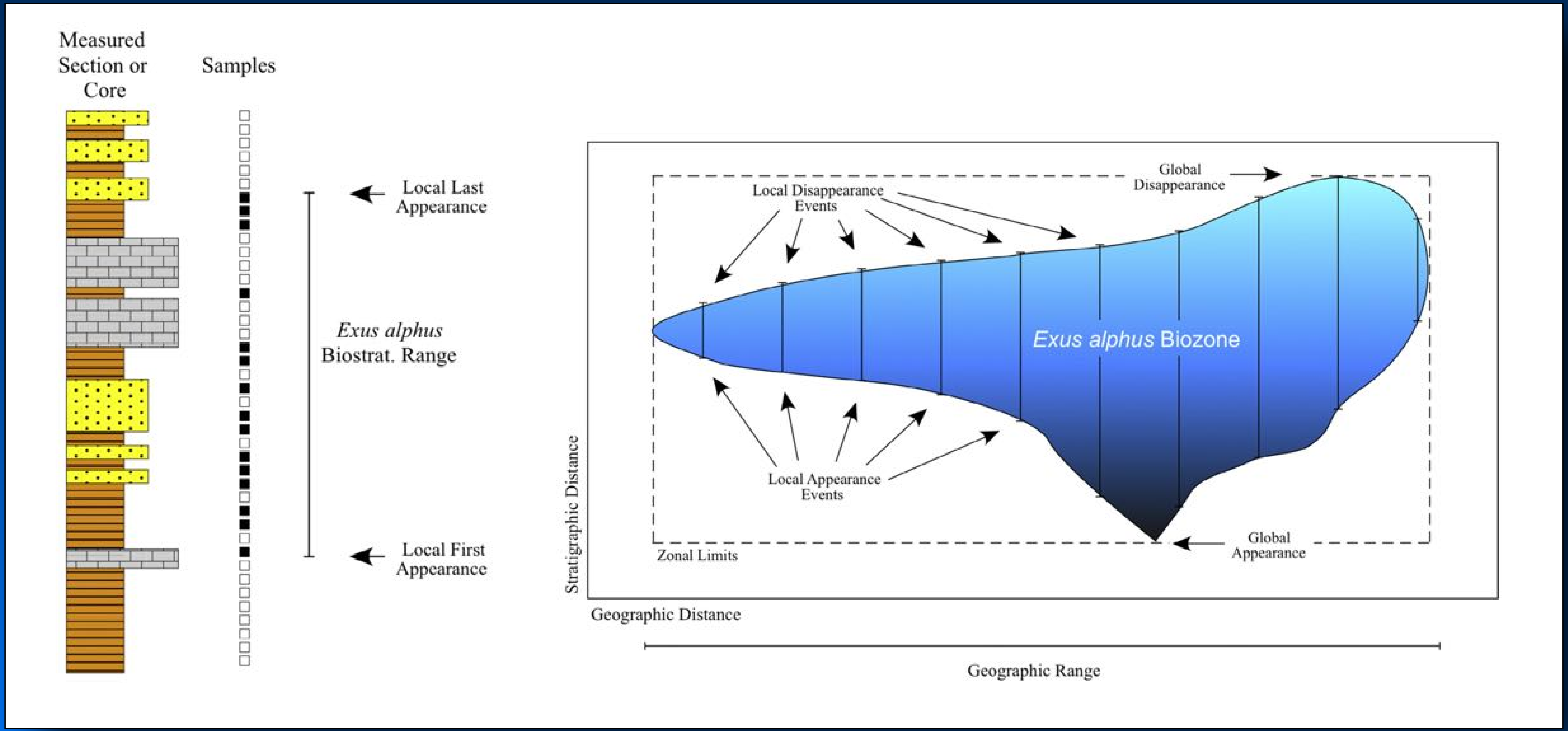


Diagram from MacLeod (2021)

Stratigraphy: Zonation & Correlation

Biofacies

Owing to ecological factors fossil species may have had their distributions restricted to particular environments (biofacies). Thus, their appearance or disappearance in a local section may reflect ecology, not time.

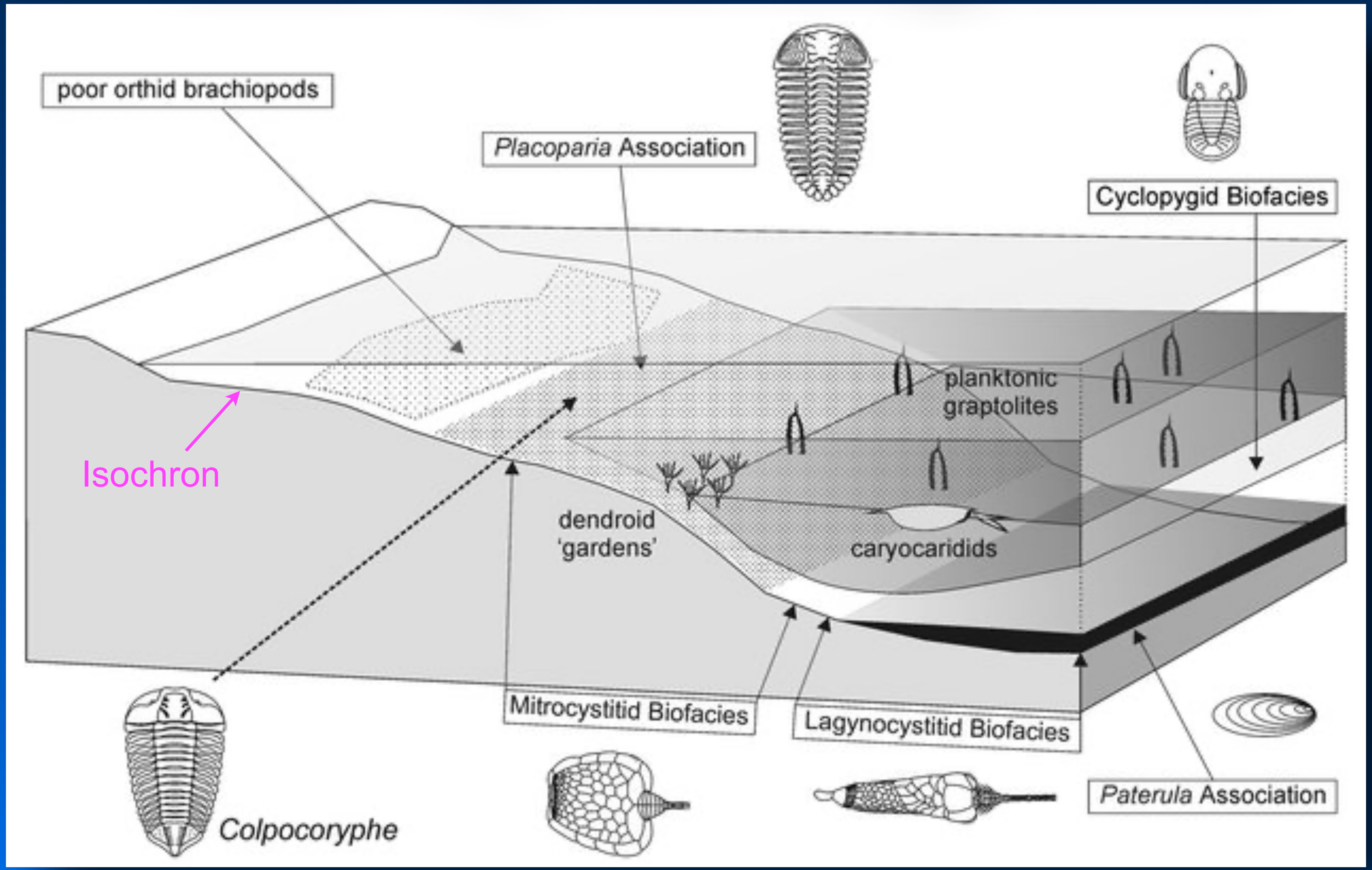
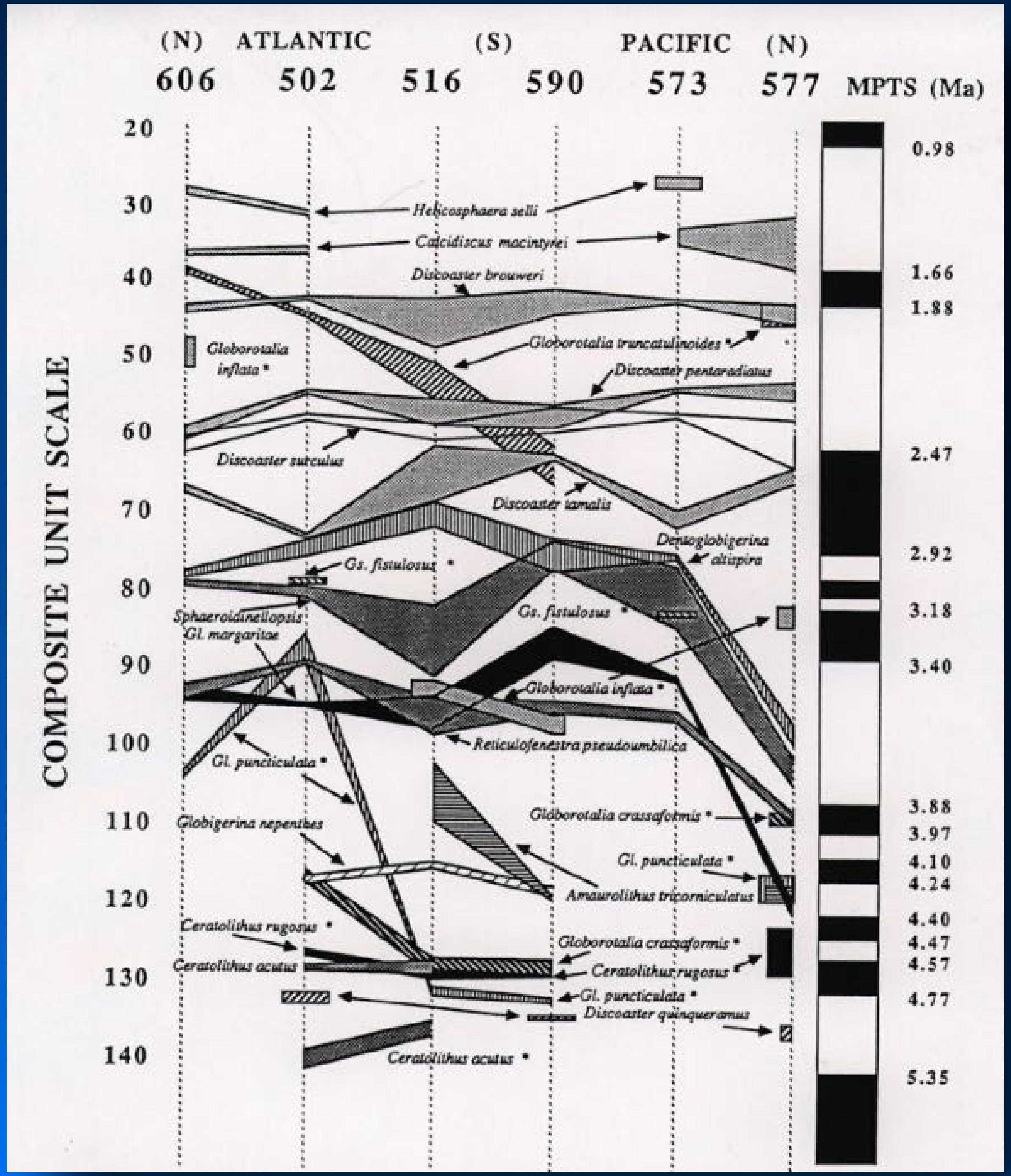


Diagram from Fatka et al. (2015)

Stratigraphy: Zonation & Correlation

Biostratigraphic Diachrony

Marine microfossils are generally acknowledged by most stratigraphers to be the fossil group that comes the closest to the classic concept of a chronostratigraphic “index fossil”.



However, note the measured levels of first and last appearance diachrony in these biozone-defining marine microfossil taxa.

In all but the most localized analyses it is inappropriate to assume any biostratigraphic datum represents an isochron irrespective of fossil group, depositional basin, and/or stratigraphic situation

Diagram from Dowsett (1989)

Stratigraphy: Zonation & Correlation

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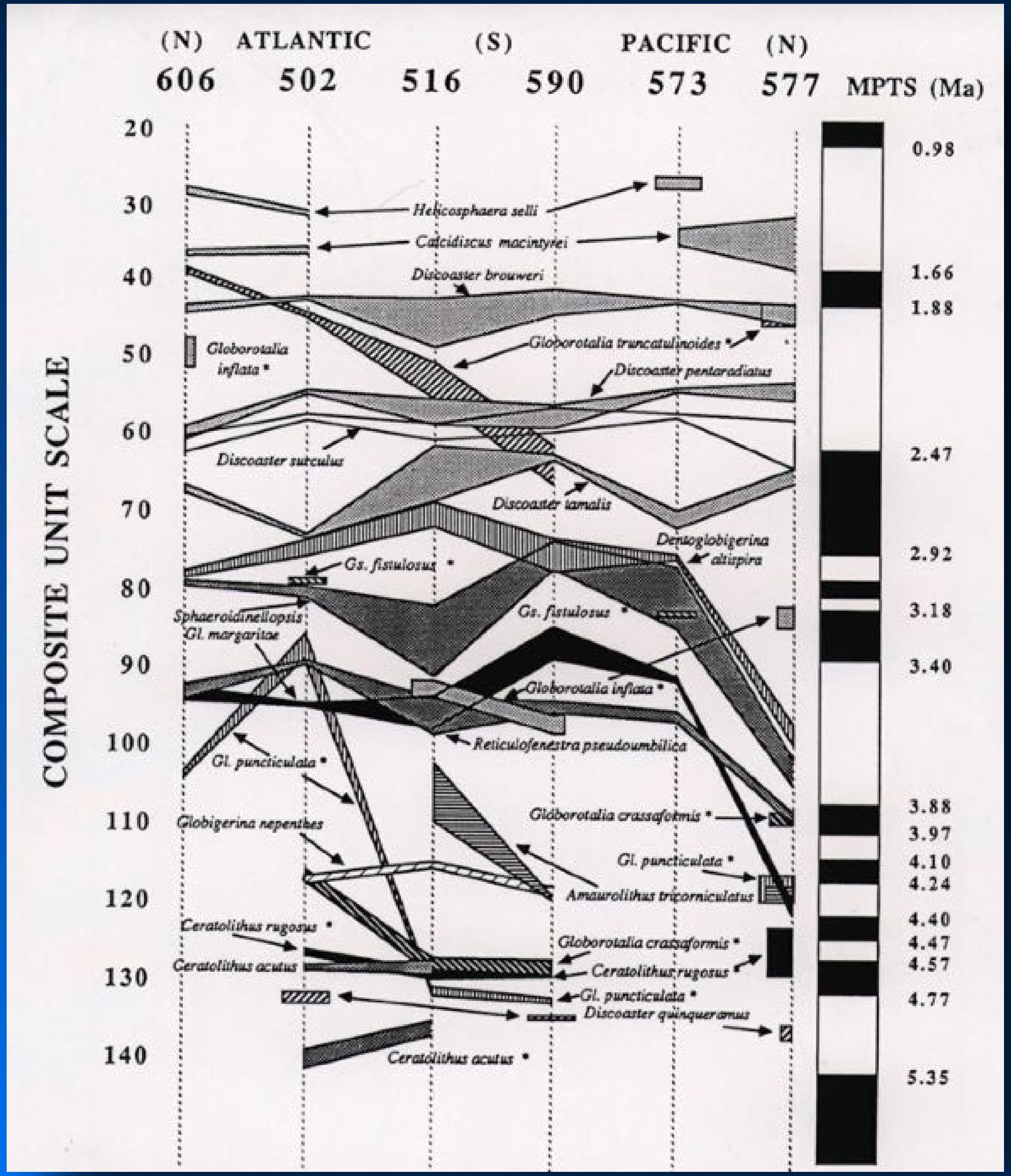

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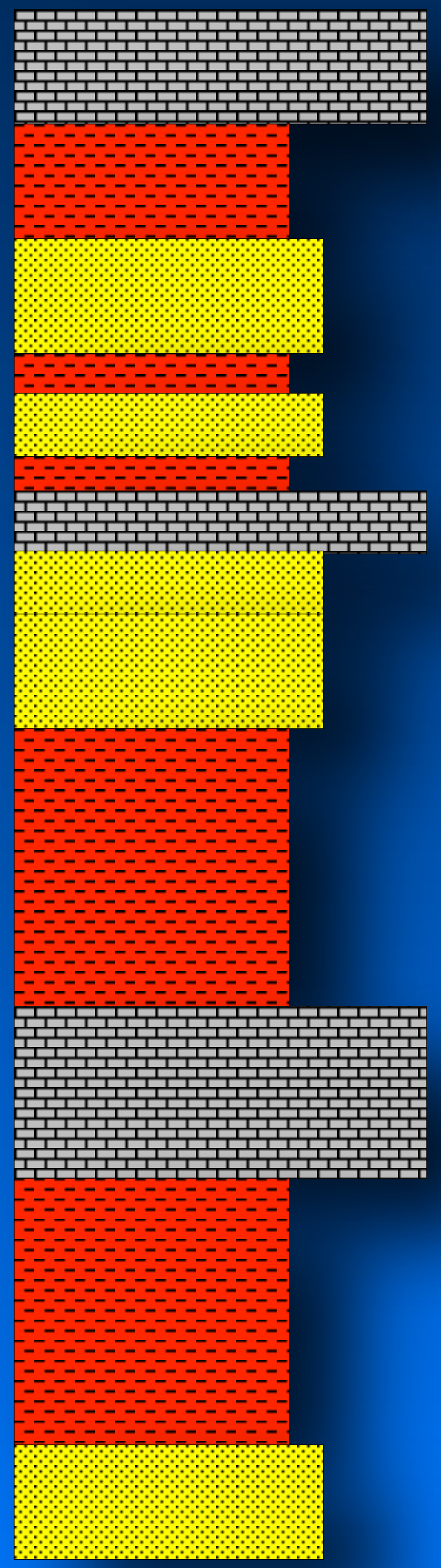
Diagram from Dowsett (1989)

Stratigraphy: Zonation & Correlation

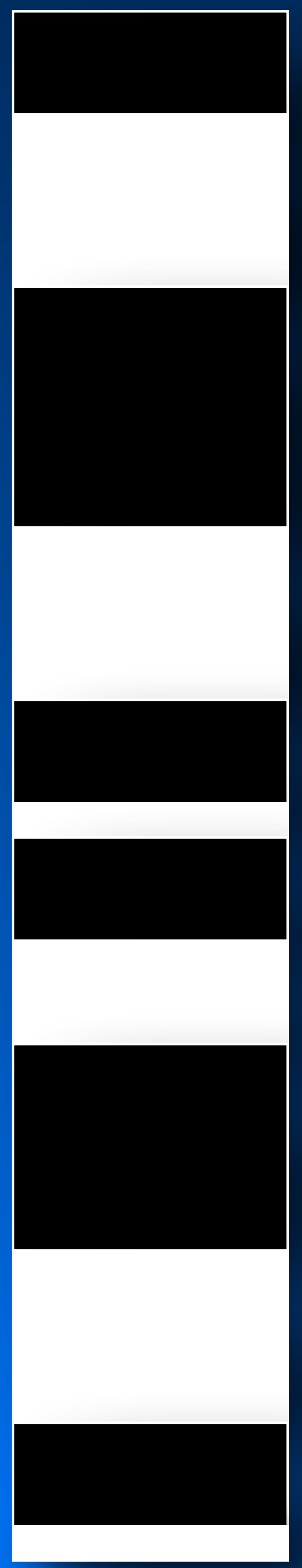
Magnetostratigraphy

The branch of stratigraphy that deals with the magnetic polarity of strata and with their organization into units based on polarity orientations.

Section 1

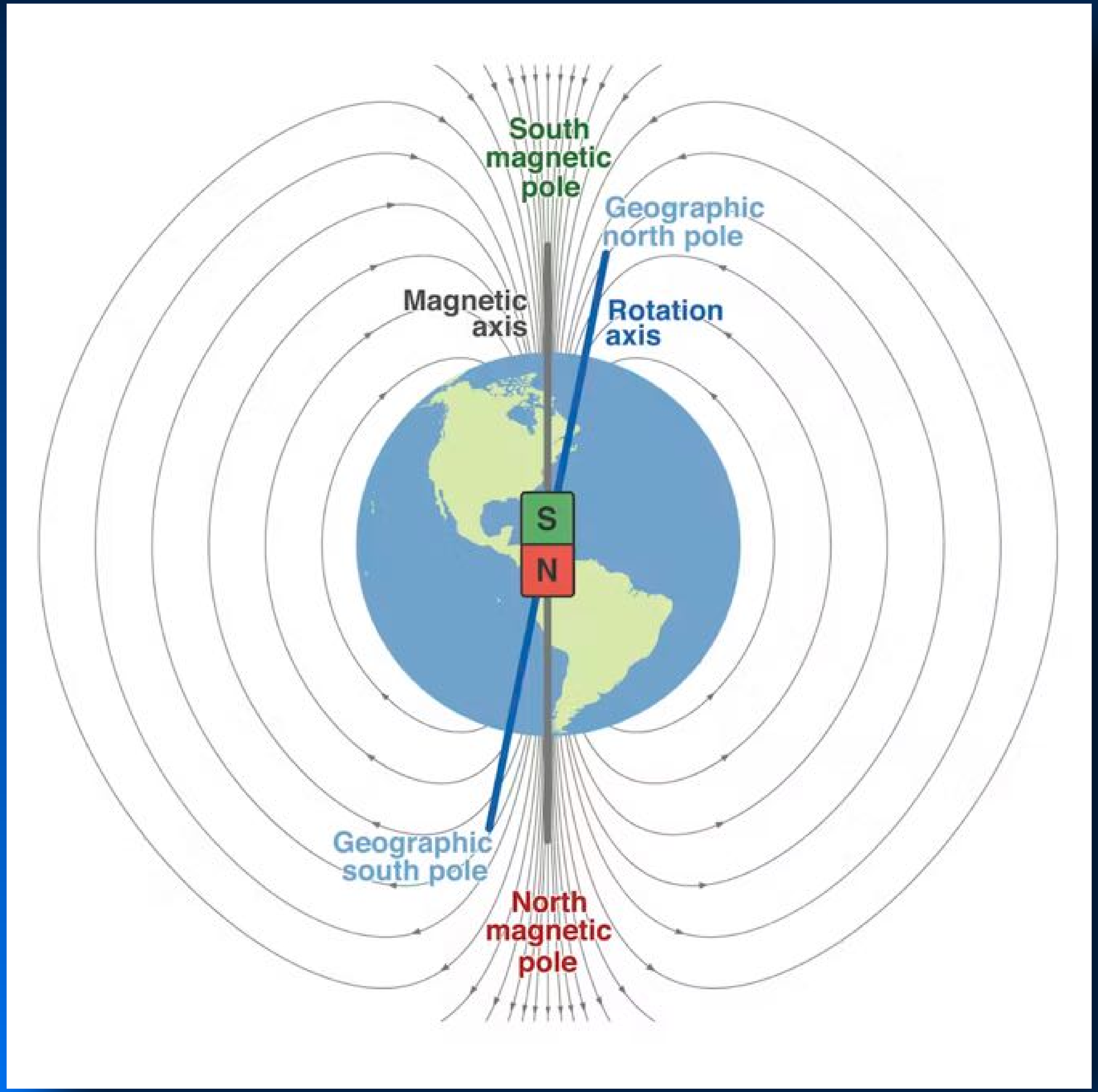


Section 1



Normal Polarity

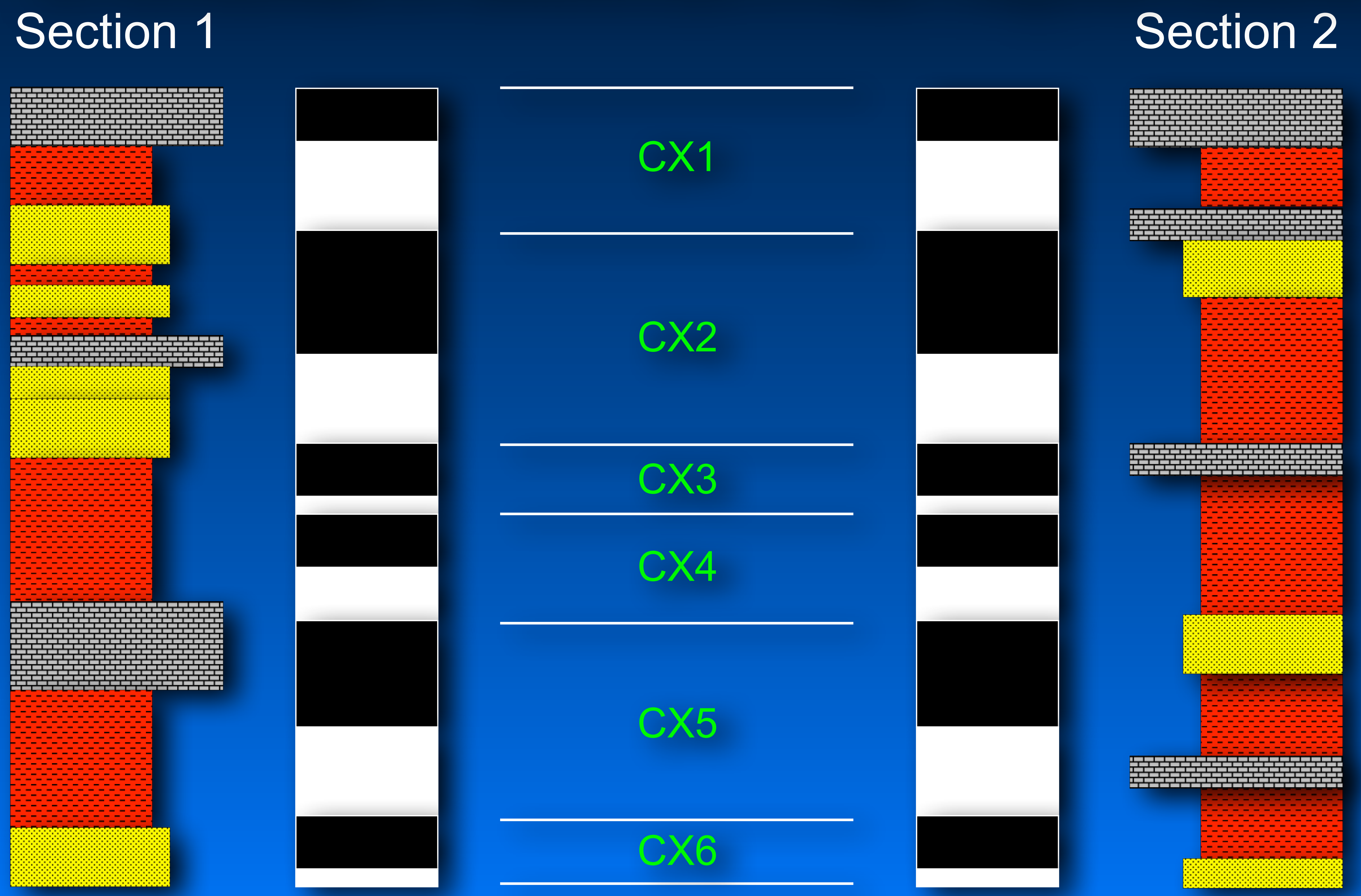
Reversed Polarity



Stratigraphy: Zonation & Correlation

Magnetostratigraphic Correlation

The matching of magnetozones in different stratigraphic sections or cores based on similarities or differences in their magnetic polarity.



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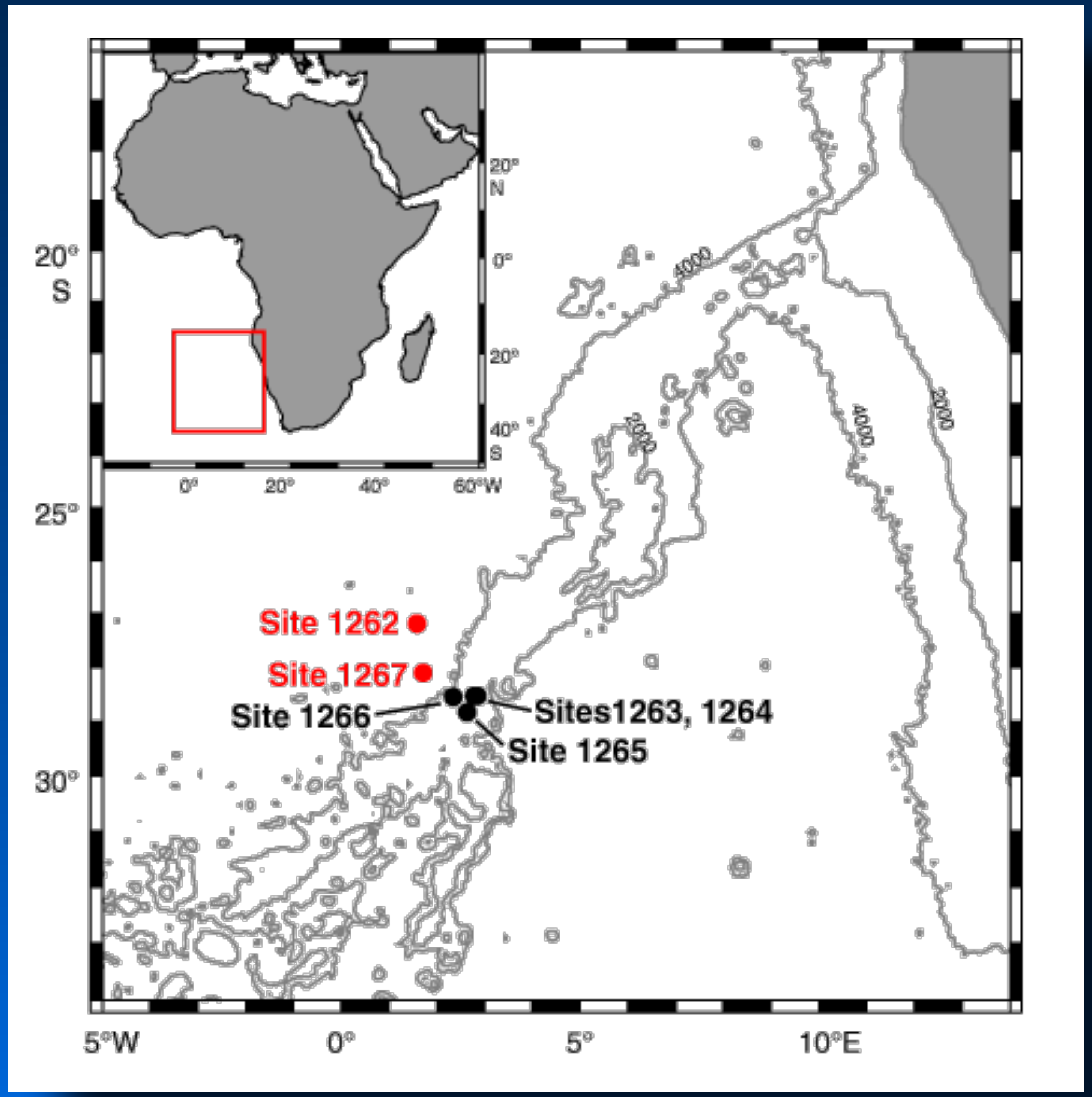
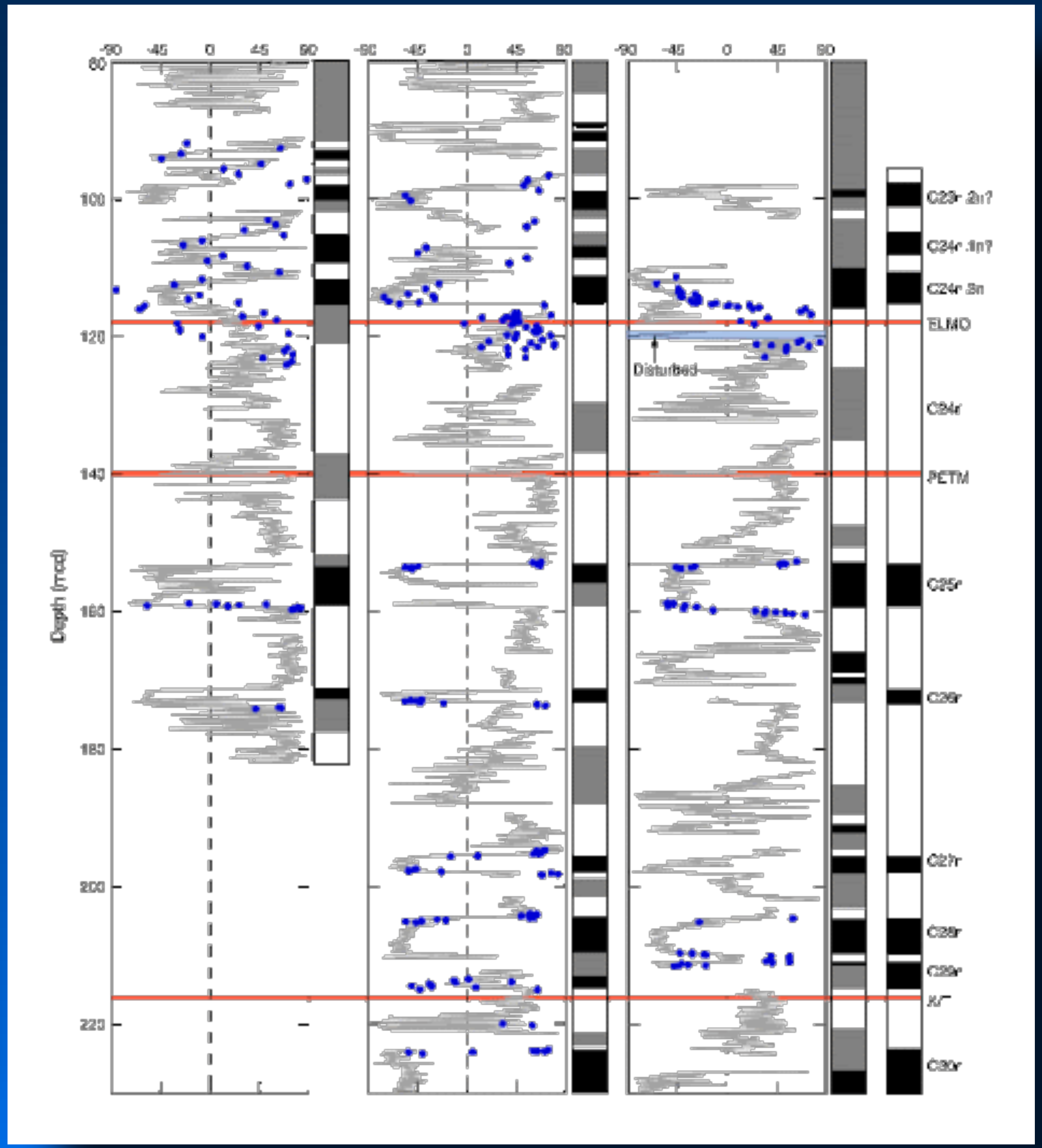


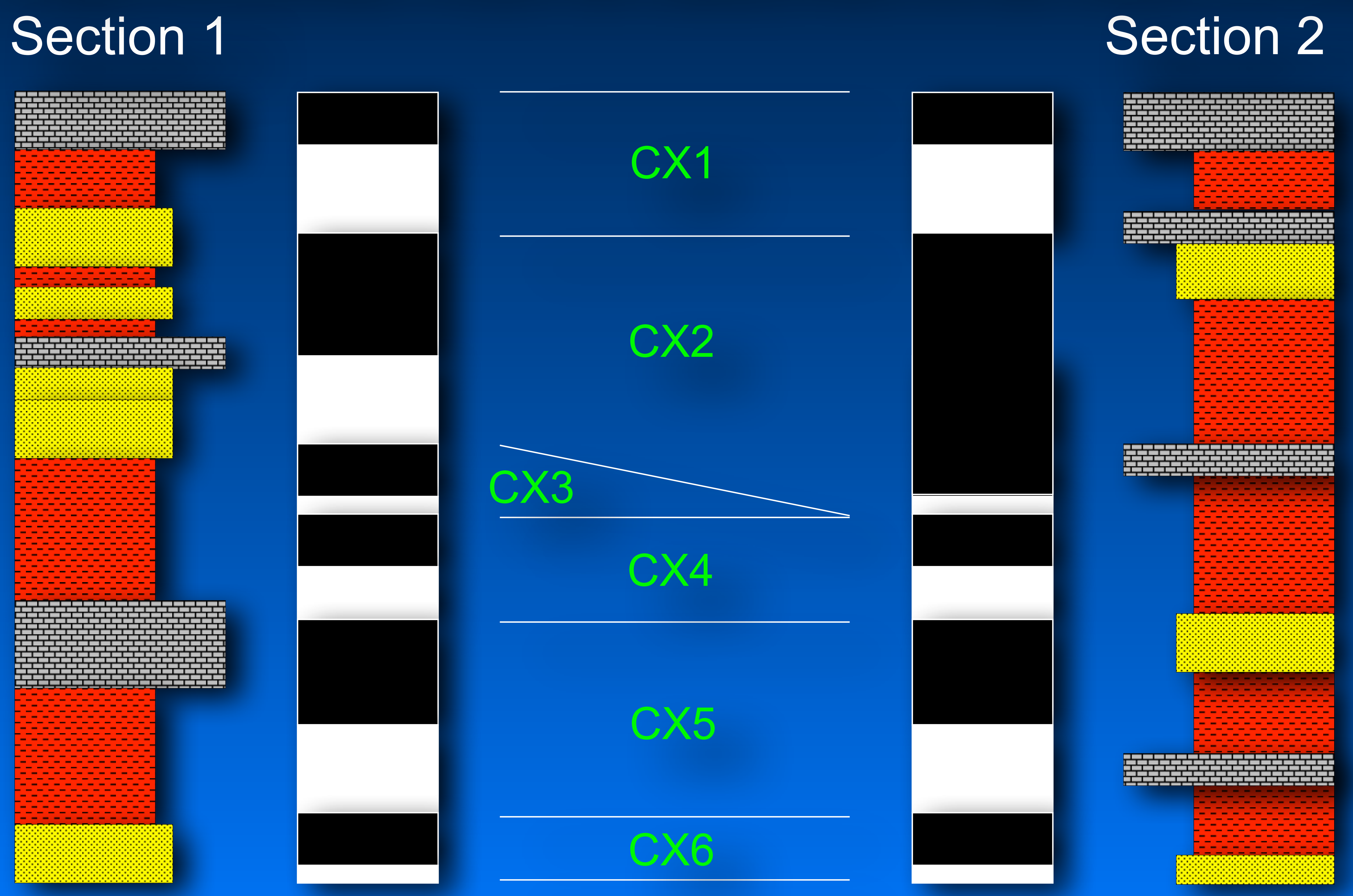


Note degree of interpretation necessary to transform magnetic inclination measurements into a magnetozonation and the level of variation in the pattern of magnetic polarity intervals among even closely spaced cores.

Stratigraphy: Zonation & Correlation

Magnetostratigraphic Correlation

Magnetostratigraphic units per se have no chronostratigraphic significance. The boundaries of comparable magnetic polarity reversals are isochronous. But all magnetozones must be assumed to be diachronous.



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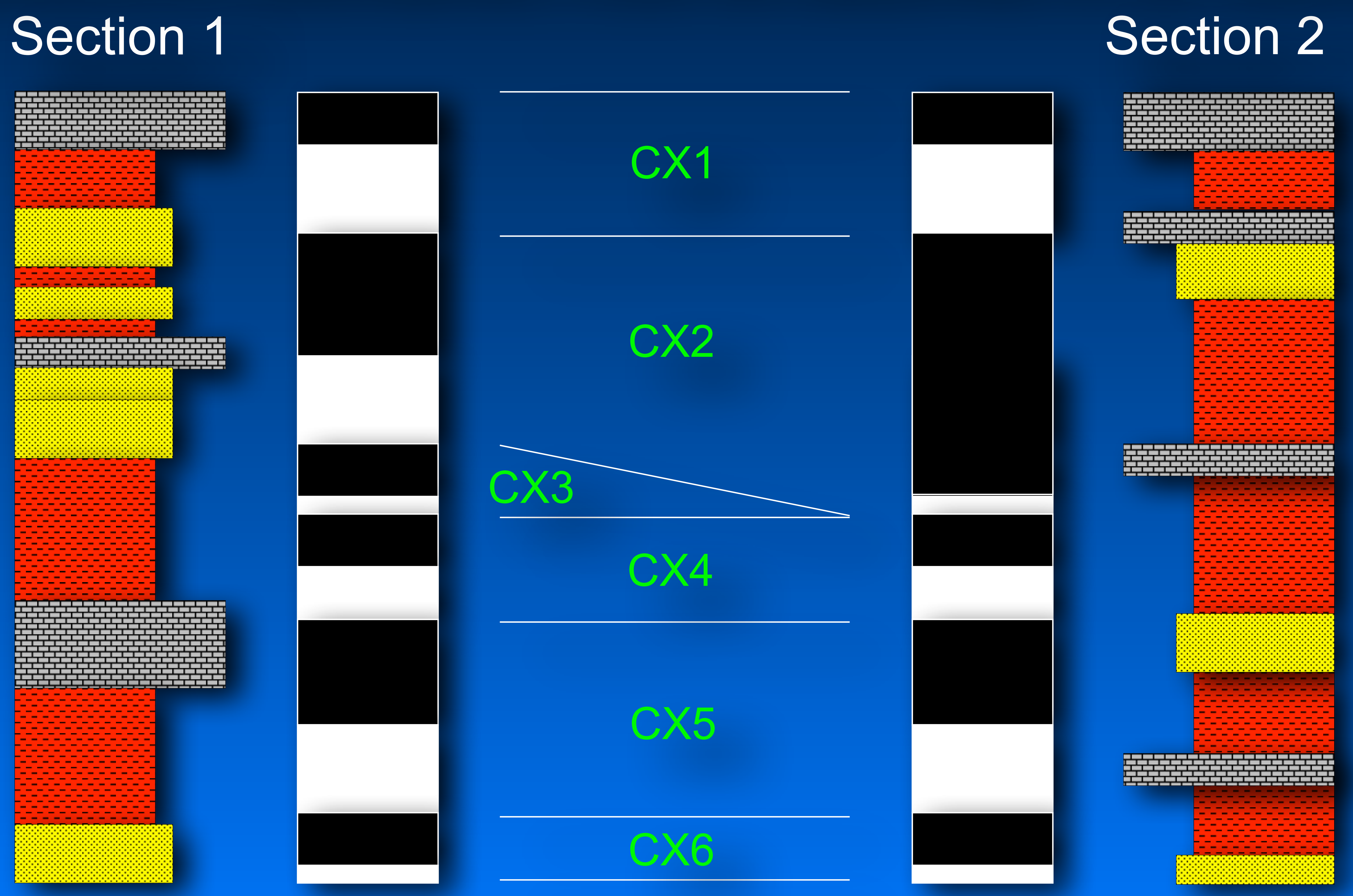
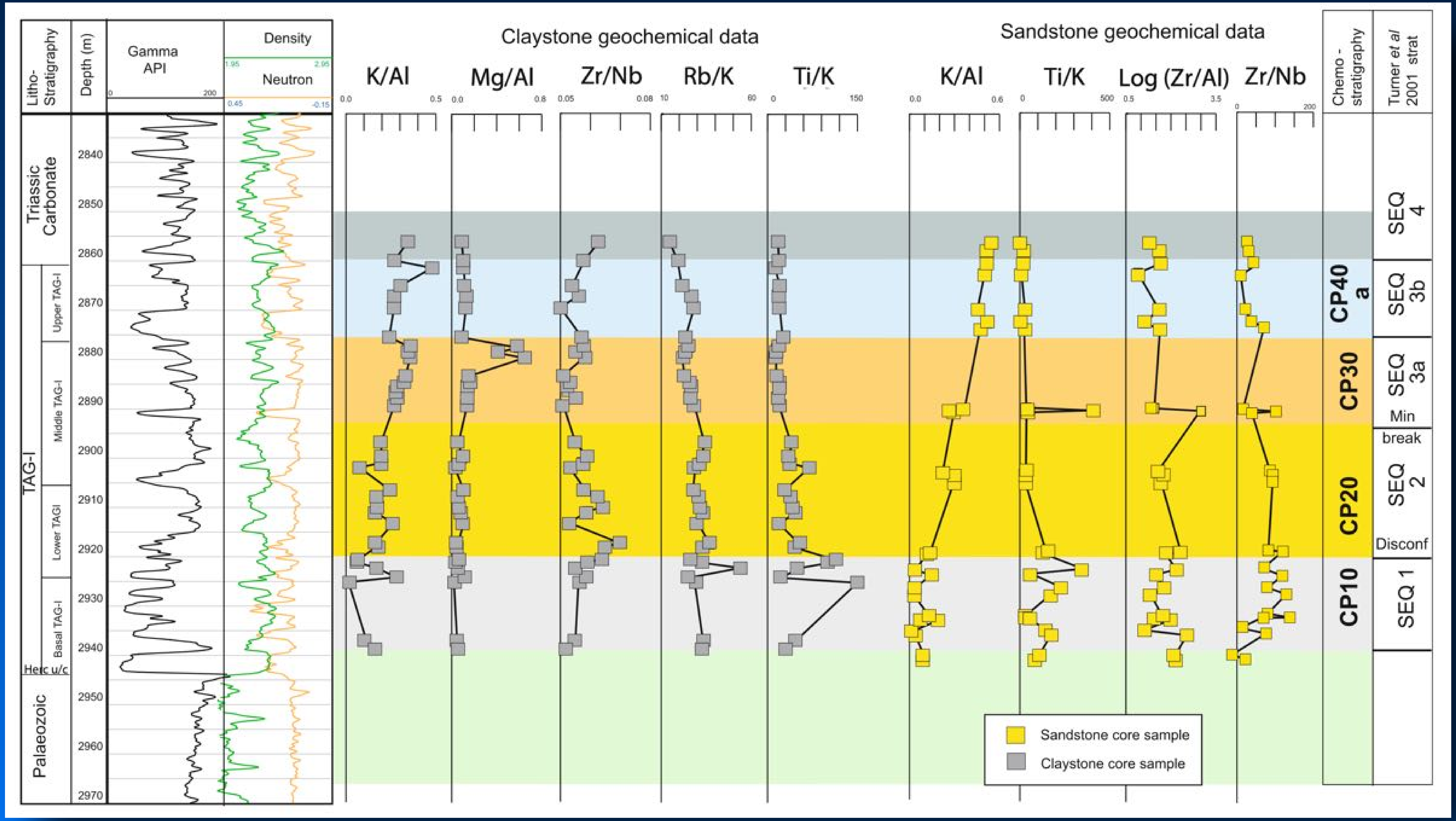


Stratigraphy: Zonation & Correlation

Chemostratigraphic Correlation

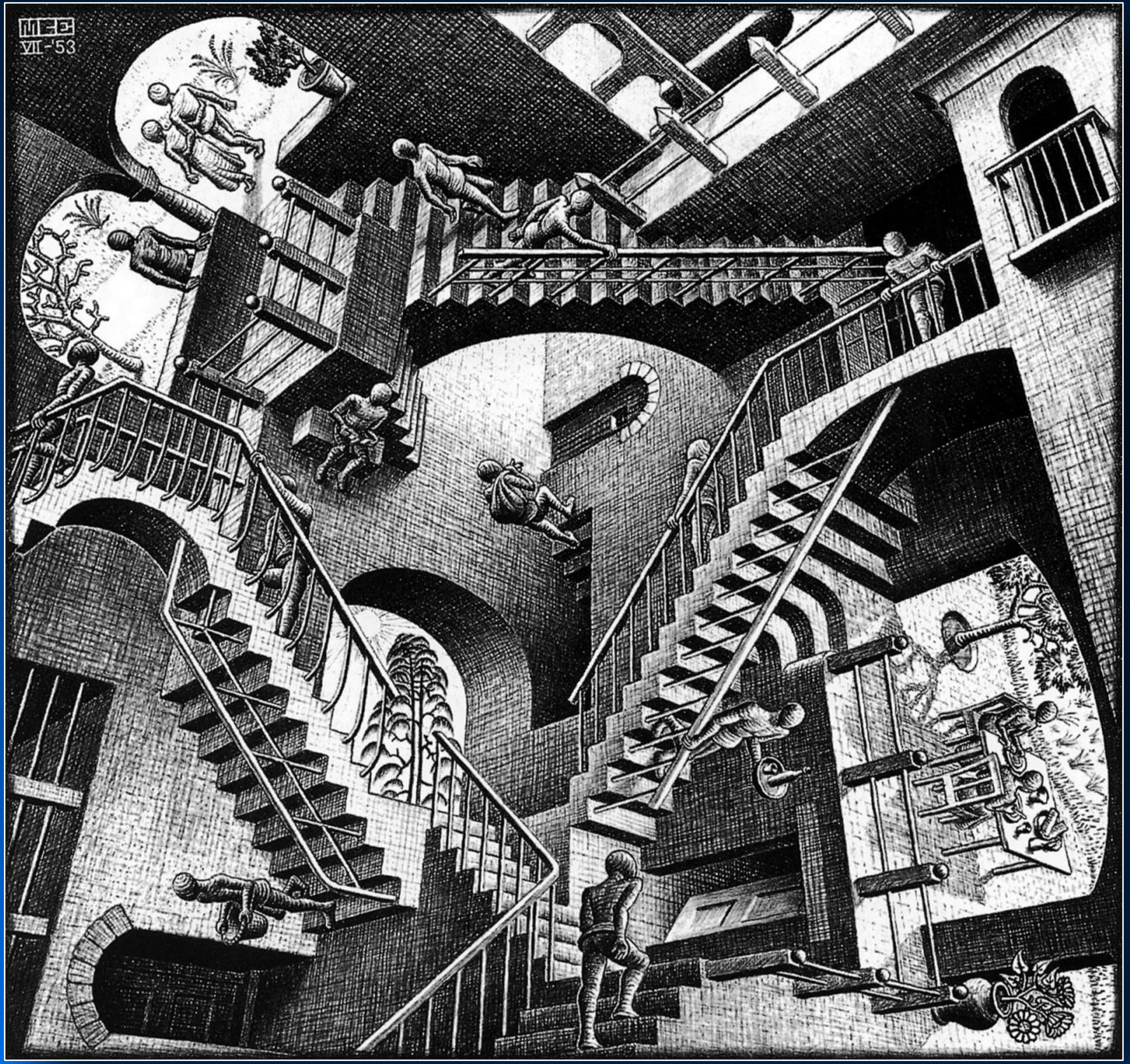
Use of chemical/isotopic logs collected from stratigraphic sections or cores to define chemo zones based on coordinated patterns of variation.



Stratigraphy: Zonation & Correlation

Paradox of Chronostratigraphy

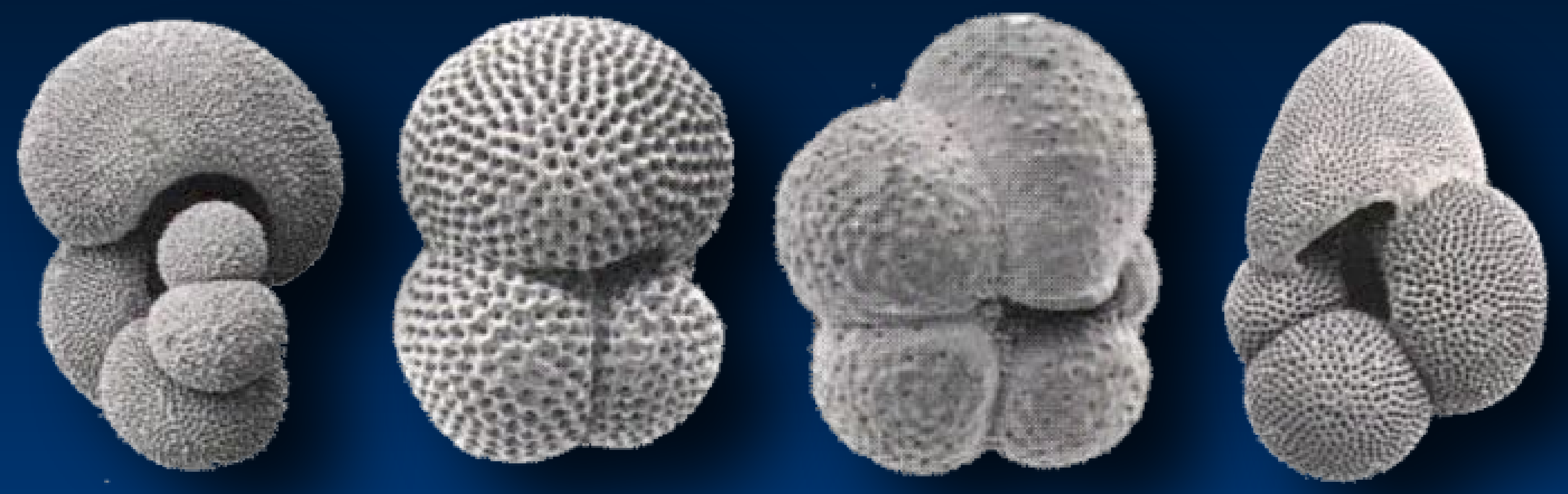
- In order to interpret the chronostratigraphy of a stratigraphic succession correctly the time relations between the stratigraphic datums must be known.
- In order to know the time relations that exist between stratigraphic datums the chronostratigraphy of the stratigraphic succession must be known.

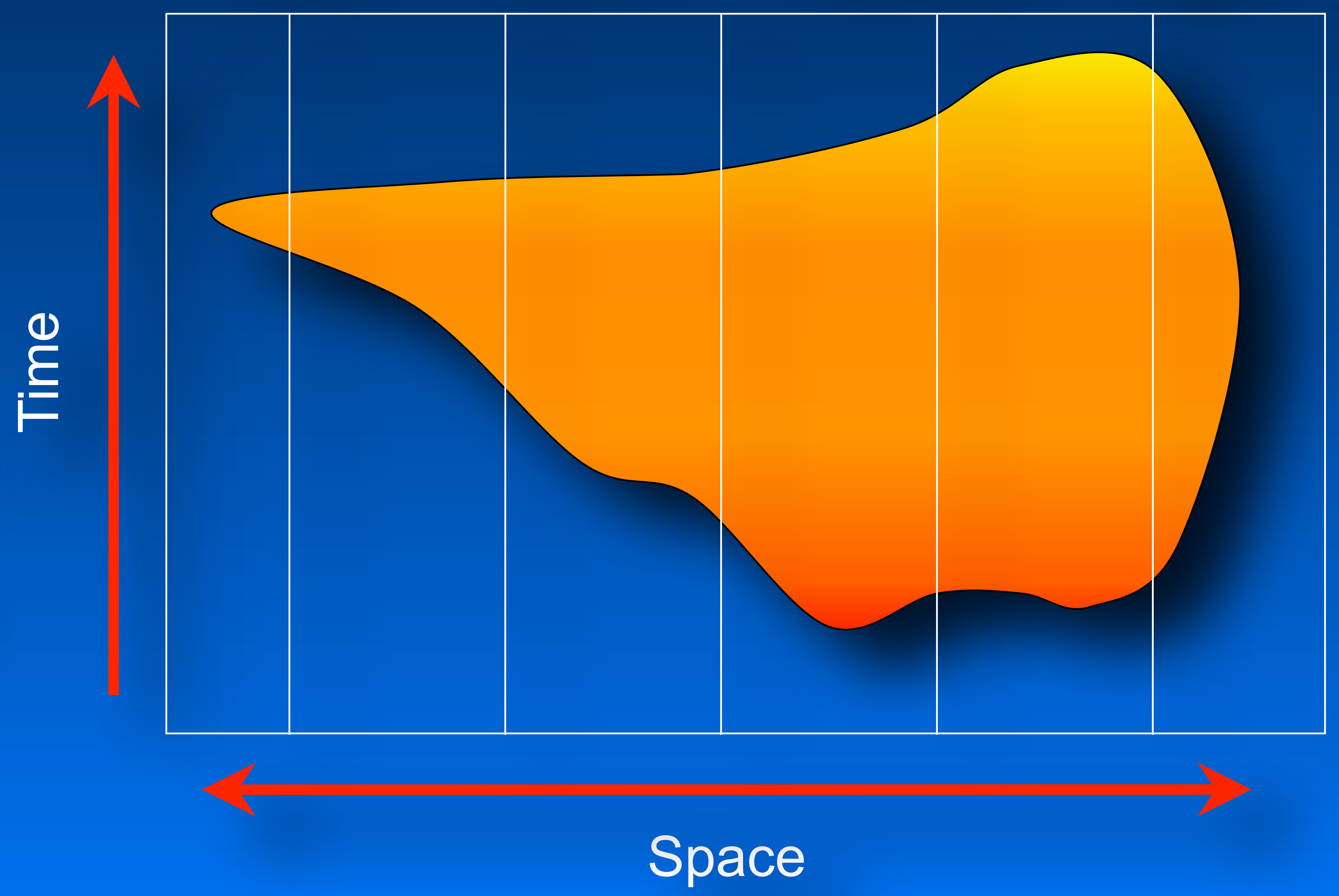


Stratigraphy: Zonation & Correlation

Chronostratigraphic Correlation

- Fossils provide the richest and most widely distributed set of observations we can use to make chronostratigraphic correlations.
- Fossils also have the advantage of being unique in terms of their morphologies and occurring in a well-established temporal sequence
- But the distribution of fossils in time and space is complex and often counterintuitive. Thus, a simplistic approach to chrono-stratigraphic analysis – even with the aid of fossils – is unwarranted.

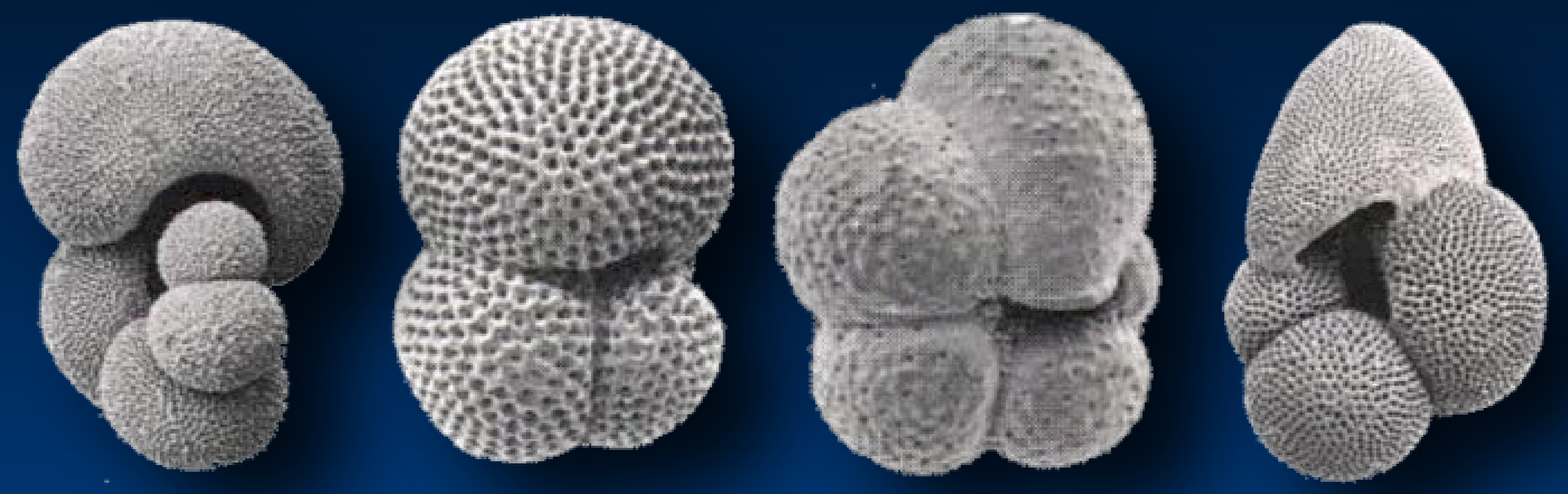


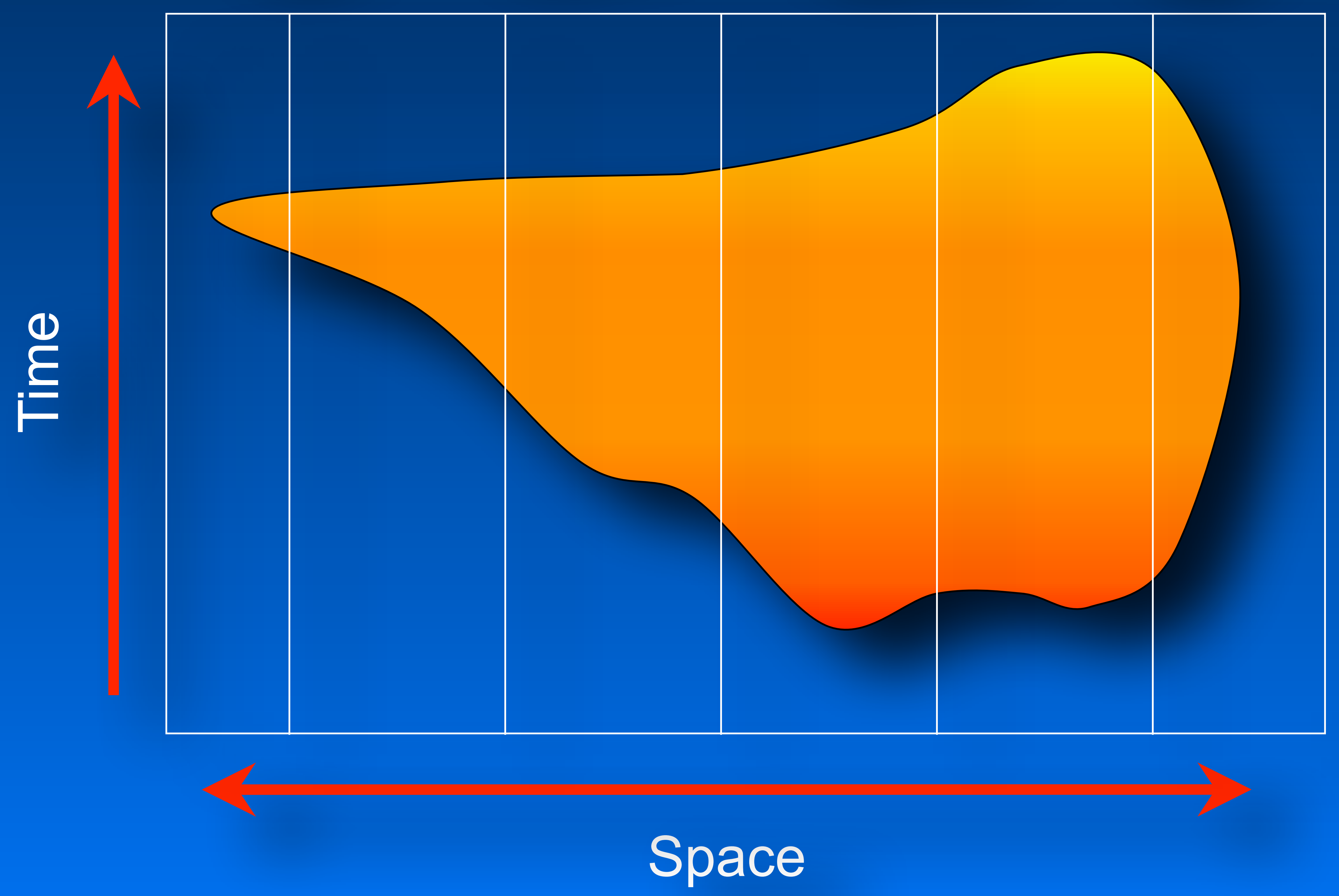


Stratigraphy: Zonation & Correlation

Chronostratigraphic Correlation

- In order to achieve the best possible chronostratigraphic collections there is no substitute for adopting an explicitly comparative approach that allows all stratigraphically relevant information to be brought together and compared in a structured manner that takes advantage of the strengths, and minimizes the weaknesses of each data type.

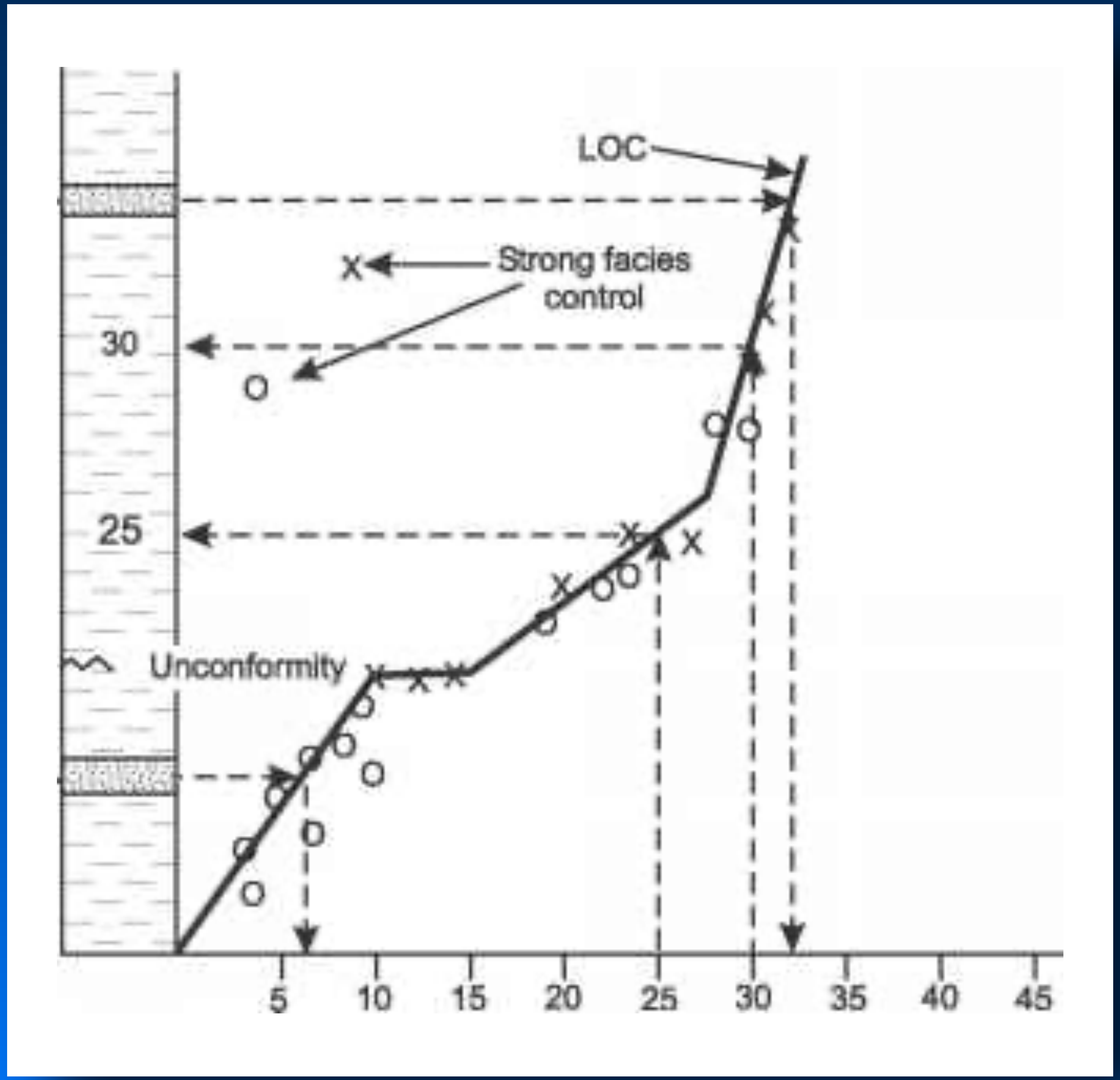




Stratigraphy: Zonation & Correlation

Quantitative Stratigraphy

The branch of stratigraphy that deals with the quantitative analysis of distributions of geological observations in time and space for the purpose of describing stratigraphic data and inferring chronostratigraphical relations.



Stratigraphy: Zonation & Correlation

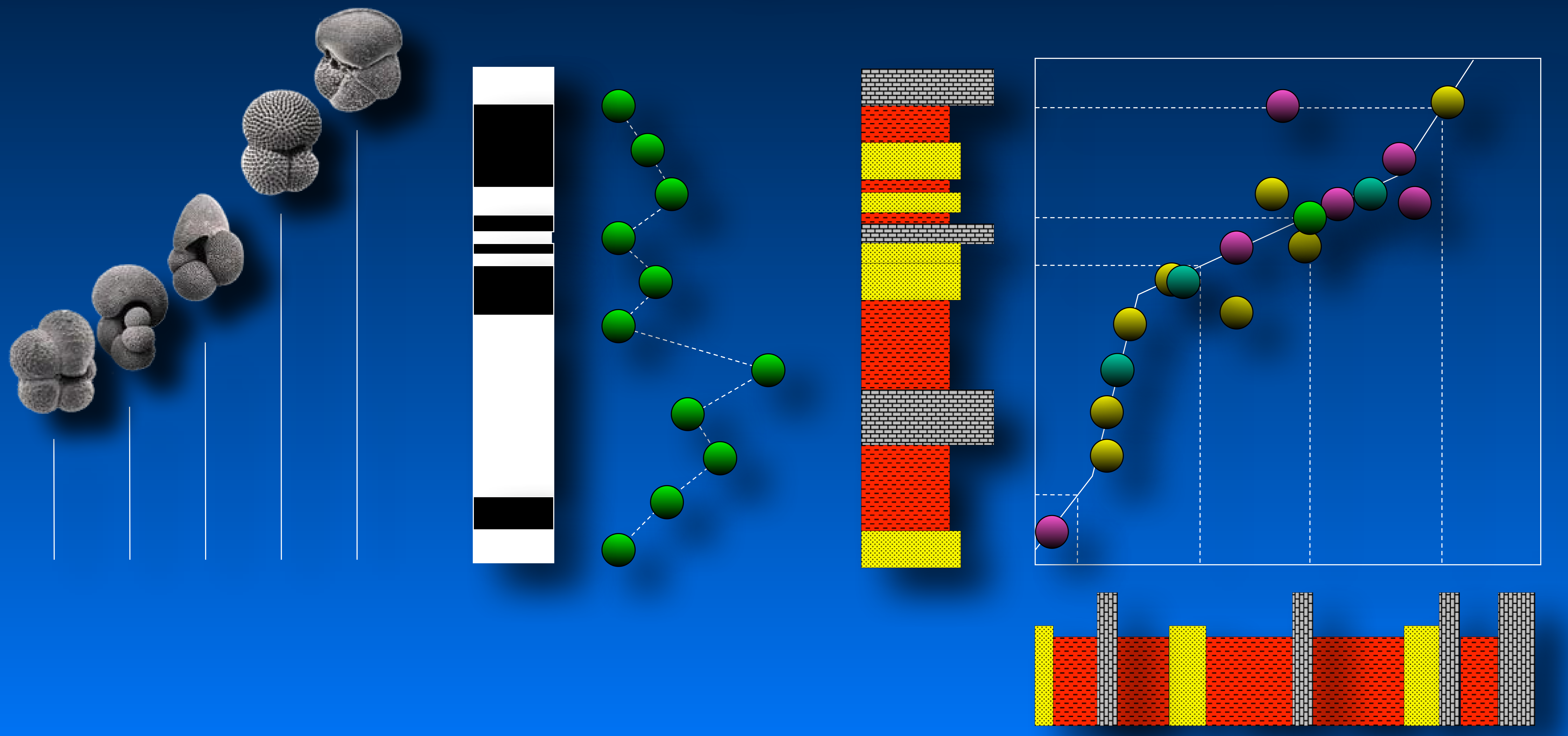
Quantitative Stratigraphy

- Graphic Correlation (GC) - uses spatial data to summarize and infer the correct sequence and spatial placement of datums in the stratigraphic record.
- Ranking & Scaling (RASC) - uses a probabilistic model derived from sequence data to infer the correct relative placement of datums in the stratigraphic record.
- Unitary Associations (UA) - uses a graphic theoretic approach to the seriation problem to infer the correct relative placement of datums in the stratigraphic record.
- Stratigraphic Constrained Optimization (sCONOP) - uses an optimization approach to solve the seriation & scaling problems simultaneously in a quasi-spatial context.

Stratigraphy: Zonation & Correlation

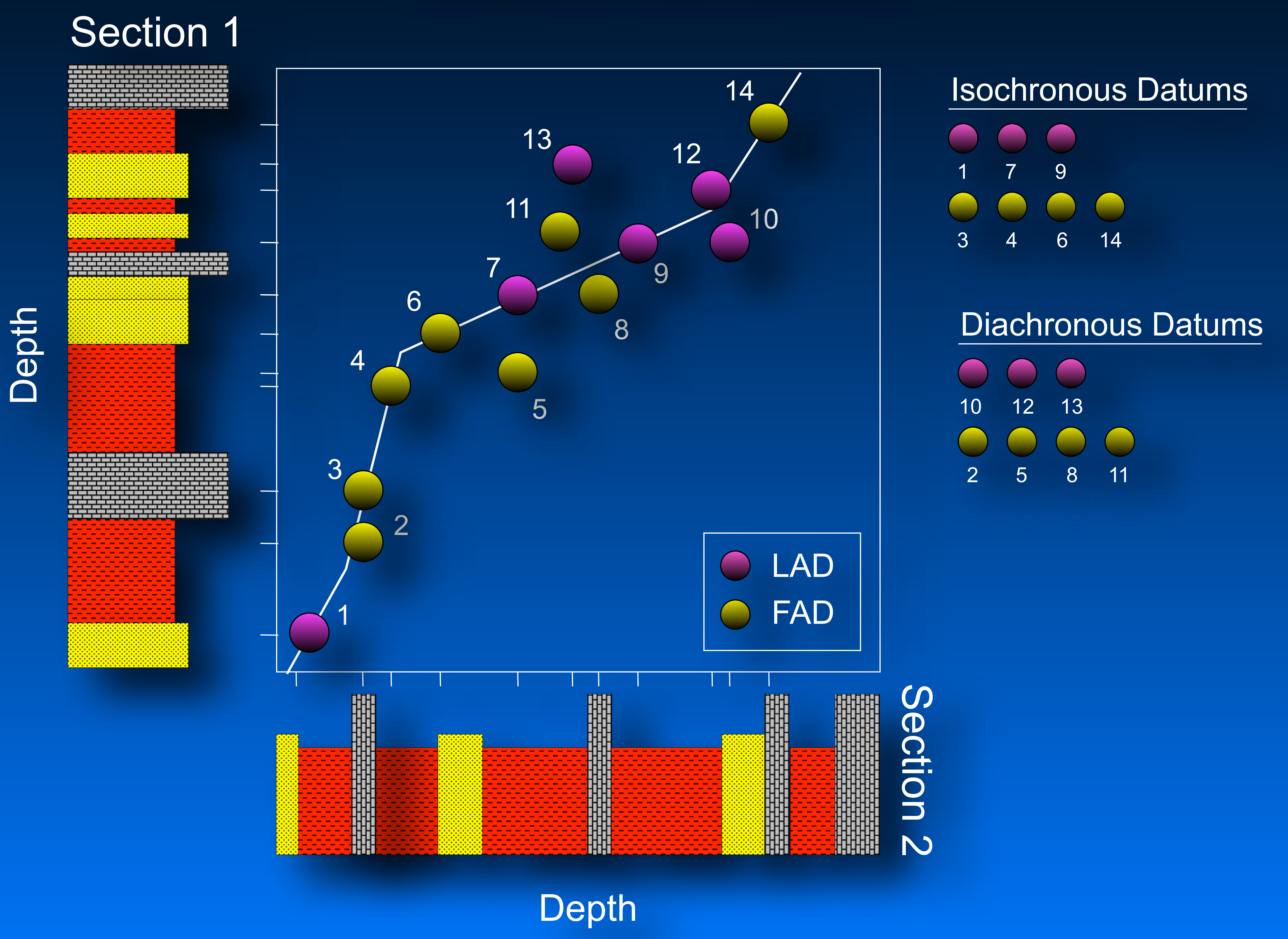
Graphic Correlation

A simple graphical approach to stratigraphic correlation that can be used to infer the series and sequence of any set of stratigraphic datums in two or more sections/cores.



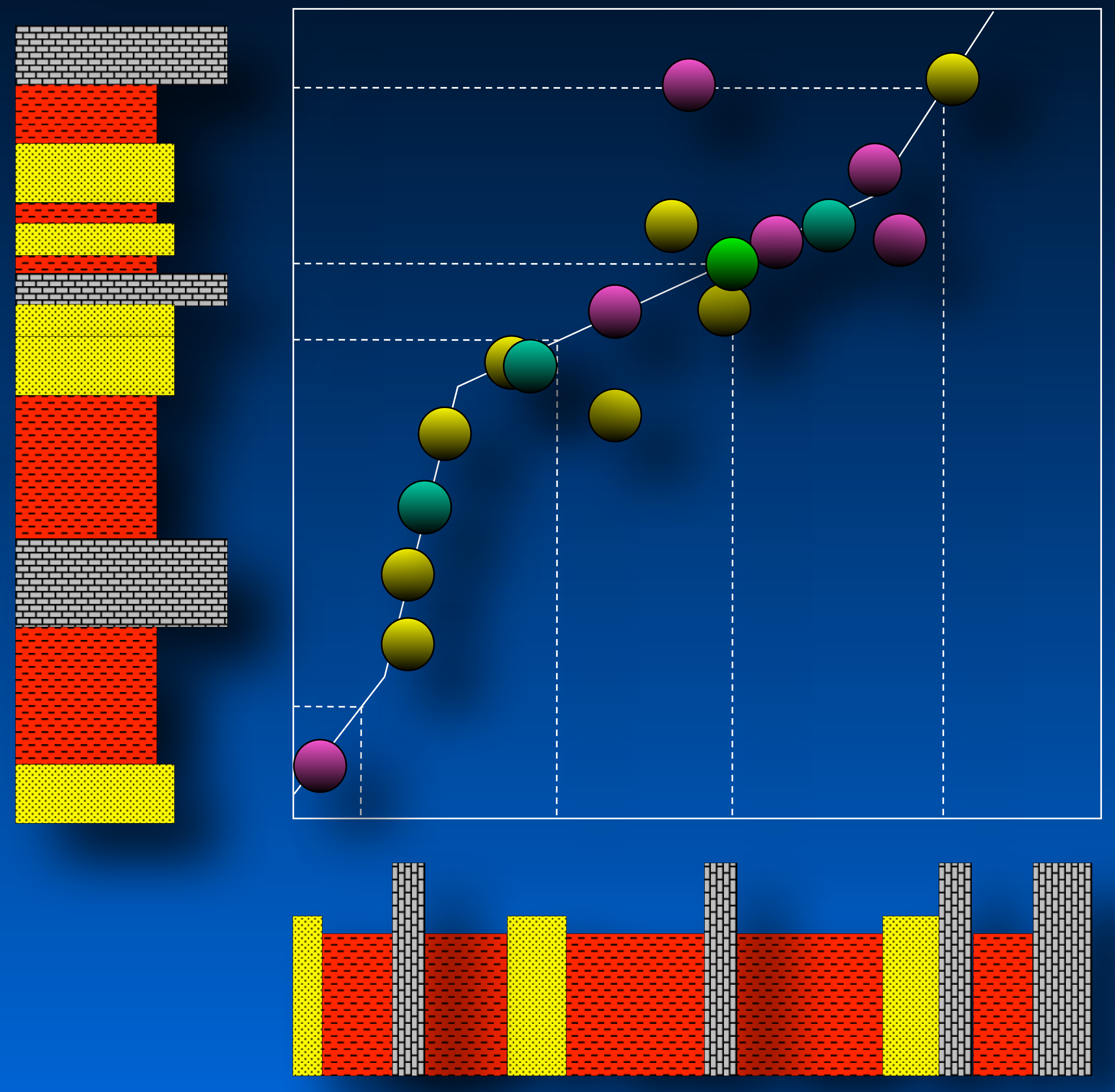
Stratigraphy: Zonation & Correlation

Graphic Correlation



Stratigraphy: Zonation & Correlation

Graphic Correlation (GC) Event Sequence Inference



Advantages

- Logically consistent
- Data driven
- Takes advantage of all data available
- Produces results that are the product of a search for an optimal solution using a simple, graphical model
- Results in very fine scale chronostratigraphic correlations

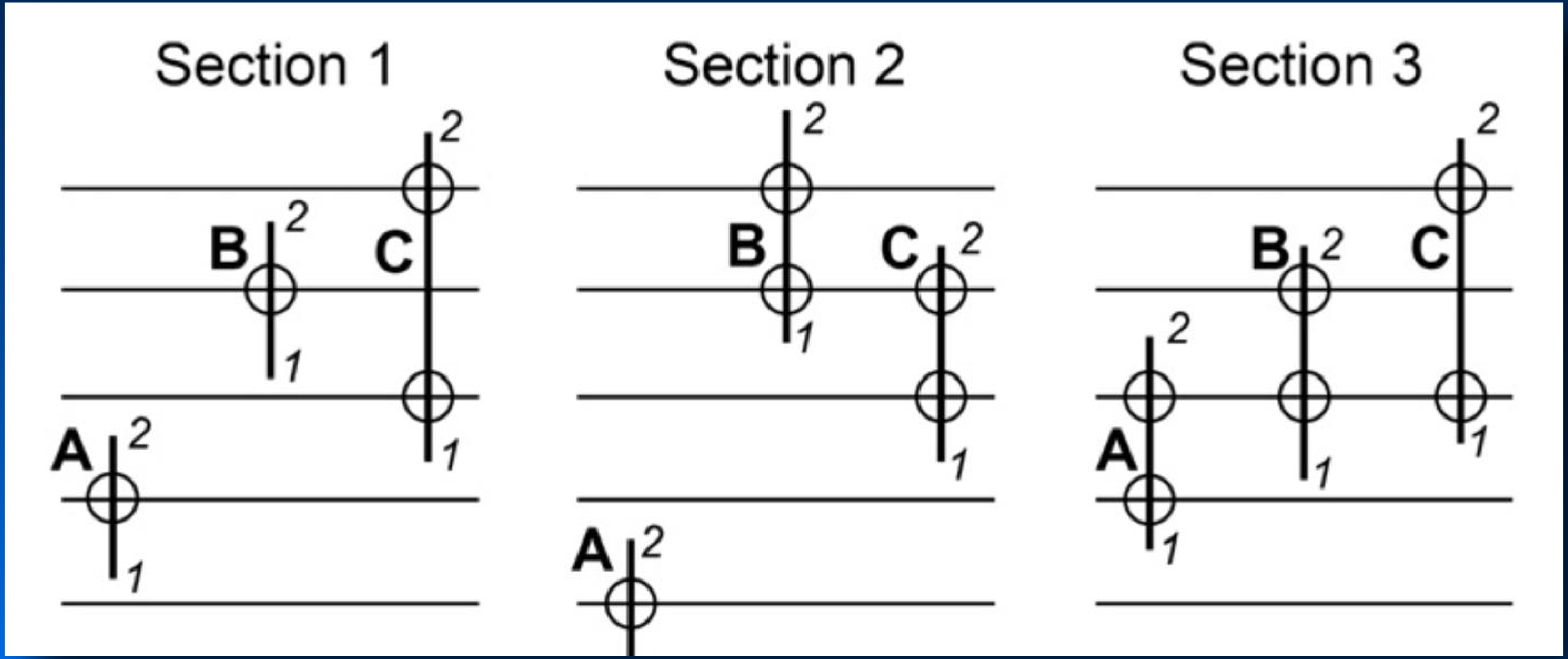
Disadvantages

- Very labor/calculation-intensive to implement
- Depends on user's skill to find optimal solutions
- Results dependent on the order in which sections/ core are composited
- Lack of user-friendly software

Stratigraphy: Zonation & Correlation

Ranking & Scaling (RASC)

RASC differs from graphic correlation by focusing on the average datum occurrence sequence (FADs and LADs) rather than the maximum/minimum sequence.



Stratigraphy: Zonation & Correlation

Ranking & Scaling (RASC)

Superposition Matrix

Datums	C_2	C_1	B_2	B_1	A_2	A_1
C_2	-	3	2	2.5	3	3
C_1	0	-	0	0.5	2.5	3
B_2	1	3	-	3	3	3
B_1	0.5	2.5	0	-	2.5	3
A_2	0	0.5	0	0.5	-	3
A_1	0	0	0	0	0	-

- Count number of times in which the row datum overlies the column datum.
- Last appearances are always counted as overlying first appearances of the same taxon (+1) even when these coincide.
- Coincidence between datums of different taxa count 0.5.
- Re-arrange the columns and rows so that the counts increase from left to right in each row of the upper diagonal and decrease from top to bottom in each column of the lower diagonal.

Stratigraphy: Zonation & Correlation

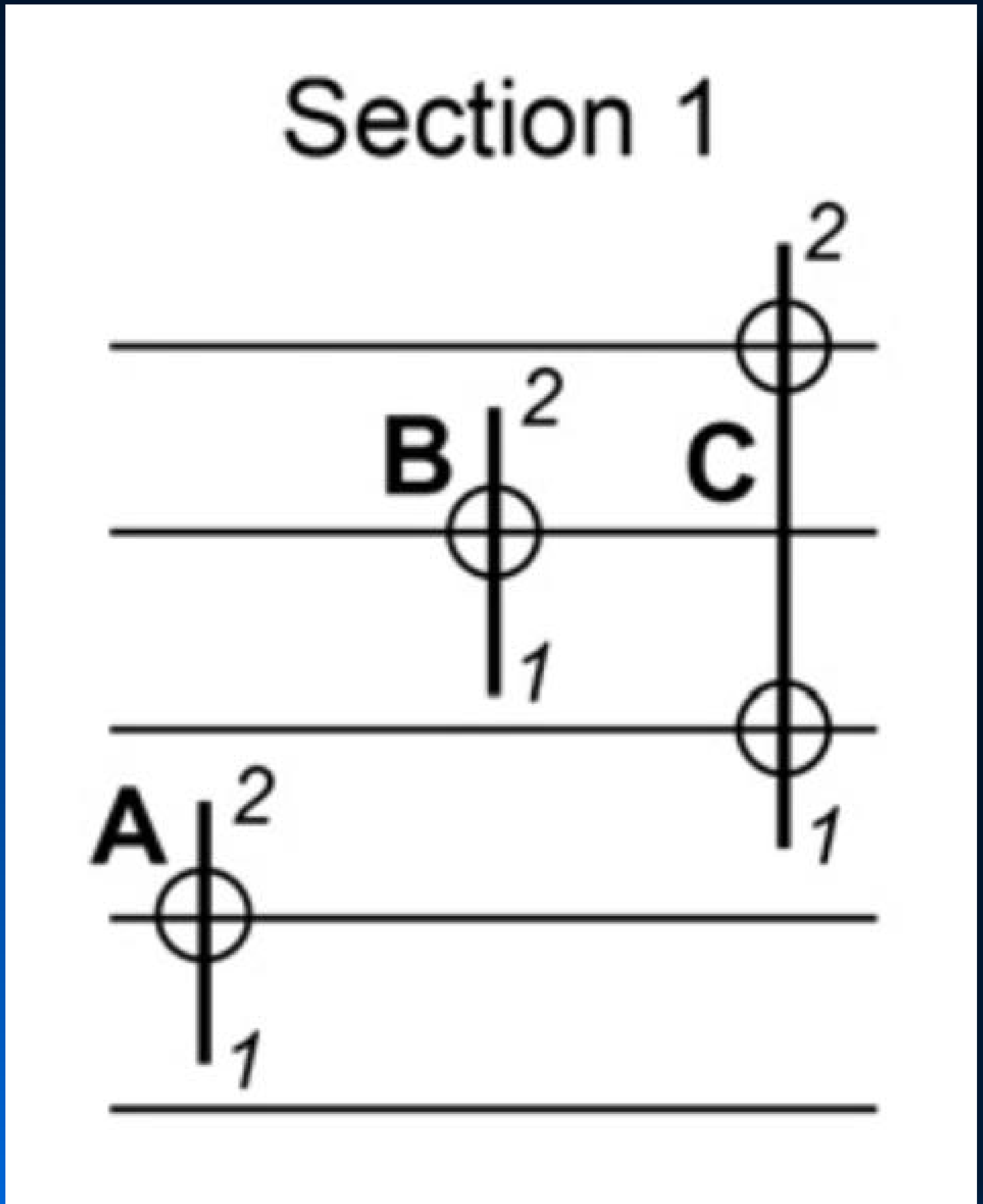
Ranking & Scaling (RASC) Event Sequence Inference

Advantages

- Logically consistent
- Objective, data-driven, data-integrative procedure
- Strong statistical & probabilistic underpinning

Disadvantages

- Estimates sequence of events most likely to be observed, not those most likely to have occurred.
- Relies on ad hoc procedures to obtain a solution at various stages in the procedure.
- Makes a variety of parametric assumptions about the data in order to apply its probability-based model.



Stratigraphy: Zonation & Correlation

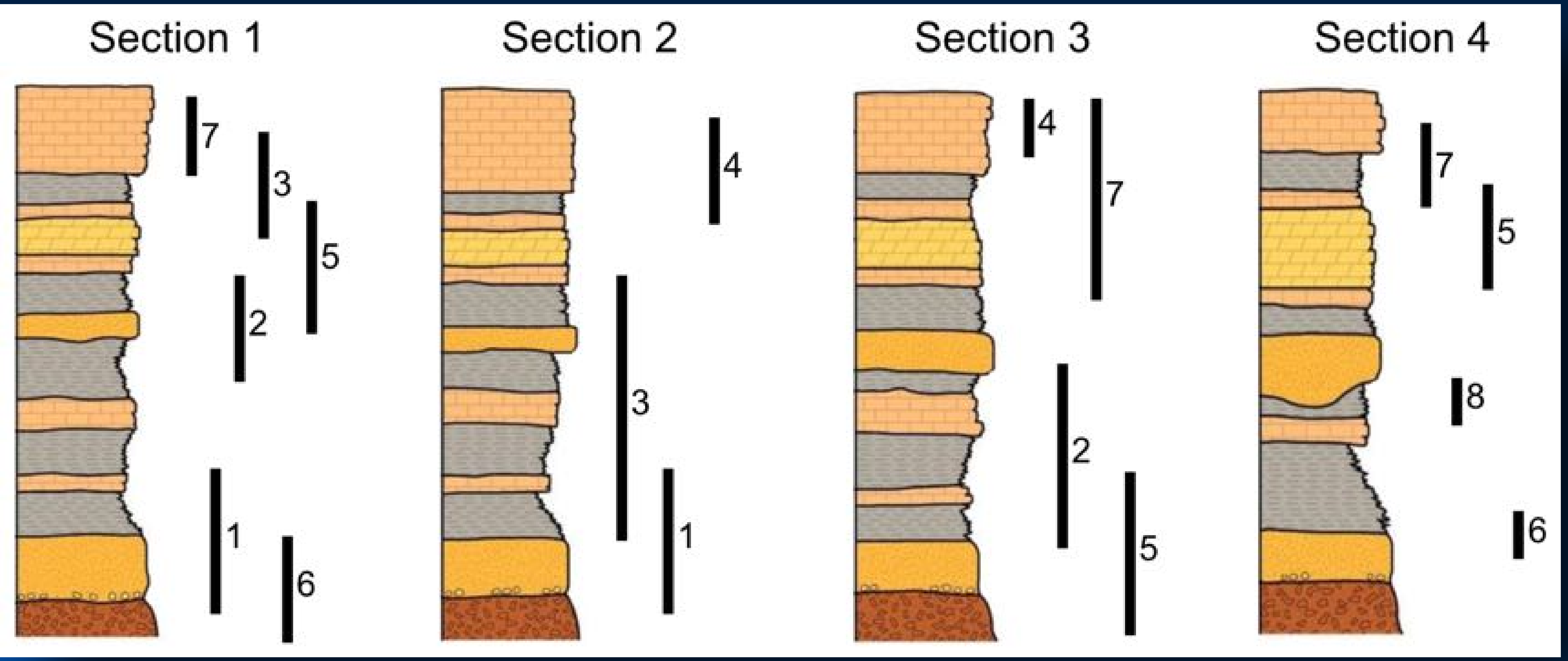
Unitary Associations (UA) Analysis

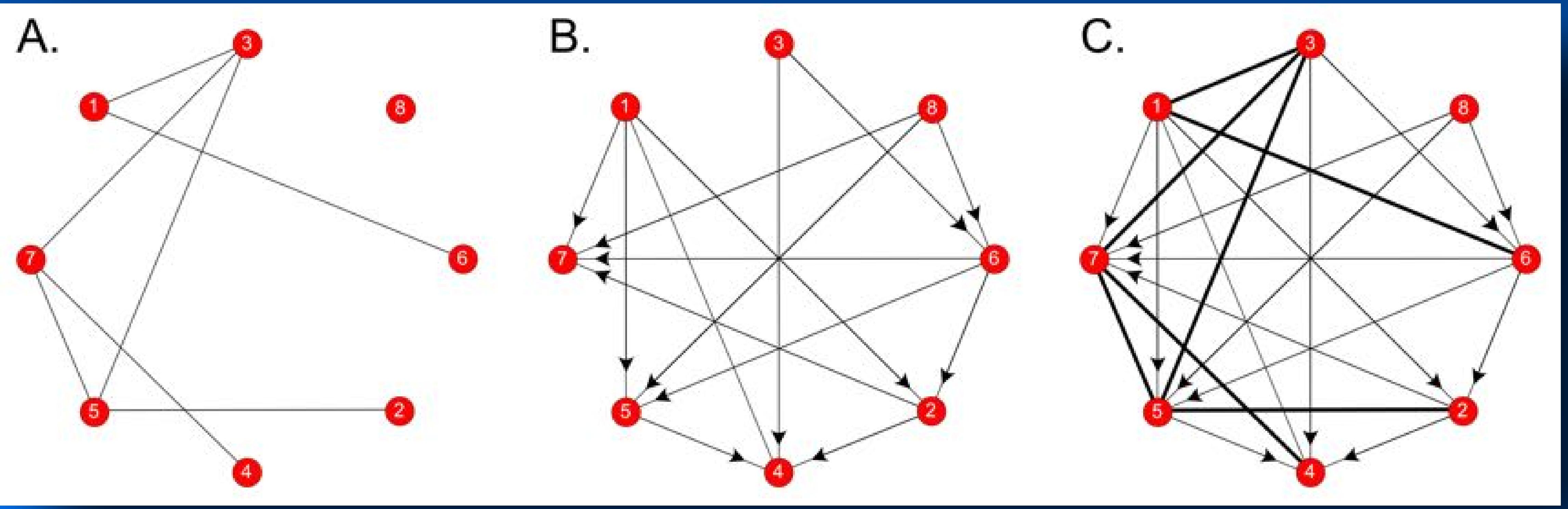
Graph Analysis

Given a series of taxon occurrences across multiple stratigraphic successions patterns of superposition (A.) and co-occurrence (B.) can be summarized as a summed mathematical network diagram (C.).

This diagram can then be inspected for consistencies, any inconsistencies identified and resolved, usually using some form of majority voting.

The result then represents a set of commonly observed event sequences.





Stratigraphy: Zonation & Correlation

Unitary Associations (UA) Analysis

Steps in a UA Analysis

- Calculate range-through stratigraphic ranges
- Eliminate all datums that don’t occur in multiple stratigraphic successions
- Inspect all remaining samples and tabulate superposition relations: A<B & B<A means A-B
- Graph relations
- Define maximal (= self-contained) cliques
- Assess superposition relations among maximal cliques
- Resolve conflicts/inconsistencies by majority vote; these are the unitary associations
- If any cycles remain resolve these by eliminating the ‘weakest link’
- Make final adjustments

Stratigraphy: Zonation & Correlation

Unitary Associations (UA) Analysis

Steps in a UA Analysis

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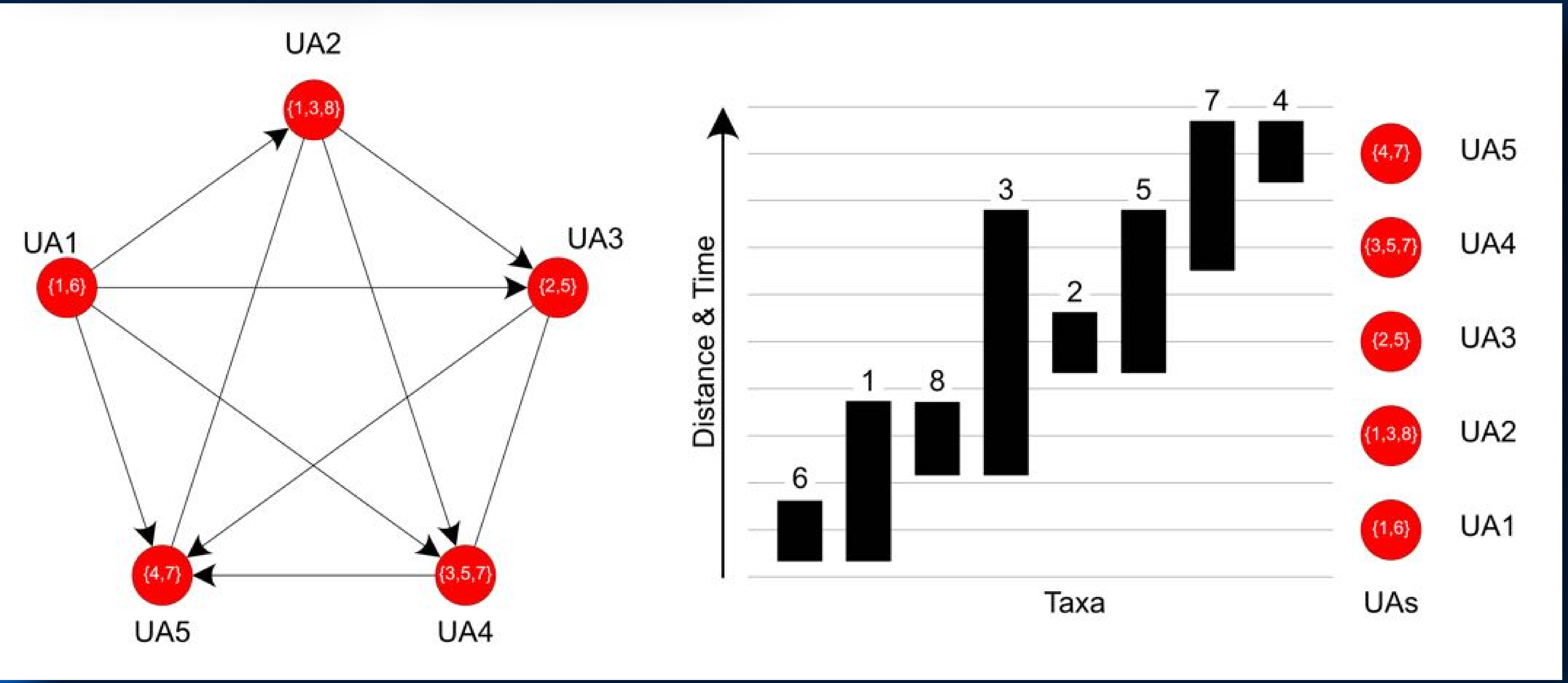
Stratigraphy: Zonation & Correlation

Unitary Associations (UA) Analysis

The Unitary Associations

Final UA result for the data shown in the previous slide.



The "unitary associations" of a UA analysis are a strati-graphically ranked series of taxon co-occurrences (= assemblage zones) whose common occurrence across the suite of successions analyses makes them useful for the purpose of inter-succession correlation.

These unitary associations will often be separated from one another by stratigraphic intervals in which the UA assignment is uncertain. Note the same taxon can be a member of more than a single unitary association.

Stratigraphy: Zonation & Correlation

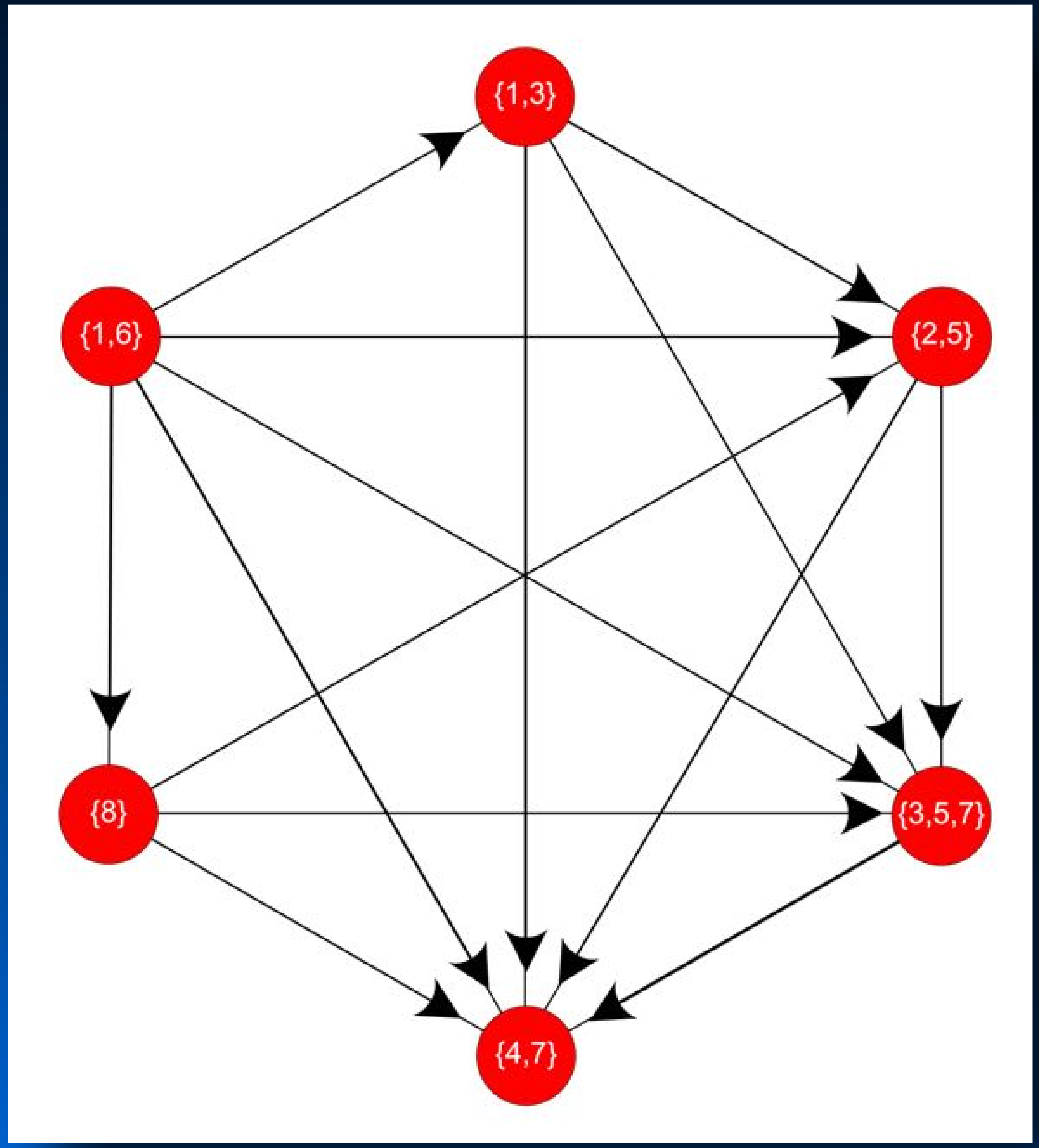
Unitary Association Event Sequence Inference

Advantages

- Logically consistent
- Objective, data-driven
- Produces results conceptually consistent with traditional analyses

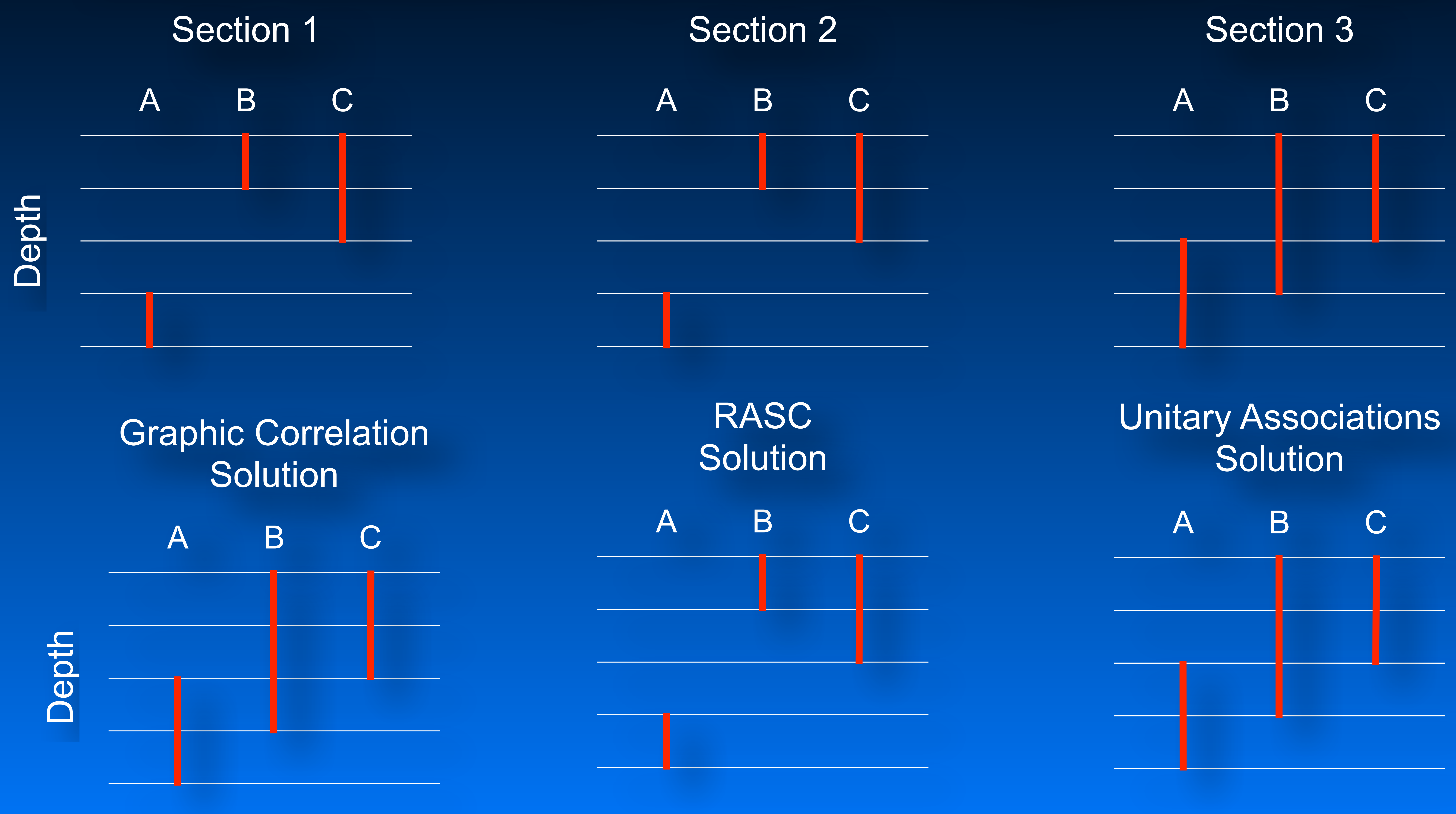
Disadvantages

- Exclusive focus on associations amounts to throwing data away.
- Relatively coarse temporal resolution.
- Relies on ad hoc rules to obtain a solution at various stages in the procedure.
- Makes a variety of stratigraphic assumptions about the data (e.g., no diachrony) to enable stratigraphic correlation.



Stratigraphy: Zonation & Correlation

Unitary Associations (UA) Analysis: A Comparative Example

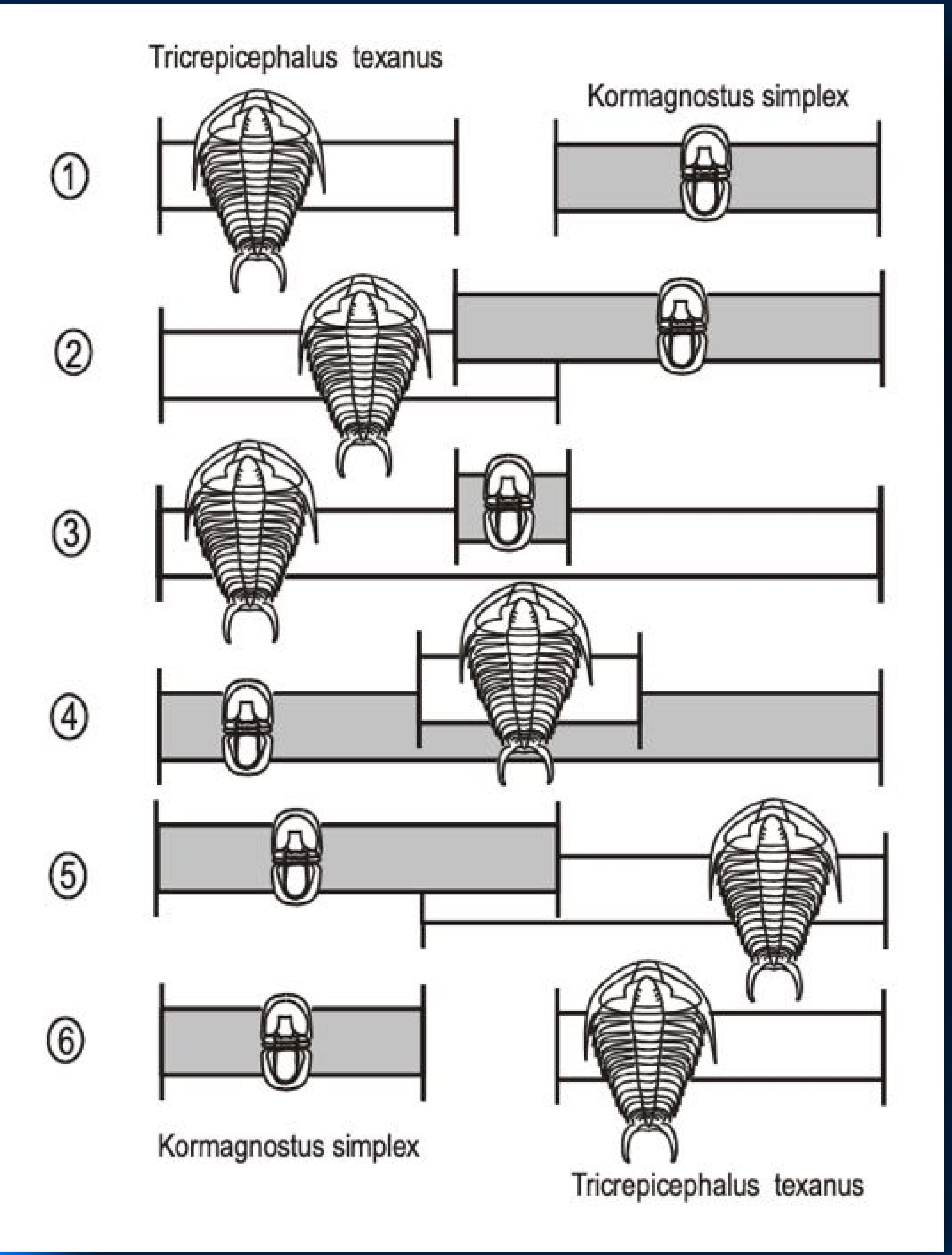


Stratigraphy: Zonation & Correlation

Stratigraphic Constrained Optimization (sCONOP)

Key Points

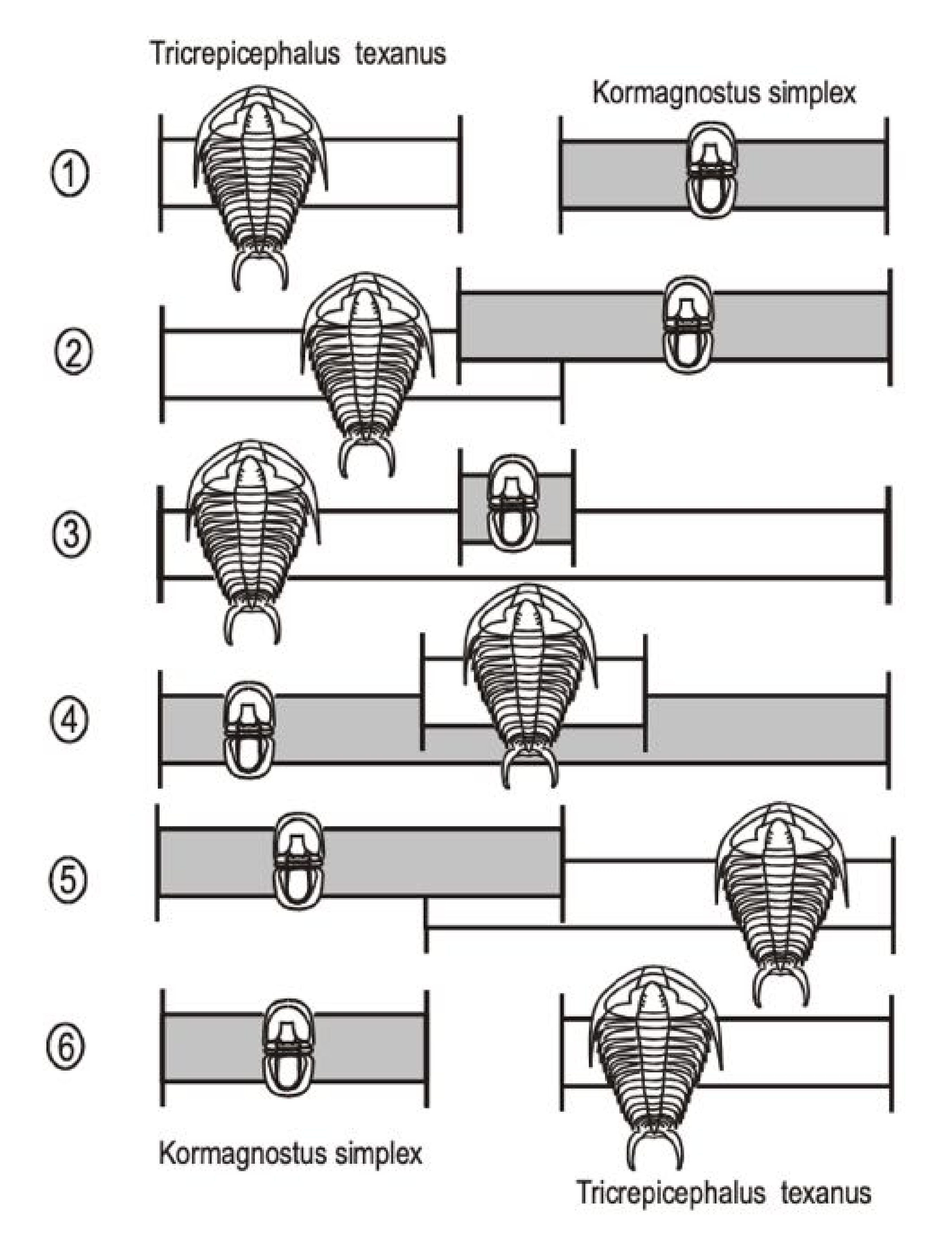
- Developed by William Kemple, Peter Sadler and David Strauss (1995).
- Conceived as a multivariate and numerically optimized extension of Shaw's (1964) graphic correlation method.
- Solves the (seriation) ranking and scaling problem simultaneously via searching the possible correlation space for solutions that minimize ranking inconsistencies and imply minimum range extensions for biostratigraphic datums.
- Based on the mathematically well-understood procedures of constrained optimization and simulated annealing.
- Algorithmically similar to contemporary approaches to machine learning (often referred to as artificial intelligence).



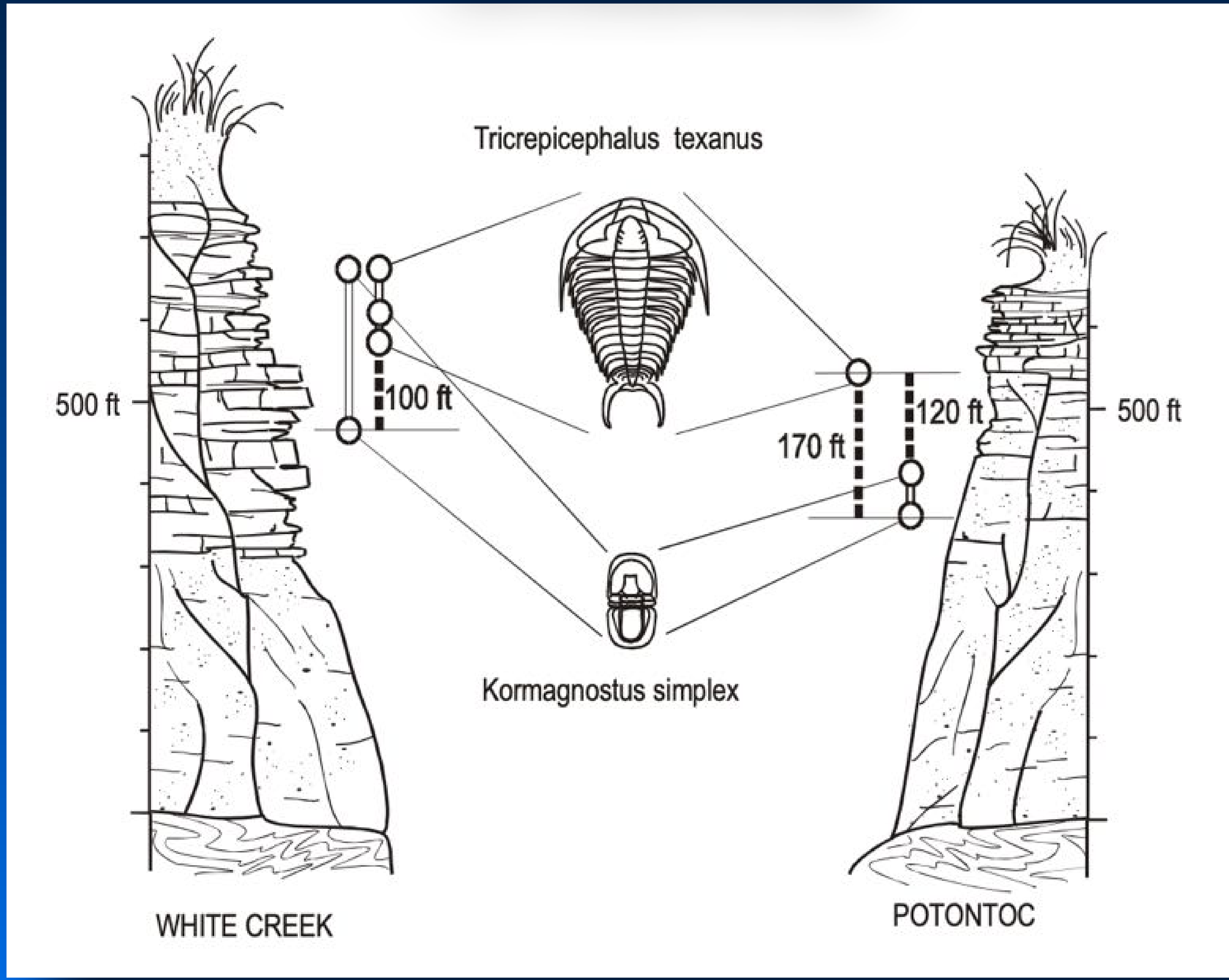
Stratigraphy: Zonation & Correlation

Stratigraphic Constrained Optimization (sCONOP)

All Possible Alternative Arrangements



Range Extensions Implied by Co-Occurrence



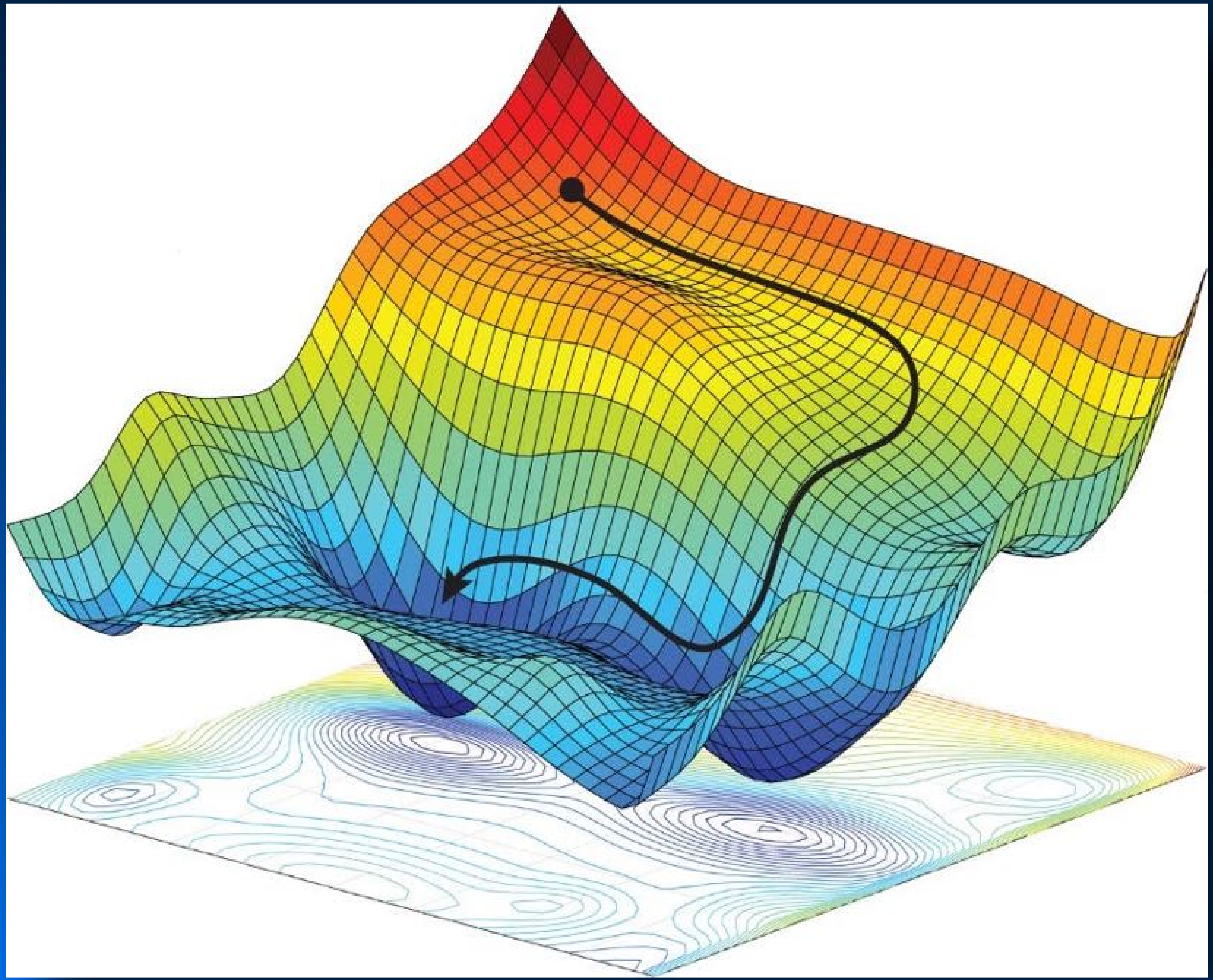
Diagrams from Sadler & Cooper (2003)

Stratigraphy: Zonation & Correlation

Stratigraphic Constrained Optimization (sCONOP)

Constrained Optimization

Kemple et al. (1995) regarded the strati-graphic event-sequence inference problem to be an exercise in constrained optimization in with the point of the process was to search through all possible datum-sequences configurations and determine the constraint penalty value associated with each (e.g., first appearance < last appearances, no co-occurrences, only extensions of observed ranges allowed). The solution surface thus defined can them be subjected to a search for the globally optimal (min. penalty) event-sequence solution.



Stratigraphy: Zonation & Correlation

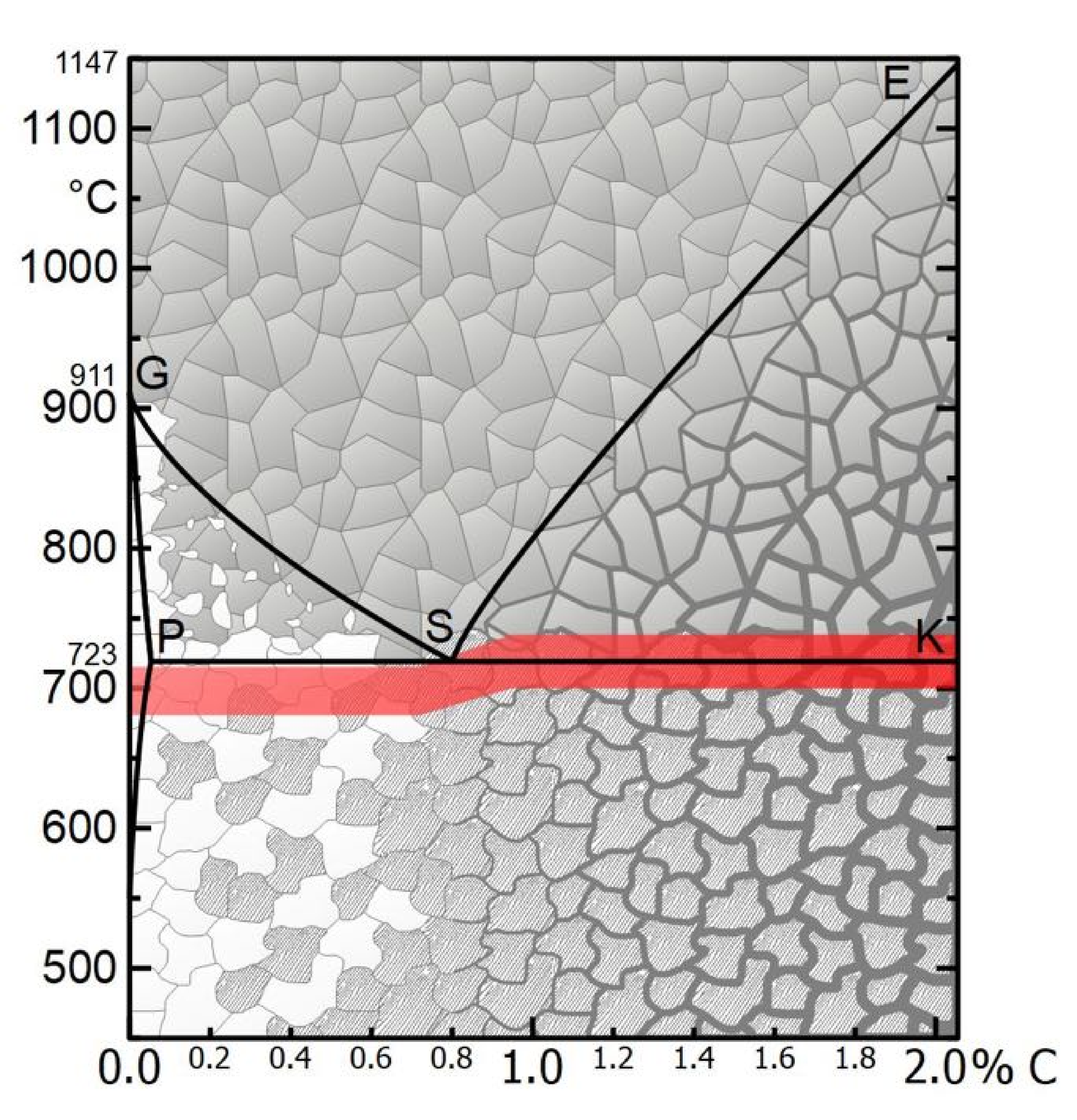
Stratigraphic Constrained Optimization (sCONOP)

Annealing

Annealing is a process, most commonly used in metallurgy by which a material is heated to its recrystallization temperature and then cooled slowly, according to a schedule that varies with the material and desired outcome of the process.

During the heating phase the microstructure of the material is altered such that it can reconfigure itself without changing the structure of the whole.

During the cooling phase the mobilized materials are free to move to new and more regular configurations, thus changing the material's physical properties.



Stratigraphy: Zonation & Correlation

Stratigraphic Constrained Optimization (sCONOP)

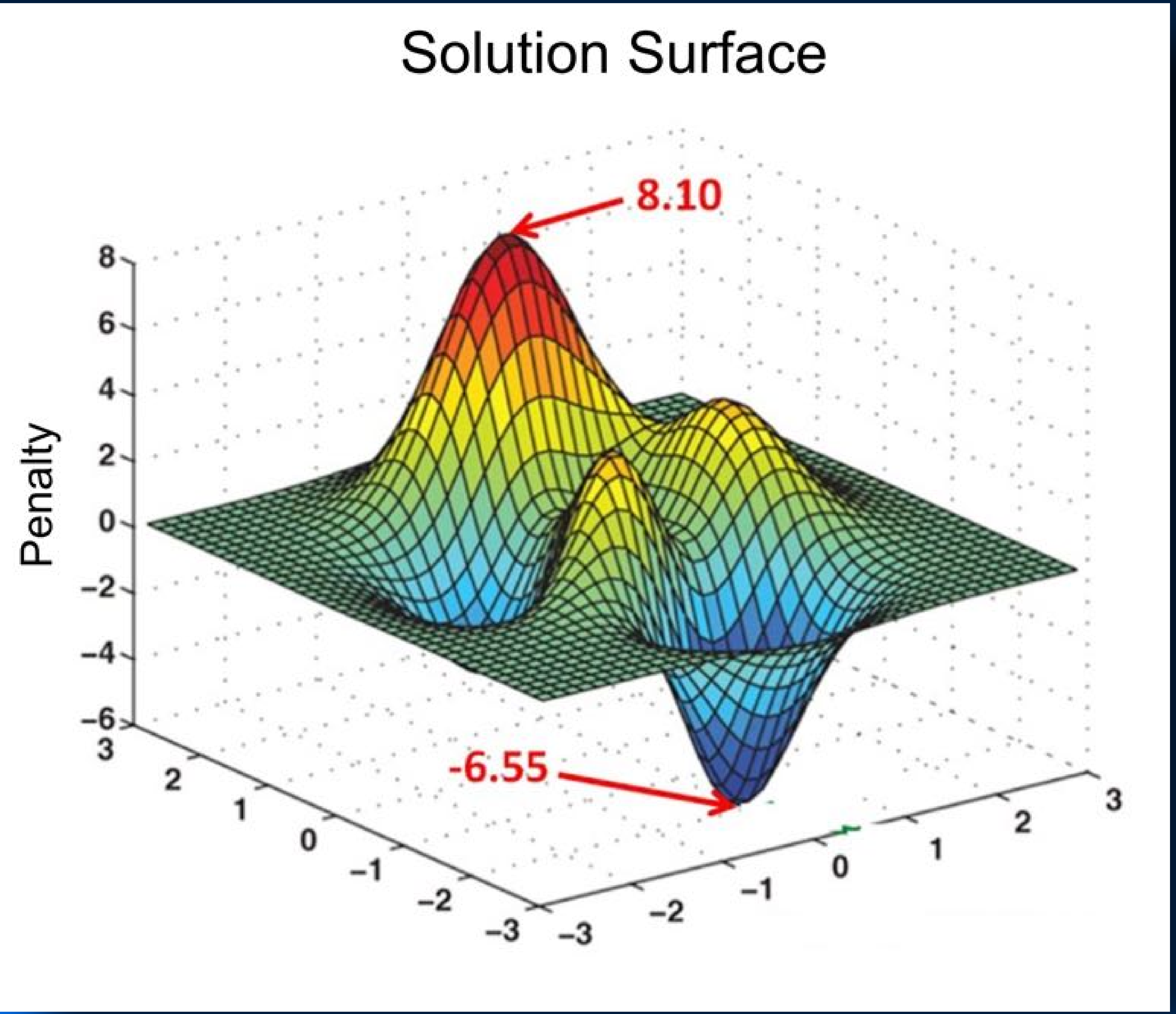
Simulated Annealing

Simulated annealing is an optimization search algorithm used to estimate the global max./min. of a topologically variable solution surface.

The search begins at a random location and proceeds by exploring the surface via saltation in which the goal is to progressively move to more optimized solutions.

At the beginning of the search moved to less optimized solutions are allowed so the search can climb out of local minima.

As the search progresses, however, the probability of accepting a lower-optimization move is reduced, slowly.

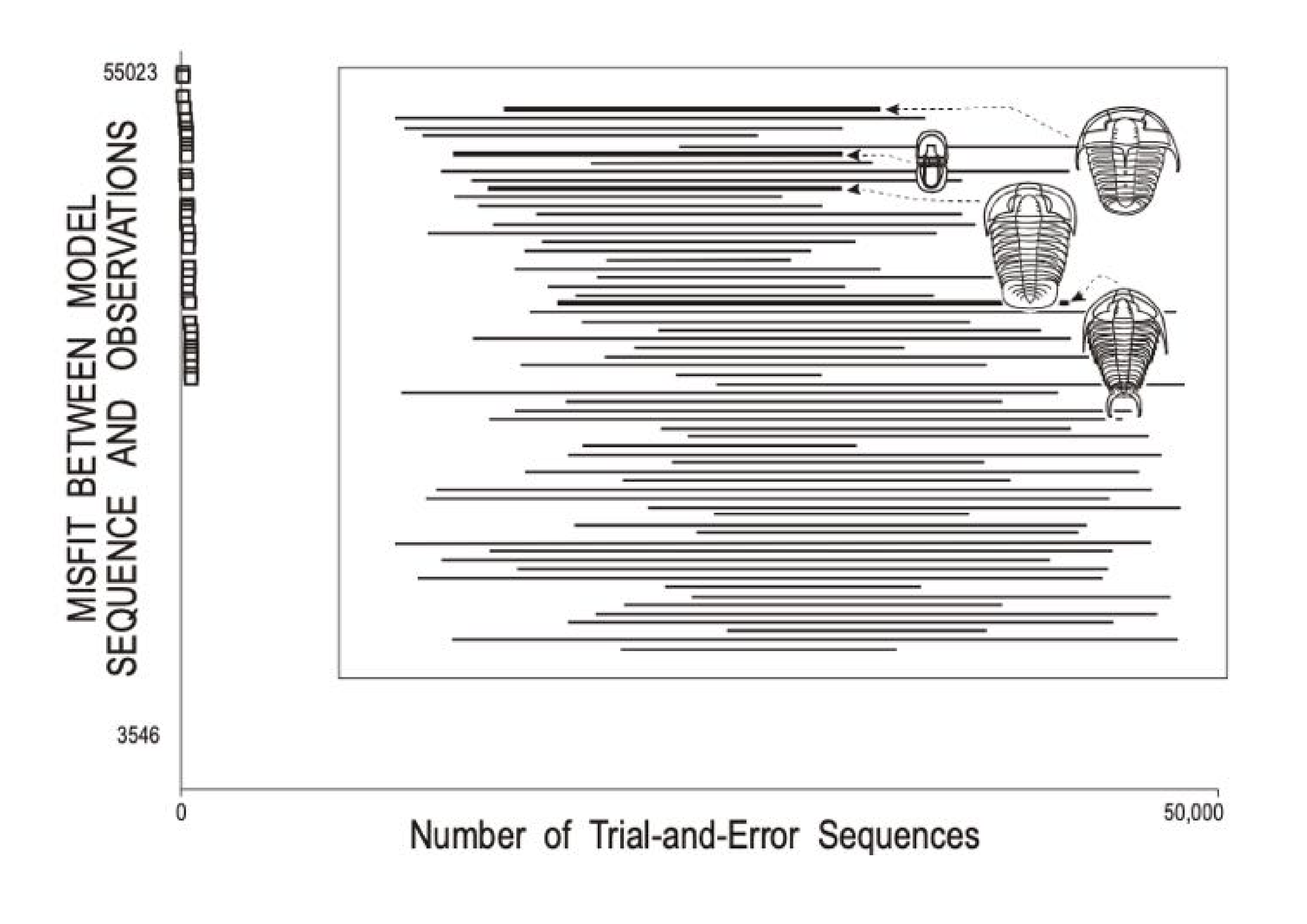


Stratigraphy: Zonation & Correlation

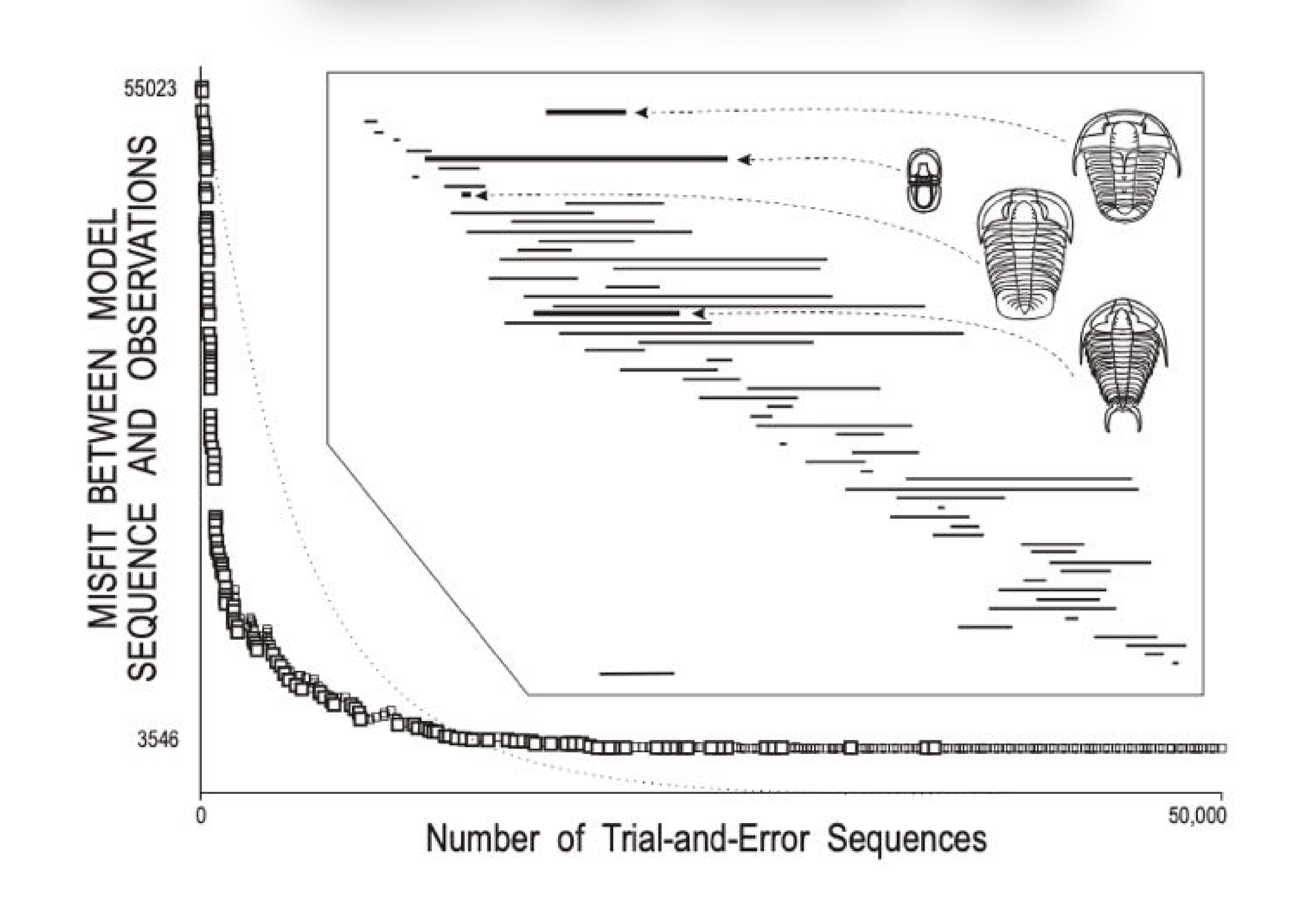
Stratigraphic Constrained Optimization (sCONOP)

The Quantification of Stratigraphic Fit

Search after 1,000 Trials



Search after 50,000 Trials



Stratigraphic CONOP employs different search algorithms, but favors the simulated annealing procedure to find the best sequence.

Diagrams from Sadler & Cooper (2003)

Stratigraphy: Zonation & Correlation

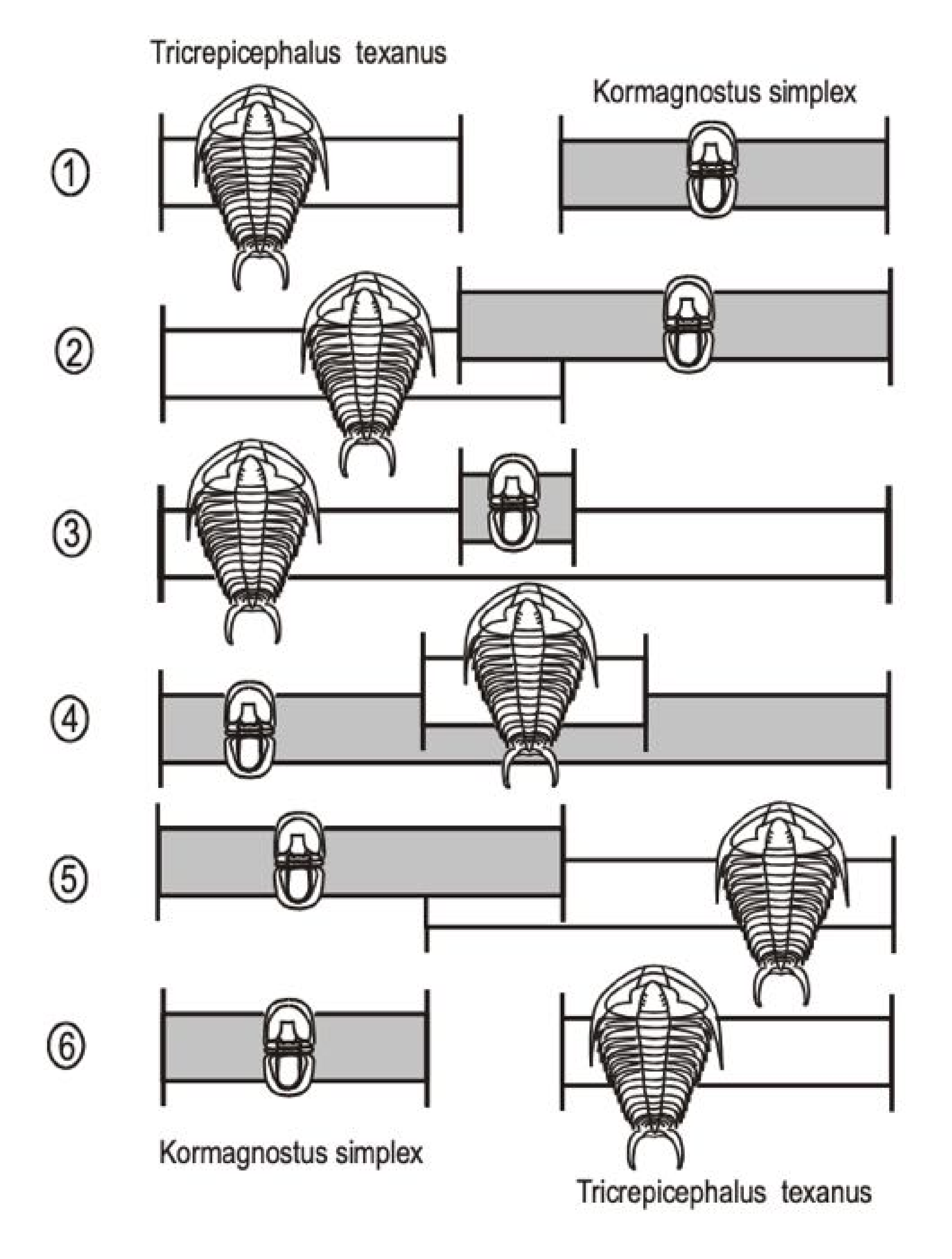
Stratigraphic Constrained Optimization (sCONOP) Event Sequence Inference

Advantages

- Logically consistent
- Objective, data driven
- Takes advantage of all data available
- Produces results that are the product of extensive searching for an optimal solution using an advanced data-analysis model
- Results in very fine scale chronostratigraphic correlations

Disadvantages

- Very calculation-intensive to implement
- Issues with finding locally (instead of globally) optimal solutions
- Lack of user-friendly software



Stratigraphy: Zonation & Correlation

Summary

- The aim of stratigraphic correlation is to infer the chronostratigraphy of one or more stratigraphical successions.
- While all types of stratigraphical observations have the potential to be isochronous two or more successions, no observational type is inherently isochronous (e.g., The Fundamental Paradox of Chronostratigraphy).
- Graphic correlation, RASC/CASC, UA and sCONOP all represent rule-based systems of chronostratigraphical induction that are able to construct internally-consistent stratigraphic models out of sets of observations and assess which are likely to be isochronous.
- The technical differences between these approaches are insignificant beside the alternative to attempting to qualitatively infer correlations among large numbers of datums by eye or based on small sets of “index fossils”.
- More research is necessary to identify each methods optimum domain(s).

NJU Course

Principles of Paleobiology

Stratigraphy: Zonation & Correlation