

GEOLOGY DEPARTMENT

SCHOOL OF MINES

UNIVERSITY OF ZAMBIA

GGY 3031 STRATIGRAPHY AND PALAEOLOGY *Pre-Requisite -GG211 & GG212*

COURSE AIMS

This course introduces students to the science of stratigraphy and the use of aerial photographs and satellite imagery to geological interpretation. The course covers in detail the branches of stratigraphy; namely lithostratigraphy, biostratigraphy, chronostratigraphy and sequence stratigraphy. Palaeontology, radiometric dating and facies are also introduced.

COURSE OBJECTIVES

On completion of the course, students should be able to:

1. Define stratigraphy and various stratigraphic terminologies,
2. Define and differentiate between branches of stratigraphy: lithostratigraphy, biostratigraphy, chronostratigraphy, magnetostratigraphy and sequence stratigraphy
3. Understand the science of lithostratigraphy, biostratigraphy and sequence stratigraphy.
4. Understand the concepts of stratification and cyclic sedimentation,
5. Identify stratigraphic relations, unconformities and facies,
6. Understand stratigraphic nomenclature and be able to correlate stratigraphic units,
7. Know principles of palaeontology; be able to recognise the most important groups of fossils and date rocks (geological dating) as well as the absolute (radiometric) dating methods,
8. Understand broad patterns of sedimentation, plate tectonics and sedimentation, and the stratigraphic evolution of Zambia,
9. Apply the stratigraphic principles and concepts to geological field mapping,

COURSE CONTENTS

1. Stratigraphy

a) Introduction

Development of the Science of Stratigraphy

Laws of Superposition, Principle of Uniformitarianism

Lithostratigraphy, biostratigraphy, chronostratigraphy, magnetostratigraphy and sequence stratigraphy

Facies, faunal succession

b) Basic stratigraphic relations

Stratification, lateral persistence, cyclic stratification, criteria for superposition,

Breaks in the stratigraphic record: unconformities

Facies and their time relations

Broad patterns of sedimentation, Plate tectonics and sedimentation

Stratigraphic evolution of Zambia

c) The system of stratigraphic nomenclature

Categories of stratigraphic classification

Observable units, inferential units

Correlation: types of correlation

2. Palaeontology

Fossils and fossilisation

Identification of main index fossils

Evolution, dating of fossils and fossil bearing sedimentary rocks

Relative and absolute dating

3. Sequence Stratigraphy

Terminology, Seismic Stratigraphy

Sea level fluctuations

Strata units, System tracts

Sequence boundary, identification criteria

5. One field trip

METHOD OF TEACHING

4 lectures and one lab session (3 hours) per week.

COURSE ASSESSMENT

Continuous Assessment 40%

Labs - 15%

Assignments - 5%

Test(s) - 20%

Final Examination 60%

Paper I (Theory) - 30%

Paper II (Practical) - 30%

PRESCRIBED TEXTBOOK

Boggs S, Jr. 1992. Principles of Sedimentology and stratigraphy. Merrill Publishing company. Columbus, Ohio. U.S.A.

Van Wagoner, J. C., Mitchum, R. M., Campion, K. M., and Rahmanian, V. D., 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for High-Resolution Correlation of Time and facies. AAPG Methods in Exploration Series, No. 7. Tulsa, Oklahoma, U.S.A.

Avery E. Thomas and Berlin L. Graydon, 1992. Fundamentals of Remote Sensing and Airphoto Interpretation. Fifth Edition, Prentice Hall, Upper Saddle River, New Jersey 07458.

Clarke C. Keith, 1999. Getting Started with Geographic Information Systems. Second Edition. Prentice Hall, Upper Saddle River, New Jersey 07458.

Allum, J, 1969. Photogeology and Regional Mapping. Pergamon.

SUPPLEMENTARY TEXTBOOKS

Prothero D.R. 1990. Interpreting the Stratigraphic Record. W.H. Preeman and Company, New York.

Mathews R.K. 1974. Dynamic Stratigraphy. Prentice-Hall.

Boulter, C.A. 1989. Four Dimensional analysis and Geological Maps: Techniques of Interpretation. John Wiley and Sons.

GGY 3031 STRATIGRAPHY AND PALAEOONTOLOGY INTRODUCTION

- Sedimentary Rocks form at the Earth's surface by a variety of low-temperature, low pressure processes.
- The rocks are composed either of particles derived from pre-existing rocks by weathering and erosion or of crystalline materials precipitated from sea water or fresh water by chemical and biochemical processes.
- The rocks cover approximately 3/4 of the surface area of the continents and even larger %ge of the ocean basins; average thickness 1800m on the continents and 240m in the oceans (Blatt, 1970), 13 Km (Pettijohn, 1975).
- The rocks are characterised by their distinctive layers (due to sediment particle size and mineral composition); some by unique suites of fossils.

WHY DO WE STUDY THEM?

- Because a record of Earth History dating back almost four billion years is preserved.
- Because they are of economic importance containing resources such as fossil fuels, minerals(e.g. Cu) and building materials.

STRATIGRAPHY

- is a science of rock strata i.e.study of rock strata, including layered igneous and metamorphic rocks.
- stratigraphers are more concerned with:
 1. age relationships of strata
 2. successions of beds
 3. local and world wide correlation of strata
 4. stratigraphic order and
 5. chronological arrangement of beds in the geologic column.

DEVELOPMENT OF STRATIGRAPHY & SEDIMENTOLOGY.

- **Nicolas Steno**(1669) formulated the basic principles
- **Principle of Superposition:** which states that in any sequence of flat laying strata the oldest layers are at the bottom and the youngest at the top.
- **Principle of Original Horizontality:** which states that beds are always deposited initially in a rarely horizontal position even though they may later be found dipping steeply.
- **Principle of original continuity:** which states that a sedimentary layer forms at the time of it's deposition a continuous sheet that ends either by thinning to disappearance by changing to abed of different composition or by stopping against a wall of barrier.

Following Steno, other workers realised that systematic study of rock strata required organisation of the strata into some kind of stratigraphic sequence e.g.Gioranni Arduino & Johann Gottlob Lehman

Arduino(1714-1795) divided all rocks into four groups:

- a) Primary mountains
- b) Secondary mountains

c) Tertiary low mountains. Tertiary survived and become part of modern stratigraphy others attempted to sub-divide rocks according to their time of formation. Most influential was Abraham Werner.

Volcanic series

Really the person who started Stratigraphy on a scientific basis was James Hutton (1790's) He recognised and described the cyclic behaviour of earth processes and materials.

- visualized tectonics uplift, erosion, sediment transport, and deposition as parts of a continuous cycle, repeated through out the geologic time-a concept labelled later as **GEOLOGIC CYCLE**.
- conceived the principle of **UNIFORMITARIANISM** (some times called Actualism)- means that processes that shaped Earth throughout geologic time were the same as those observable today or rocks could be explained by the same processes as we see operating today or simply "the present is the key to the past".
- on the side of fossils, biostratigraphy & stratigraphic correlation was initiated by William Smith(1769-1839). Smith
- discovered that different layers of strata are characterised by unique assemblages of fossils
- initiated the use of fossils for correlation of sedimentary strata from one area to another.
- laid foundation for the development of the law of faunal succession: the formal statement of the principle that fossil organism succeed each other in the stratigraphic record in an orderly, recognisable fashion
- recognised that granites were intrusive rocks formed from molten magma-plutonism. Such terms as:

a) Stage introduced by Alcide D'orbigny as major subdivisions of strata, containing characteristic assemblage of fossils and each stage follows one another and that are of world wide extent.

b) Biologic zone or Biozone introduced by Albert Oppel (1856) to represent small scale stratigraphic units that include all the strata deposited during the existence of specific fossil organisms.

Smith, D'orbigny & Oppel laid the foundation for developing a standard world wide **STRATIGRAPHIC COLUMN**.

- The study of well exposed sections of strata in different areas of Europe led to a **COMPOSITE STANDARD STRATIGRAPHIC COLUMN COVERING THE ENTIRE ROCK RECORD** and it's subdivisions called systems named and defined.

Unconformities and characterised by fossil contents and rock types.

- Relative ages were initially assigned to the systems on the basis of their fossil content, but with the advent of radiochronologic methods (radiometric dating), absolute ages have gradually been assigned to the boundaries of the systems e.g. the Pre-Cambrian-Palaeozoic boundary; Palaeozoic-Mesozoic boundary and Mesozoic- Cenozoic boundary.
- New tools and techniques led to the development of specialised fields since about the 1960's.

- 1) Seismic stratigraphy: which is the study of stratigraphic relationships and depositional facies as interpreted from seismic data.
- 2) Magnetostratigraphy: which is based on the study of the natural remnant magnetic fields in sedimentary rocks.

PRINCIPLES OF STRATIGRAPHIC CLASSIFICATION.

Rock strata have many different properties by which they can be classified:

- Lithology, fossil content, magnetic polarity, electrical properties, seismic response, chemical mineralogy composition, time of origin or environment of genesis.

But note that the stratigraphic position of change for any one property or attribute does not necessarily coincide with that for any other.

CATEGORIES OF STRATIGRAPHIC CLASSIFICATION.

Rock strata may be classified into many different categories, each with its own distinctive units. The three categories are the best known and mostly widely used:

1. Lithostratigraphy-that element of stratigraphy which is concerned with the organisation of strata into units based on their lithologic character.
2. Biostratigraphy-that element of stratigraphy which is concerned with the organisation of strata into units based on their fossil content.
3. Chronostratigraphy-that element of stratigraphy which is concerned with organisation of strata into units based on their age relationships.

Out of these three, chronostratigraphy offers a worldwide application because they are based on time of deposition whereas the first two formations a universal property are good in local areas.

- Because chronostratigraphic units can often be recognised worldwide, they offer best means for international communication among stratigraphers with respect to position in the stratigraphic column.e.g.your colleague will understand if you tell him that you will be studying the Jurassic of the same area, but will not understand you if you say you say you have been studying the Lusaka formation, a biostratigraphic zone or any local stratigraphic unit.

DISTINGUISHING TERMINOLOGIES FOR EACH CATEGORY.

Appropriate terminologies are needed for each:

- For lithostratigraphy and chronostratigraphy the numerous terms represent different hierarchical ranks;
- For biostratigraphic units they result from the recognition of various kinds of biozones.

CHRONOSTRATIGRAPHIC AND GEOCHRONOLOGIC UNITS.

- Each interval of stratified rocks represents a certain interval of geologic time, each chronostratigraphic unit(interval of rock strata) has a corresponding geochronologic unit(interval of geologic time).
- Geochronologic units are not themselves stratigraphic units because they are units of geologic time-an intangible property.e.g.chronostratigraphic unit-sand that flows through an hourglass during a certain interval of time while geochronologic unit can be compared to the interval of time during which the sand flows. It may be said that

the duration of the sand flow measures a certain interval of time an hour for instance - but the sand itself can not be said to be an hour.

INCOMPLETENESS OF ROCK RECORD.

- Stratigraphic classifications deals primarily with the Earth's rock sequence.
- But in any one area the rock record is far from continuous or complete.
- It is commonly broken by innumerable diastems, discontinuities, and erosional unconformities.
- These missing intervals are part of stratigraphy and are a very important contribution to Earth History.

LITHOSTRATIGRAPHY is the study and organisation of strata on the basis of their lithologic characteristics.

Lithology-term used by geologists in two different but related ways:

- strictly, it refers to study and description of the physical character of rocks, particularly in hand specimens & outcrops..
- it also refers to the physical lithologic characteristics such as rock type, colour, mineral composition and grain size.

e.g. we may refer to the lithology of a particular stratigraphic unit as sandstone, shale, limestone etc. & therefore lithostratigraphic units are rock units defined or delineated on the basis of their physical properties i.e. bodies of sedimentary, extrusive igneous, metasedimentary or metavolcanic rock.

LITHOSTRATIGRAPHIC UNIT(S)

1. conforms to the law of superposition.
2. are commonly stratified or tabular.
3. recognised and defined on the basis of observable rock characteristics.
4. are defined strictly on the basis of lithic criteria as determined by descriptions of actual rock materials not by geophysical properties or other criteria.
5. their definition is based on a stratotype, or type section, consisting of readily accessible rocks, where possible, in natural outcrops, excavations, mines or boreholes.
6. boundaries between different units may be placed at clearly identifiable or distinguishable contacts or be drawn arbitrarily within a zone of graduation.
7. carry no connotation of age.
8. cannot be defined on the basis of palaeontologic criteria.
9. are independent of time concepts.

Wheeler & Mallory (1956) introduced the term **Lithosome** to refer to masses of rock of essentially uniform character and having intertonguing relationships with adjacent masses of different lithology. Stratigraphic units of a single lithology rarely exists as isolated bodies :-it is important in lithostratology to:

- 1) identify and understand the nature of contacts between vertically superposed or literally adjacent bodies.
- 2) identify single lithosomes, or subdivisions of lithosomes that are so distinctive that they form lithostratigraphic units that can be distinguished from overlaying and underlying or adjacent units-the fundamental lithostratigraphic unit of this type is the formation- which

is a lithologically distinctive stratigraphic unit that is large enough in scale to be mappable at the surface or traceable in the subsurface.

- some formations may be divided into beds, which are the smallest formal lithostratigraphic units.
- formations having some kind of stratigraphic units can be combined to form groups and groups can be combined to form supergroups.

All formal lithostratigraphic units are given names, which are derived from some geographic features in the area where they are studied.

BASIC STRATIGRAPHIC RELATIONS

STRATIFICATION AND BEDFORMS

Stratification or bedding is one of the fundamental characteristic of sedimentary rocks. All sedimentary rocks occur in beds of some kind.

- (1) Beds: tabular to lenticular layers of sedimentary rock having characteristics that distinguish them from strata above and below.
 - distinction based on: composition, size, shape, orientation and packing of sediment. (>1 cm thick) by Mackee & Weir, 1953.
 - separated by bedding planes or bounding planes.
 - marked discontinuities within beds are called Amalgamation surfaces.
- (2) Bedding planes or Bounding planes: are planes of non deposition; an abrupt change in depositional conditions; or an erosion surface.2 set beds or strata may be separated by a "shaly parting."

Note: some planes are post depositional-- created by burrowing organism, diagenesis or weathering.

Otto(1938) regarded beds as sedimentation units; i.e.the thickness of sediment deposited under essentially constant physical conditions.

- (3) Laminae: layers thinner than 1cm according to Mckee and Weir, 1953. Thickness of a particular bed depends on the rate of sedimentation; thicker beds may form rapidly e.g. in floods or stormy environments; or slowly e.g.in deep marine basins 1.2mm / 1 000 yrs.

TERMINOLOGY.

- Stratification, lamination, bedding are abstract terms.
 - strata, bed, lamina are terms for specific, concrete features.
- (1) Layers: term used loosely for any bed or stratum of rock (Blatt et al.,1980) suggested term to be used for parts of a bed thicker than laminae and separated by minor but distinct discontinuities in texture or composition.
 - (2) Bands and lenses are subdivisions based on colour composition, texture or cementation. Lens also used less formally for any body of rock that is thick in the middle and thin at the edges.
 - The gross geometry of a bed depends upon the relationship between bedding plane surfaces, a relationship that may be either parallel or non parallel.
 - Internal layers and laminae that are essentially parallel to the bedding planes constitute laminated bedding or planar stratification.

- (3) Planar Stratified: beds possessing internal layers parallel to bounding surfaces.
- (4) Bedset: is a group of similar beds or cross beds.

COSET

- (a) Simple bed set: possess similar compositions, textures and internal structures.
- (b) Composite bed set: groups of beds differing in composition, textures and internal structures but associated genetically. Representing a common type of deposited sequence.
- (8) Cross Stratified beds: internal layers are at angle to bounding surfaces.

ORIGIN OF BEDDING AND LAMINATION.

Bedding:-beds produced essentially under constant physical, chemical or biological conditions.

Beds- rapidly produced by a single event e.g. flood only a few hours or day.

- slowly by a single episode of deposition of fine sediment from suspension.
- preservation of beds is high for beds deposited by a depositional event of great magnitude e.g. a very large flood.

LAMINATION.

Laminae = are produced by less severe or shorter lived, fluctuations in sedimentation conditions than the fluctuation that generate beds.

Result from changing depositional conditions that cause variations in

- a. Grain size- alternating layers of fine and coarser grained sediment (boundaries either sharp or gradational).
- b. Content of clay and organic material.
- c. Mineral composition(e.g. alternating Mica enriched and Mica-poor laminae); heavy mineral laminae and light mineral laminae)
- d. Microfossil content of sediment.
- e. Colour changes accentuates laminae and results from variations in the content or oxidation state of iron e.g. reduced iron yields green colours, oxidized iron gives red or brown colours.

LATERAL PERSISTENCE

Some strata may be very persistent laterally: may extend for many Kms indicating that the environment of deposition extended over a wide region on the surface of the earth.

Impersistent e.g.lenticular bed.

Beds terminate laterally by:

1. convergence and merging of upper and lower boundary surfaces(pinchout).
2. lateral gradation of a bed of one composition into another bed of different composition so that the boundary bed surfaces die out or
3. meeting a cross-cutting feature such as a channel fault or unconformity.

STRATIGRAPHIC CONTACTS.

Thick sequences of strata do not provide a complete record of geologic time, but contain contacts (breaks) which are plain or irregular surfaces between different types of rocks.

These breaks are periods of geologic time for which no strata are present (e.g. bedding planes-short time span; or profound breaks in the record).

- For example in Zambia, in the mid Zambezi Valley.

This break represents about 900m.yrs of Earth's History.

- such a major break is termed as an unconformity.

Unconformity is a surface of erosion or non deposition, separating younger strata from older rocks, that represents a significant hiatus.

Unconformities indicate:

- a) a lack of continuity in deposition and correspond to periods of non deposition.
- b) weathering, or erosion, either subaerial or subaqueous, prior to deposition of younger beds.

So vertically superposed strata are said to be either **UNCONFORMABLE OR CONFORMABLE**.

Disconformity is the surface that separates younger strata from older rocks, but along which there is no physical evidence of non deposition.

- A Hiatus is the total interval of geologic time represented by missing strata at a specific position along a stratigraphic surface.
- Contacts between lateral adjacent lithosomes (equivalent age) developed different lithologies owing to different conditions in the depositional environment and can be **GRADATIONAL** (i.e. where one rock type grades gradually into another) or they may be intertonguing.

CONTACTS BETWEEN CONFORMABLE STRATA.

These may be either abrupt or gradational.

Abrupt contacts: occur as a result of sudden distinct changes in lithology.

- Coincide with primary depositional bedding planes that formed as a result of changes in local depositional conditions (minor breaks).
- Such minor depositional breaks, involving only short hiatuses in sedimentation with little or no erosion before deposition is resumed are called **Diastems**.

Abrupt contacts may be caused also by:

- a) post depositional chemical alteration of beds producing changes in colour owing to oxidation or reduction of iron-bearing minerals.
- b) changes in grain size owing to recrystallisation or dolomitization.
- c) changes in resistance to weathering owing to cementation by silica or carbonate minerals.

Conformable contacts are said to be Gradational if the changes from one lithology to another is gradual, reflecting gradual change in depositional conditions with time.

Two types:-

1. **Progressive Gradual Contacts:** occurs when one lithology grades into another by progressive, more or less uniform changes in grain size, mineral composition e.t.c. e.g. a sandstone that progressively becomes finer upward into mudstones.
2. **Intercalated Contacts:** occurs when there is an increasing number of interbeds of another lithology that appear upward in the section.

CONTACTS BETWEEN UNCONFORMABLE STRATA

The surfaces that separate unconformable strata are called unconformities. Four main types are: 1. angular unconformity 2. disconformity 3. paraconformity 4. nonconformity.

They are recognised on the basis of:-

1. the presence or absence of an angular relationship between the unconformable strata.
 2. the presence or absence of a marked erosional surface separating these strata.
 3. the nature of the rocks underlying the surface of unconformity.
- 1, 2 & 3 unconformities occur between bodies of sedimentary rocks;
4 occurs between sedimentary rocks and metamorphic or igneous rocks.
1. **Angular unconformity:** unconformity in which younger sediments rest upon the eroded surface of tilted or folded older rocks; that is the older rock dip at a different, commonly steeper, angle than do the younger rocks.
 2. **Disconformity:** unconformity in which the bedding planes above and below the unconformable surface are essentially parallel and the contact between younger and older beds is marked by a visible, irregular, or even erosional surface.
 - recognised by the erosional surface with relief up to tens of meters.
 - may be marked by fossil soil zones or
 - may include (ag-gravel deposits lying immediately above the unconformable surface and containing pebbles of the same lithology as the underlying unit.
 - formed as a result of a significant period of erosion during which older rocks remained eventually horizontal during nearly vertical uplift and subsequent downwarping.
 3. **Paraconformity:** is an obscure unconformity in which the beds above and below the unconformity contact are parallel and in which no erosional surface or other physical evidence of unconformity is discernable.
 - the unconformity is simply a bedding plane.
 - recognised on the basis of a missing strata as determined from paleontologic evidence (fossils) such as absence of faunal zones or abrupt faunal changes.
 4. **Nonconformity:** unconformity developed between sedimentary rocks and older igneous or massive metamorphic rock that has been exposed to erosion prior to being covered by sediments. Generally represents a prolonged period of time:
 - i. metamorphic rock; intrusive of plutonic rocks
 - ii. cooling
 - iii. uplift and erosion -100's or 1 000's of meters of overlying rock removed to expose these deep seated rocks at the surface.
 - iv. deposition of overlying strata e.g. the Zambian example-900 my unconformity. Again difficult to judge how much time is missing without the help of fossils.

In Summary

Unconformities:

- represent major gaps in the stratigraphic record.
- represent major changes in depositional environmental history of the rocks.
- represent incomplete record of past sedimentation.
- represent a geologic event i.e. an episode of uplift and erosion or less likely, an extended period of nondeposition.

CONTACTS BETWEEN LATERALLY ADJACENT LITHOSOMES

- Preceding discussion showed us stratigraphic contacts or boundaries that separate sedimentary units into distinct vertical lithological sequences.
- Lateral changes do exist as well, and may be accompanied by:-
 - i. Progressive thinning of units to extinction - Pinchouts.
 - ii. Lateral splitting of lithological unit into many thin units that pinch out independently- Intertonguing or
 - iii. Progressive lateral Gradation, similar to progressive vertical gradation.

VERTICAL SUCCESSIONS OF STRATA.

Different types of beds can succeed each other vertically in a great variety of ways, and distinctions can be drawn between rock units characterised by:

1. lithologic uniformity
2. lithologic heterogeneity
3. cyclic successions (Weller,1960)

CYCLIC SEDIMENTATION, OR RHYTHMIC SEDIMENTATION

Repetitions of strata that reflect a sequence of related depositional processes and conditions that occurred in the same order. e.g.

1. varies- short- term events due to seasonal climate changes.
2. cyclotherms or large-scale sediment cycle caused by long-period, cyclic migration of depositional environments. e.g. global changes in sea level.

LATERAL SUCCESSIONS OF STRATA

SEDIMENTARY FACIES

Term facies introduced by Nicolas Steno (1669)

- modern usage credited to Amans Gressly (1838)

Facies (Moore, 1949 p.32) - any areally restricted part of a designated stratigraphic unit which exhibits characters significantly different from those of other parts of the unit.

- facies comprise "one or any two or more different sorts of deposits which are partially or wholly equivalent in age and which occur side by side or in somewhat close neighbourhood.
- according to Moore's definition, facies are restricted in areal extent but the same facies could be found at different levels within the same stratigraphic unit.
- many European Geologists/Gressly consider facies simply as stratigraphic units distinguished by lithologic structural, and organic aspects detectable in the field.

- it is now common practice to designate facies identified on the basis of lithologic characteristics as Lithofacies and facies distinguished by palaeontologic characteristics (fossil content) without regard to lithologic character as Biofacies.
- important objectives of facies is to make environmental interpretation and hence terms such as "continental facies", "fluvial facies" etc.

COMBINED VERTICAL AND LATERAL STRATIGRAPHIC RELATIONSHIPS

WALTER'S LAW or LAW OF THE CORRELATION (or succession of facies)

- most important concept in stratigraphy states that a direct environmental relationship exists between lateral facies and vertically stacked or superimposed successions of strata.
- stated by Johannes Walther in 1894.
- interpreted to mean that facies that occur in conformable vertical successions of strata also occurred in laterally adjacent environments.
- the entire lateral sequence of deposits in contiguous environments may not be preserved but those deposits that are preserved in the vertical sequence originally occurred side by side.

Transgressions and Regressions

Transgressions: refers to movement of a shoreline in a land ward direction, also called Retrogradation.

- transgression of shoreline produces vertical sequences of sedimentary units in which deeper water, fine grained sediments are superimposed on coarser grained near shore sediments, creating fine upwards transgressions of strata.
- it occurs during a relative rise in sea level when the influx of terrigenous sediments from land sources is low enough to allow deeper water marine sediments to encroach landward over nearshore deposits, a process called Coastal Encroachment.

Regression: seaward movement of a shoreline, also called Progradation.

- also leads to vertical superimposition of contiguous lateral facies, where coarse grained near shore sediments become progressively stacked on top of finer grained, deeper water sediments, leading to coarsening upward successions.
- it occurs during:
 - i. a relative rise in sea level or
 - ii. a relative fall in sea level or
 - iii. static sea level if the influx of terrigenous clastic is high.

A Wedge of sediments is produced when transgression is followed by regression in which deeper water sediments are deposited on top of shallower water sediments in the basal part of the wedge, and shallower water sediments are deposited on top of the deeper water sediments in the top part of the wedge.

Mid Term Test

Coastal Toplap: is a type of deposition that occurs during a relative stand still of the sea, when relative sea level is neither rising nor falling and terrigenous influx is sufficiently high.

EFFECTS OF CLIMATE ON COASTAL SEDIMENTATION PATTERNS.

- sedimentation patterns in coastal areas and the continental shelf are controlled by rate of influx of terrigenous clastic sediments and relative change in sea level.
- terrigenous influx influenced by tectonism and climatic conditions.
- tectonism produces changes in elevation of sediment source areas and affecting rates of erosion; generally erosion increases with increase in land elevation.
- climate regulates sediment influx by controlling rates of weathering and erosion, sediment transport conditions, and sediment mechanism e.g. high sediment input in rainy climate conditions.

EFFECTS OF SEA LEVEL CHANGES IN SEDIMENTATION PATTERNS.

Two kinds of sea-level changes:

1. Relative sea level changes-result from tectonics uplift or downwarping of land masses.
 - local effect
2. Eustatic sea level changes- are Worldwide changes that affect sea level on all continents essentially simultaneously.
 - causes include a.continental glaciation; sea water locked on land as ice, but melt and rises during interglacial stages.b.increase in volume of ocean water owing to generation of juvenile water (water derived from magmas) at mid-ocean ridge and consequent rise in sea level.

Application of the Facies Concept.

Vertical sequences of beds in an outcrop section or well boring located along the edge of a basin is a good example where Walter's law can be applied and prediction of the lateral succession of facies can be made.

- important in the petroleum reservoir is important.

NOMENCLATURE AND CLASSIFICATION OF LITHOSTRATIGRAPHIC UNITS

- the formal system for defining, classifying, and naming geologic units is necessary for systematic study of the physical properties and sequence relationships of sedimentary strata -is an essential requirement for interpretation of depositional environments and other aspects of the Earth History.
- the evolution to organise and classify strata resulted in formation of the internationally used Geologic Time Scale and the Geologic, or stratigraphic, column.

STRATIGRAPHY

A. INTRODUCTION

Stratigraphy is the study of the distribution of layered rocks in space and in time. It records the occurrence and distribution of strata in terms of the four dimensions of geographic extent, thickness and age. It involves the drawing of boundaries -- actual boundaries between rocks of different physical character, or interpreted boundaries such as those separating rocks of different age. It provides the "framework" within which information on layered rocks can be arranged for study, interpretation and communication.

Fundamental to establishing a stratigraphic "framework" are techniques of correlation, which attempt to show that rocks in one area are equivalent to rocks elsewhere.

- Rocks in different locations can be correlated if they can be shown to be the same age -- time correlation based on evidence of absolute age or relative age.
- Equivalence can also be shown if rocks in different locations have the same or similar physical properties, and there is also evidence that they belong to the same original body of rock -- physical correlation that may be or may not represent equivalence in age as well.

1. Main fields

A great variety of physical, chemical and biological information is contained in layered rocks and contributes in different ways to stratigraphic analysis:

- a. Diverse physical information on rock composition, textures and structures is basic to **Lithostratigraphy**. Correlations are made and boundaries are drawn that separate strata which differ in these physical properties. The boundaries define "packages" of strata, or units (e.g. "formations"), that can be represented, for example, on geologic maps.
- b. Other physical properties that require measurement by geophysical instruments can be used similarly. Magnetic properties of rocks (or certain minerals contained in them) can be recorded and used to define stratigraphic units in the field of Magnetic stratigraphy. Seismic properties are widely used in subsurface studies: boundaries between different rock layers reflect shock waves (natural and artificial) and the field of Seismic stratigraphy makes use of this property to determine the depths to boundaries, and the thickness and horizontal extent of subsurface units.
- c. Fossils contained in sedimentary rocks are the basic tools in **Biostratigraphy**:
 - Because of the evolution of animals and plants through geological time, different fossils are found in rocks of different ages. The distinctive fossils can be used to divide stratified rocks into units known as "biozones". The fossil zones, assembled in correct order, form a time scale.
 - The fossil content of sedimentary rocks can also change because depositional environments change and different organisms are adapted to different environments. The different fossils that occur in rocks deposited at the same time in different environments can be used to define "biofacies" or "ecostratigraphic" units in much the same ways as textures and sedimentary structures are used to define units that reflect particular sedimentary environments.

- Various techniques for determining the age of rock strata are part of the field of **Chronostratigraphy**:
 - Fossils and fossil zones are the oldest and most widely used tools, and provide an indication of relative age.
 - Absolute age can be determined with a number of different radiometric techniques. Radiogenic nuclides in certain minerals undergo spontaneous decay at fixed rates through time, and the age of formation of the mineral can be calculated using knowledge of the proportions of parent material and decay products and decay rate.
 - The record of a distinctive event in the sedimentary record (e.g. the widespread accumulation of a layer of volcanic ash in lake and ocean sediments after a volcanic eruption) can also be an important indicator of position in a relative time scale, and can be particularly useful in correlation.
 - The record of changes in Earth's magnetic field through times (preserved in magnetic minerals,) provides a third geochronological (relative) time scale, independent of biostratigraphic, radiometric.

2. Representation

Stratigraphic information can be organised and displayed in various ways:

- stratigraphic and geophysical logs, that use a single spatial dimension (thickness) to illustrate vertical succession of rock strata. Various symbols are used to represent lithology, grain size, sedimentary structures, geophysical properties, etc.
- cross sections, that place two or more logs in a two-dimensional spatial framework, showing thickness and one horizontal (geographic) dimension of stratigraphic units - - show how logs correlate.
- maps, that are also two- dimensional representations, and show the horizontal distribution (geographic extent) of stratigraphic units. Geological maps also represent correlation. Various interpretive maps are also possible, for example representing aspects of paleogeography.
- block diagrams, fence diagrams and other techniques that show spatial distribution of rock strata in a three-dimensional framework.

Usually all of these representations also involve some portrayal of age and age relationships of the strata, the fourth dimension.

The synthesis of stratigraphic, sedimentologic, paleontologic, and tectonics information for an entire depositional system is a study that is commonly called Basin analysis.

- Basin analysis makes use of physical, paleontological, and geochemical properties of the rocks to determine depositional environments and ages.
- These are integrated in a basin-wide stratigraphic framework, constructed using available surface and/or subsurface information, and showing the geometry of rock units, their geographic distributions, changes with stratigraphic level, and the positioning of related tectonics events.
- The ultimate objective is an interpretation of the history of the depositional basin:
- when, where, in what environments all the strata were deposited,
- when and where changes occurred in terms of the distribution of depositional environments,

- how these changes were related to the dynamics of the basin (e.g. crustal uplift or subsidence, sea level changes, etc.),
- what post-depositional changes occurred that, for example, modified original properties of the strata.

3. Stratigraphic Codes

Because of the variety of methods used to define stratigraphic units, and because the studies initially progressed independently in different countries, a large and complex system of stratigraphic names has evolved. By international agreement there are now "Codes of Stratigraphic Nomenclature" (see Boggs, 1987, p. 727-761) that are formal attempts to encourage consistent international definition and use of stratigraphic terms, and to help to reduce the larger number of redundant terms. These are necessary if stratigraphic information is to be conveyed clearly and unambiguously from one person to another or one continent to another.

Three basic and long-standing systems are widely used in stratigraphic work:

- a) lithostratigraphic (rock-stratigraphic) units form a hierarchy of terms referring to units defined solely on the basis of lithic properties and stratigraphic position. The most fundamental of these terms is the formation, which is the type of unit most commonly represented on geologic maps.
- b) biostratigraphic units are bodies of rock defined by fossil content. the most fundamental units are the biozone, which is defined by the vertical or time distribution of fossils and is the basic "building block" in relative time scales in chronostratigraphy, and the biofacies, which is defined by the geographic/paleoenvironmental distribution of fossils.
- c) chronostratigraphic (time-stratigraphic) units form a third major hierarchy of stratigraphic terms, used to refer to units defined on age. It has proven useful to distinguish intervals of geologic time from the rock units that were deposited during those time intervals. This resulted in the parallel hierarchies of time units (Palaeozoic Era, Ordovician Period, etc.) and of time-rock units (Palaeozoic Erathem, Ordovician System, etc.)
- d) Other types of stratigraphic units are variations of these, developed for particular applications, or are based on more recently developed techniques such as the use of magnetic polarity of rocks in Magnetic stratigraphy. These are summarised in the copy of the Stratigraphic Code in Boggs (1987, p. 739).

B. LITHOSTRATIGRAPHY [Boggs, 1987, Chapter 14 -- p. 523 - 558]

1. Units

The fundamental and most widely used type of formally named unit is the formation, which is a "package" of strata that is lithologically distinctive and has mappable extent. Geologic maps commonly show the distribution of formations as the units most conveniently represented at the particular scale of mapping.

Formations can be divided into smaller formally-named units called members, and members in turn subdivided formally into the smallest units of stratification called beds (more commonly informal units).

Related formations can be included in larger formally-named units called groups.

Lithostratigraphic terms commonly evolve, and what is defined as a formation during reconnaissance mapping in an area, may later become a group, as remapping on a more detailed scale allows map definition of smaller units. [For example, the "Ottawa Limestone",

originally mapped as a formation in the Ottawa valley, was subsequently elevated to "Ottawa Limestone Group", with several named formations within it.]

Lithostratigraphic terms also evolve when there is broader geographic consideration of formations that were named independently in different areas. The names that were defined and used earlier usually are given priority, and unnecessary later names discarded. [For example, after recent remapping in eastern Ontario, the O.G.S (Williams and Telford, 1986) proposed that several formations assigned to the Ottawa Limestone Group in the Ottawa Valley by Wilson (1946) be replaced by formation names that have priority because they were defined earlier and are used outside the Ottawa Valley for essentially the same rock sequence.]

2. Facies

The concept of sedimentary facies is one that is very widely used in studies of sedimentary rocks. Although the term facies has been used to somewhat different senses by different people (see Boggs, 1987, p. 530 - 532), it is commonly used to refer to a sediment or a rock, that shows a limited range of primary sedimentary characters (such as lithology, textures, structures, fossil content) that are significantly different from those of adjacent or overlying or underlying facies. The primary characters are a result of deposition under a limited range of sedimentary environments. A particular facies might occur once or several times at the same stratigraphic level, and might be repeated more than once within the thickness of a formation.

For example, the sediments that are deposited in a sea over a period of hundreds of thousands of years might include a sand facies, representing deposition in beach/shoreface environments. At any one time, the beach sands might be discontinuously deposited along the shoreline and accumulate as discrete bodies of sand. Through time their occurrence might also be discontinuous, as water levels in the sea fluctuated. Nevertheless, each of the discontinuous bodies of the sand facies would be characterised by essentially the same physical properties (composition, textures, structures), and similar fossil remains, indicating that essentially the same set of environmental conditions were responsible for producing them. They would have physical and biological characteristics very different from those of an offshore mud facies deposited in deeper water and over a wider area.

Facies defined on the basis of lithological characters are commonly termed lithofacies and those defined on fossil content biofacies.

3. Contacts

While lithostratigraphic units contain a major part of the information about stratified rocks, the contacts, or boundaries that define the limits of units are also of major significance. Conformable contacts are those where there was no interruption in the accumulation of sediment across the boundary (no time that is not represented by sediment). These can be either gradational or intercalated or abrupt ("sharp"), indicating either gradual change in depositional conditions or more sudden change.

Unconformable contracts are abrupt contacts that reflect a hiatus, or an interruption of sedimentation -- a time during which no sediment accumulated. Such breaks in deposition can be very short (commonly called diastems) or represented progressively longer periods of geologic time. They may involve not only a cessation of sedimentation but also erosion of sediment previously deposited. These larger hiatuses are commonly termed unconformities. Various names have been applied to different types of unconformity, including the following common terms:

- paraconformity -- beds above and below the hiatus are parallel and there is no physical evidence of non-deposition or erosion. Usually identified by fossil evidence, such as missing biozones.
- disconformity -- beds above and below the hiatus are parallel and are separated by an irregular erosional surface.
- angular unconformity -- younger strata rest on the eroded surface of older tilted or folded strata.
- nonconformity -- stratified sedimentary rocks rest on the eroded surface of older igneous or metamorphic rocks.

Lateral contacts between stratigraphic units can also be abrupt or gradational. Commonly the lateral change from one unit to another is achieved by intergrading or intertonguing [pinchout as a third method listed in Boggs (1987, p. 529) is a simple version of intertonguing].

4. Succession of strata

Stratigraphic units are arranged in succession -- vertical succession of units resting one upon another and lateral succession of units arranged side-by-side geographically. Although they can be described and considered separately, lateral and vertical succession are typically intimately related.

Walther's Law, or the law of facies succession, is an expression of this relationship, first stated by Johannes Walther in 1894:

- In simple terms it states that sedimentary facies that are genetically related and in conformable contact with each other in vertical succession, also occur adjacent to each other in their respective environments of deposition.
- In other words, in conformable related sediments, the vertical succession directly reflects lateral succession of facies in environments.
- The principle can be illustrated simply by considering the arrangement of facies that might accumulate in a coastal region in which relative sea/lake level changes through time (or position of shoreline changes through prograding)
- The lateral succession of facies might include continental facies (river gravels and sands) passing laterally into marginal marine facies (deltaic sands, silts) and eventually into open marine facies (silts and clays)
- With lowering of sea level, the continental facies might be expected to build out (prograde) eastwards over top of a marginal marine facies, and the marginal marine facies over marine facies, resulting eventually in vertical succession of continental over marginal marine over open marine facies.
- If, instead, sea level rose rapidly, the reverse might be expected in vertical succession.
- In either situation, the order of sedimentary facies in vertical succession would indicate directly which facies were adjacent to each at the time of deposition.
- This important fundamental stratigraphic principle is a significant predictive tool and widely applicable at large and small scales of study -- the order of facies seen in measured stratigraphic sections becomes an important clue in interpreting the original geographic arrangement of their depositional environments. It is particularly useful in studying sedimentary rocks that were deposited in environments whose modern equivalents are inaccessible or difficult to study (such as deep-sea environments).

Depositional environments are commonly subject to orderly changes through time, for example due to climatic fluctuations or tectonic changes that combine to affect sea levels, rates of sediment supply, and crustal uplift and subsidence.

The individual or combined effects of these factors can be:

- submergence -- relative rise of sea level as the sea progressively floods an adjacent land area (shoreline moves landward -- transgression). [e.g. could be produced by rapid eustatic sea level rise resulting from the melting of continental glaciers, by crustal subsidence].
- emergence -- relative drop of sea level as the sea progressively withdraws from shallow areas adjacent to the land (shorelines move seaward -- regression). [e.g. could be produced by eustatic sea level rise resulting from withdrawal of large amounts of sea water during formation of continental glaciers, or by crustal uplift]
- stillstand -- relative sea level remains stationary

Widely used terms that imply sediment accumulation and the direction of building of sediment packages:

- aggradation -- building vertically toward or above sea level
- progradation -- building literally into deeper water
- retrogradation -- building shorewards [term little used]

With repetition of these changes at different times, many stratigraphic successions become cyclic. Repeated events can produce a cyclic succession in which part or all of a sequence of similar or identical sedimentary facies are repeated.

- The cyclicity is seldom ideal -- cycles can be interrupted or terminated prematurely by randomly occurring events, such as storm erosion or deposition. Walther's Law can only be applied within the portion of a succession that are not interrupted by erosional breaks or randomly occurring units.

5. Physical correlation

Correlation in lithostratigraphy, is demonstrating physical equivalence. This involves demonstration that the units correlated are similar or identical in their physical properties and that they originally were part of the same body of rock. There is no implication that the units correlated are exactly the same age, although they may be.

Physical correlation is easiest in areas where there is continuous exposure of rocks (for example in desert or mountain regions), and where the rocks are not complicated structurally (not folded, faulted, etc.). Discontinuous exposure and structural complexity make physical correlation more difficult and it becomes increasingly necessary to seek age indicators to confirm the equivalence.

Physical correlation is a fundamental aspect of geologic mapping: the drawing of formation boundaries on a map is in effect the result of correlating all the rocks belonging to each formation within the map area.

Physical correlation makes use of a wide variety of properties and techniques, many of which have little or no time-significance:

- a) Continuity of exposure
- b) Constancy of physical properties
 - Composition
 - Major components
 - Heavy minerals
 - Trace elements
 - Marker beds
 - Properties related to composition
 - Colour

- Weathering character
 - Textures and structures
 - grain size, fabric, bedding character and thickness, primary structures.
- c) Position in sequence
- d) Unconformities and Sequence stratigraphy
- e) Tectonics: metamorphic character and geological history of stratigraphic units
- reflect horizons can be traced laterally (correlated) to show the lateral extent and continuity of stratigraphic units in the subsurface; in combination with lithological and/or fossil information from a single well drilled, they can be used to demonstrate the extent of rocks of a particular lithology or age.

Sequence stratigraphy with its distinctive terminology (offlap, downlap, toplap, etc.) evolved through the use of seismic records.

Seismic reflectors such as bedding planes and unconformities are widely considered to be time-significant. They represent events or changes in conditions of sedimentation:

- sediment type changing, or
- sedimentation stopping, or
- sediment being removed by erosion

The event can be very brief (instantaneous in geological terms) where represented by bedding planes in an otherwise uniform lithology, or of longer duration, such as a period of erosion that produces an unconformable surface.

E. BIOSTRATIGRAPHY [Boggs, 1987, Chapter 17 -- p. 619-656]

1. Principles

The fossils contained in sedimentary rocks are the "tools" used in biostratigraphy. They are used for the following purposes:

- to arrange strata in terms of relative age (e.g. they are the basis for the division of strata in the Phanerozoic time scale)
- to correlate strata of different areas (show them to be time-equivalent)
- to identify gaps (hiatuses) in stratigraphic sequences (interruptions of sedimentation that may otherwise be unmarked or obscure)
- to demonstrate the diachronous (time-transgressive) nature of some lithostratigraphic boundaries
- as a major source of information about sedimentary environments, and through this, to interpret changes in sedimentary environments spatially and temporally.

Traditionally, biostratigraphy has involved the division of stratigraphic sequences into units that are time-significant -- temporal biostratigraphic units (zones and stages). This division is based on the fact that organisms have changed progressively (evolved) through geological time and, therefore, have left fossil remains that are characteristic of particular stratigraphic units. These fossils, occurring in a particular order (faunal succession) in stratigraphic sequences, are the basis for determining relative age.

Elements of this faunal succession were recognised and used long before the principle behind it was understood.

- the existence of faunal succession was recognised in the earth 1800-s by a surveyor and civil engineer, William Smith, who was constructing canals through fossil-bearing rocks exposed in England and Wales.
- the first temporal stratigraphic units to be formally defined were large units called stages (the work of d'Orbigny on Cretaceous rock in Europe in the 1840's) -- defined as units containing the same major assemblages of fossils.
- subsequently Albert Opper (1856) divided the Jurassic sequence in Europe into small scale units called zones, based on the geological time ranges of contained fossil species. He introduced the idea of the "index fossil" -- a particular species that characterises a zone and has its name used to name the zone.

More recently the geographic/environmental distribution of fossils has also been recognised as a significant aspect of biostratigraphy, and spatial biostratigraphic units (also called biofacies, or econstratigraphic units by others) have been established. These are based on the fact that different groups of organisms prefer and occupy different environments at any one time. This can be recognised in the geological record from the fact that different fossils have different geographic ranges and occur in different types of sedimentary rock. The fossils preserved may provide the major or only evidence of environmental change in situations where little or no change occurred in the physical conditions and sediment record (e.g. change in oxygen levels in water).

2. Biological considerations

Definition of temporal biostratigraphic units depends on changes in the fossil record through time. Such changes were recognised and used long before the reasons for the changes were understood (e.g. see reference to Wm. Smith, d'Orbigny and Opper, above).

Charles Darwin (1859) provided a key with his explanation of organic evolution -- the origin of species by natural selection.

- He observed that all species are variable in physical form and behaviour, each individual within a species being somewhat different from all others, and from its ancestors.
- He suggested that, through competition, the fittest individuals (those best adapted to the conditions around them) survived to reproduce and that the less fit did not.
- The fittest would therefore be most successful in transmitting their successful characters to their offspring.
- Through time this would result in gradual, one-directional change in the character of species population, an eventually to emergence of new species.

The genetic basis for this inheritance of characters, not known by Darwin, was later demonstrated by the Australian monk Gregor Mendel (1865).

In addition to the appearance of new species by gradual change from previous species, natural selection is thought to lead to the extinction of other species -- those unable to adapt to rapidly changing conditions, or to competition with more successful species, and unable to migrate to suitable environments elsewhere.

The fossil record, thus, shows first appearances and last appearances of species, that are then used to define boundaries of biozones. The fossil record also suggests that different species evolved at different rates -- some very rapidly, others more slowly. Species, therefore, show stratigraphic ranges that are very different in length, representing different range of absolute time. Species that evolved rapidly and have very short time ranges may allow for more detailed division of the time scale.

The appearance or disappearance of species in a particular area or a particular stratigraphic section can be attributed to environmental change and the migration of species, as well as to

evolution. If the environment in an area changes progressively through time, a number of results might be expected:

- processes of sedimentation may change, possibly resulting in changes in the sedimentary record -- different sediment types, structures, etc.
- some species originally living in the area may be able to adapt to the new conditions, and continue to live there, and to be preserved as fossils. These more broadly adapted "generalists" will be found as fossils in a wider variety of sedimentary rocks representing a range of sea floor environments.
- other species originally living in the area may be unable to adapt, and may migrate elsewhere, to occupy new areas that are suitable, or become extinct if migration is not possible. These more narrowly adapted "specialists" will tend to occur only in one or very few types of sedimentary rocks, representing a very particular type of sea floor environment.
- still other species will migrate into the area from elsewhere, finding the new conditions suitable, and contributing their fossil remains to a changed assemblage of species.
- still other species will be unaffected by environmental conditions on the sea floor, because they live as swimmers or floaters in near-surface waters. They can be widely transported by ocean currents. Their shells and skeletons, settling to the sea floor after death can accumulate worldwide in almost any sea floor sediment.

These differences in habitat and adaptability result in marked differences in how the resulting fossils can be used biostratigraphically:

- rapidly evolving, pelagic/planktonic species (e.g. of graptolites, foraminifera) are more likely to be useful in defining biozones that can be correlated widely, even world-wide.
- rapidly evolving benthic species (e.g. many trilobites) can be equally useful as biozone fossils, but on a more local scale, limited by the distances they can migrate.
- establishment of biofacies depends to a large extent on the presence of benthic species, regardless of their rates of evolution. The more narrowly specialised the species, the greater the potential for dividing stratigraphic sequences into biofacies.

3. Units

Formal units called biozones are the fundamental temporal units defined:

- they have been defined in different ways, leading to the recognition of various categories (e.g. referred to as interval zones, range zones, assemblage zones, acme zones, etc. -- summarised in Boggs, 1987, p. 624 - 627)
- the different types simply make different use of first and last appearances, abundance etc., and some authorities would argue that giving them special names is unnecessary.

In its essential form, a biozone can be defined as a succession of strata that is characterised by a number of associated species. The base of the succession is defined by the first occurrence of a single species at a type locality, and the zone can be correlated to areas beyond the type locality. The top of the zone is defined by the base of the overlying zone. The zone is named after a single species.

Biozones are assumed to be time-significant (collectively form a scale of relative time), and commonly serve as the basic "building block" in chronostratigraphy (below). Their boundaries are rarely (if ever) wholly time-constant. Nevertheless, biozones based on fossils that had the best potential for geographic dispersal should have boundaries that are minimally time-transgressive in geological terms.

4. Application

Fig. 17.11 (Boggs) shows a hypothetical example of a stratigraphic section.

- Vertical lines show the distribution of a large number of fossil species within the section.
- First and last appearances of species are used to define the boundaries of 19 biozones.

Fig. 10.16 (Mintz) Note that coincident first and last appearances usually indicate that there is a hiatus (either no deposition, or erosion) or a "condensed" portion (due to much slower sedimentation) in the section.

Fig. 17.9 (Boggs) A species may first appear (or appear last) at different times in different regions or provinces.

- A species that appears in one region may be initially prevented from migrating to a second region by some barrier, such as a temporary land barrier between two seas. If the barrier subsequently disappears and the species migrates into the second region, its first appearance there will be later in time.
- Local ranges are therefore combined to determine the total range in time of a species...

Fig. 2.7 (Fritz and Moore) A biozone based on an assemblage of species is likely to be more effective than zones based on a single species -- there is a better chance of finding some of the assemblage in different areas.

- A zonal assemblage established in one region can be correlated with an assemblage in another region if there are some shared species, even though there may be other species that do not occur in both regions.
- A composite biozone that combine the taxa of both regions provides a more complete record of the fossils that occurred in that time interval regionally, and has better potential for use in correlation regionally.
- A quantitative (statistical) method of correlating two or more sections using fossil ranges was devised by Allen Shaw (1964)

Fig. 17.14 shows two stratigraphic sections that contain the same fossils (only shared species are shown; others are not), and represent the same interval of time.

- One section is shorter because of a slower rate of sediment accumulation.
- The stratigraphic ranges of 12 shared species are shown with first and last occurrences marked by distances above the base of each section. Fig. 17.15 uses the data above to correlate the two sections -- distance above base in section A links plotted against distance above base in section B.
- A single bentonite (volcanic ash layer) can be correlated confidently as it represents an essentially instantaneous event in geological terms.
- First and last occurrences of each species are also plotted as "events" that have potential for correlation (e.g. species 7 first occurs at 62 m in section A and at 31 m in section B).
- A "best fit" line is drawn through the scatter of points.
- Co-ordinates at any point along this line provide a precise time-stratigraphic correlation for all levels in the section, even those without fossils.
- A straight, sloping line indicates continuous, uniform sedimentation.

Fig. 17.16 -- change in slope of the correlation line indicates change in the relative rate of sedimentation in the two sections.

Fig. 17.17 -- a horizontal step in a correlation line indicates a hiatus -- sedimentation stopped or erosion having occurred.

Fig. 11 (Ludvigsen et al.) -- summarises the relationship of biofacies and biozones, using trilobites from the Upper Cambrian of North America.

- Five different biofacies are recognised, most named after the trilobite genus or family that is most characteristic (e.g. loganellid biofacies in which 60% of the trilobites belong to the family Loganellidae)
- Each biofacies is characteristic of a particular rock type (e.g. grainstone vs. wackestone) that represents a particular environment or position in a range of platform to slope environments.
- Through them and species composition in each biofacies changes (evolution/extinction of species) and can be used to divide each biofacies into temporal units or biozones..
- Species that are shared between 2 or more biofacies can be used to define composite biozones and to correlate from one lithofacies to another.

F. CHRONOSTRATIGRAPHY [Boggs, 1987, Chapter 18 -- p. 657-696]

1. Units

Units are defined on age. It has proven useful to distinguish intervals of geologic time from the rock units that were deposited during those time intervals. This results in the following formal units, in descending order of scale:

TIME UNITS	TIME-ROCK UNITS
Eon (e.g. Phanerozoic Eon)	Eonothem (e.g. Phanerozoic Eonothem)
Era (e.g. Paleozoic Era)	Erathem (e.g. Paleozoic Erathem)
Period (e.g. Ordovician Period)	System (e.g. Ordovician System)
Epoch (e.g. Late Ordovician)	Series (e.g. Upper Ordovician)
Age (e.g. Ashgillian Age)	Stage (e.g. Ashgillian Stage)
Chron	Chronozone (=biozone)

Commonly used examples of purely time units that are familiar to all geologists include the "Palaeozoic Era", which is divided into a number of periods, such as the "Ordovician Period", "Silurian Period", etc. The periods in turn are subdivided into smaller time units called epochs, such as "Early Ordovician", "Middle Ordovician", and "Late Ordovician". Still smaller scale time units that are familiar mainly to specialists working in these parts of the geological record, are units called ages, such as the Ashgillian Age in the Late Ordovician. Conveniently, the scheme of time-rock units uses a parallel set of names (Palaeozoic Erathem; Ordovician System; Lower, Middle, and Upper Ordovician Series; Ashgillian stage; etc.). The boundaries of all of these chronostratigraphic units through the Phanerozoic are ultimately defined using biozones -- the fossil record still provides the most detailed time-stratigraphic information available.

It is important to realise that these parallel names are not interchangeable: the Ordovician System in the Gwembe Valley includes only the Ordovician rocks deposited in this area, and these rocks represent only part of the time included in the Ordovician Period.

PALEONTOLOGY

INTRODUCTION

An important part of geology is the application of basic principles of pure science (e.g. from chemistry and physics) to aspects of the solid Earth.

Similarly in paleontology, a knowledge of living organisms (biology) and their functional morphology, ecology, etc., is used to interpret fossil remains of animals and plants long dead. Geology also contributes important concepts, among the most important being that of geological time -- time measured in hundreds of million of years of Earth history, in contrast to the 1000's of years of record human history. More specifically, it has provided the means of measuring both absolute and relative ages of rocks and geological events.

- ages are based on a knowledge of radio-isotopes and their rates of decay. They provide the only reliable dates for rocks > 590 MY old, back to the oldest known rocks at 3500 MY. They also provide absolute ages for younger rocks, especially those lacking fossils.
- relative ages are based on a knowledge of fossils and their evolutionary successions in the last 590 MY of Earth history where fossils are abundant and well known (the Phanerozoic).
- fossils provide a means of dating that is, as yet, more precise than radiometric dating.
- ages are based on a knowledge of evolution, and the appearance and disappearance of different organisms through geologic history.
- relative dating using fossils is the basis for the formal subdivision of the geological time scale for the Phanerozoic -- a system of name that is widely used in geology. Long before radiometric dating was discovered, the last 590 MY of Earth history had been subdivided in detail using fossils, to establish the relative **TIME SCALE:**

EON	ERA	PERIOD	EPOCH	
PHANEROZOIC	CENOZOIC	Quaternary	Recent Pleistocene	
		Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	
				65 MY
	MESOZOIC	Cretaceous Jurassic Triassic		
				250 MY

	PALEOZOIC	Permian Pennsylvanian Mississippian Devonian Silurian Ordovician Cambrian		
				590 MY

PRECAMBRIAN (Proterozoic, Archean)

This is the time scale that will be referred to throughout the course rather than the absolute dates. The scale is further subdivided into smaller units using particular fossils (**Geological Time Scale**).

Fossils also occur in Precambrian rocks, but are much scarcer than in the Phanerozoic. The remains or evidence of Precambrian life can be grouped into 5 main categories:

- 1) chemofossils -- free C, fractionated isotopes of C and S, organic molecules.
- 2) microfossils -- remains of simple bacteria - like and alga - like structures -- single cells and cell filaments, and tubular and vase-shaped microfossils
- 3) megafossils -- disk-like and ribbon-like carbon films, impressions of soft-bodied organisms such as metazoans (e.g. jellyfish and worm-like forms)
- 4) trace fossils (ichnofossils) -- evidence of organism activity
- 5) stromatolites -- layered sediments trapped by mats of algae and bacteria.

Chemofossils, simple microfossils, and stromatolites are known from Precambrian rocks dating back to at least 3.5 BY [Geologic Time Scale]. Fossil evidence of soft-bodied metazoans (impressions, trace fossils) are known only from the latest Precambrian.

Major events in the evolution of life in the Precambrian include:

- origin of single-celled prokaryotes (cells without nuclei; DNA not arranged in chromosomes) such as bacteria and blue-green "algae" (cyanophytes) probably prior to 3.5 BY [the oldest dated rocks are sedimentary cherts about 3.7 BY old]
- developed of multi-celled from unicellular forms by 3.5 BY
- development of photosynthesis and production of free oxygen -- there were abundant photosynthetic blue-green algae by 2.0 BY and probably before.
- development of eukaryote cells in which the DNA is arranged in chromosomes and enclosed in a nucleus -- the oldest known are about 1.0 BY old (green algae)
- differentiation of multi-celled metazoans (oxygen consumers) from metaphytes (oxygen producers)

Major stages in the evolution of life in the Phanerozoic include:

- evolution of the ability to secrete mineral substances to form shells and exoskeletons (Precambrian/Cambrian boundary placed at the first appearance of invertebrate shelly fossils).
- evolution of aquatic vertebrates (early jawless fish) from invertebrate ancestors (by Late Cambrian)
- occupation of land environments by simple plants (by Late Silurian) and vascular plants (by Late Devonian)

- occupation of land environments by invertebrate animals (probably by Early Devonian) and amphibian vertebrates (by Early Carboniferous)
- evolution of endothermy (some dinosaurs, birds, mammals, in Mesozoic)

Paleontology also contributes a great amount of information concerning ancient environments: modern animals and plants have relationships to, and dependencies on, particular environments (ecology), and it can be assumed that ancient organisms were also closely dependent on particular environments e.g. modern organisms: modern reef-building corals occur only in tropical and subtropical, shallow, clear seas, and it is possible to define their range of environmental tolerance in terms of many parameters, such as:

- geographic distribution (equatorial belt)
- range of water temperatures and optimum of about 27°C
- range of water depths and optimum immediately below low tide
- range of water salinities and optimum in normal sea water (35ppt)
- characteristic associated animals and plants

Fossils equivalents: fossilised coral reefs occur throughout the first 500MY of Earth history. Ones in the Cretaceous and younger periods (<140MY) were built by many types of corals that are similar to modern groups of corals. Therefore, by analogy: it is likely that environments in Cretaceous times in areas where those reefs are found, were similar to those in which modern reef-building corals are found.

Taxonomic Classification and the Importance of Species.

- Organisms can be classified in a variety of ways, minding habitat (planktonic, nektonic, benthonic) and environmental distribution (lithoral, niritic, bathyal, etc.)
- Taxonomic classification based on genetic relationships is most pertinent to recognition of evolution and biostratigraphy situation.
- basic systems of taxonomic classification (now in use) was introduced by Swedish naturalist- Linnaeus 1735, who grouped organisms into a hierarchy of different categories based on the number of distinctive characteristics shared in common.
- System shows that degrees of similarities among organisms differ at different levels of classification.
- Differences among groups of organisms greatest at kingdom level and least at the species level.
- Species are fundamental entity of biostratigraphy.

PALEONTOLOGICAL (BIOLOGICAL) CLASSIFICATION

System of names (binominal) instead of numerical designatic "taxa"

Paleozoology			Paleobotany
KINGDOM	ANIMALIA		PLANTAE
PHYLUM	MOLLUSCA	CHORDATA	
CLASS	BIVALVIA	SUISPH:VERTERBRATE MAMMALIA	
ORDER	TAXODONTA	PRIMATES	
FAMILY	NUCULIDAE	HOMINIDAE	
GENUS	Nucula	Homo	
SPECIES	Americana	sapiens	

System is a device (arbitrary) for indicating closeness or distance of relationship.
Taxonomy involves the naming and classifying of plants and animals into related groups.
Species: a term applied to a group or assemblage of individuals having identical or near identical form (morphology) and measure distinctness from all other assemblages.
- Among living organisms, the definition requires that all individuals of a species be capable of interbreeding to produce fertile offspring.
- For practice most species can be recognised solely, on morphological criteria [morphology = entire range of physical characters of an organism]
System of names formidable, but essential. Names have meaning.

Principal aims of paleontology:

- 1) To build up a complete record as possible of ancient life (systematic paleontology and evolutionary studies)
- 2) To build up and refine a time scale into which all fossils can be fitted and by which all fossiliferous rocks can be dated (biostratigraphy or stratigraphic paleontology)
- 3) To contribute to the understanding of changes in ancient geography and the succession of ancient environments (paleoecology, paleoclimatology, paleogeography).

Aims 2) and 3), above, depend very much on how accurate and complete the systematic studies have been -- there are many examples of fossil dates and correlation that have later been shown to be in error because of wrongly identified fossils.

As a result there are two aspects to that paleontology course:

- an emphasis on aspects of systematic -- familiarity with fossils is essential, and the ability to recognise diagnostic characters is essential before identification can be assured. It is important to consider fossils as the remains of once-living organisms, not just curious objects.
- and introduction to the ways in which fossils can contribute to related geological studies, by dating and correlating stratigraphic successions, and by providing information about ancient depositional environments.

Several common groups of invertebrate fossils, fossil algae and trace fossils will be studied, considering the basic morphology (physical characters) of each, and some ways in which each group can be put to practical use.

Many other invertebrate groups will not be discussed, and several major fossil groups will not be considered, such as vertebrates, most plants, and microfossils.

Objectives:

- familiarity with each group
- understanding of functional morphology
- understanding of age relationships -- evolution
- appreciation of uses for dating, correlation and interpreting depositional environments of sedimentary rocks.

FOSSIL PRESERVATION

Fossils are the remains and traces of organisms preserved by natural processes in the Earth's crust. The subject of preservation can be considered in terms of the nature of the original

materials, the various processes that lead to change of these materials, and the results or products of these changes (fossils).

MATERIALS

- 1) "Soft parts" (living tissues) -- organic substances based on the main elements that form organic molecules -- carbon, hydrogen, and oxygen
- 2) "Hard parts" (strengthening and supporting materials, for example as shells or skeletons of animals):
 - organic compounds serving these functions include a variety of carbohydrate and scleroproteins such as chitin, conchiolin, cellulose etc. These are through, flexible organic compounds, commonly resembling fingernail, horn, antler, lobster shell, etc.
 - inorganic compounds (minerals):
 - CaCO_3 is most common, in the form of calcite or aragonite; used particularly by invertebrate animals and some simple "plants" (algae) (main component of bone)
 - SiO_2 is used by certain invertebrates and some simple "plants" (algae) many other minerals occur in trace amounts and shells and skeletons (e.g. magnetite occurring in snail radulae)

These original materials have very different preservation potentials:

- Least: Living tissues are readily decomposed by bacteria after the death of an organism organic hard parts are more resistant and undergo slow decomposition CaCO_3 -- aragonite is metastable and reverts spontaneously to calcite over geological time -- calcite is more stable than aragonite but both are readily dissolved by very weak acids $\text{Ca}_3(\text{PO}_4)_2$ -- more resistant and stable than CaCO_3
- Greatest: SiO_2 -- very hard, stable, chemically resistant (exc. opaline silica)

PROCESSES

Substances can be preserved in their original state or be altered in one or more of several ways, as follows:

- 1) Organic decomposition or decay In the presence of oxygen, aerobic bacteria attack organic molecules (certain bacterial are anaerobic and can do this in conditions of reduced oxygen levels).
 - very important process , because it makes these compounds available to be "recycled" by other organisms-- provides an important nutrient supply for many groups of plants and animals
 - also important because the results in major loss of information from the fossil record
- 2) Burial and compacting
Most underwater environments are areas of sediment accumulating -- potential for any organisms on the bottom to be discovered by sediment Inorganic hard parts can be buried and preserved in the original state, possibly flattened or fractured if the sediment around the item is significantly compacted (particularly significant in fine grained sediments that contain a much larger proportion of interstitial water at the time of depositing). With reduced oxygen levels, or absence of oxygen, bacterial activity is slowed or eliminated or organic materials can accumulate with little or no decay, compacting of these sediments (contained pore water squeezed out) and of organic matter.
- 3) Carbonization

Organic material that becomes buried with little or no decay is gradually altered by a process analogous to distillation (i.e. volatile components released). Over long periods of geological time, with increased temperature and pressure, the volatile hydrogen and oxygen are driven off from the organic compounds, leaving a residue of carbon remaining.

This is the typical method of preservation of fossil plant stems, leaves, roots and of soft-bodied animals such as jelly fish or worms.

4) Recrystallization

Recrystallization involves change of size, shape, orientating and structure of mineral crystals without compositional change.

For example, metastable aragonite reverts spontaneously to stable calcite over time, involving a change of crystal structure, but the composition remains CaCO_3

Sediments deposited under water are saturated with water that fills all pore spaces, and contains many different and in solution. Skeletal substances (minerals) in this ground

water medium can be recrystallized in response to the water chemistry (e.g. pH):

- small crystals may dissolve and ions reprecipitate immediately on adjacent larger crystals
- large crystals may dissolve with ions reprecipitated as smaller crystals
- the result is commonly a mosaic of interlocking crystals of more uniform size than the original crystals
- evidence of recrystallization is not usually recognisable without thin section study

5) Dissolution (leaching) and precipitation

Migrating ground water can dissolve and remove in solution original shell material, and can also precipitate new minerals in the voids produced.

a) Mineralization

- molecule-by-molecule replacement of an original mineral by a new mineral.
- e.g. slightly acidic ground water can really dissolve CaCO_3 , remove Ca^{2+} and CO_3^{2-} ions in solution, and immediately precipitate pyrite as molecule-sized voids become available.
- quartz, pyrite and iron oxides are common replacement minerals

b) "Permineralization"

- process affecting fossils that were originally porous, such as vertebrate bone and some invertebrate calcite skeletons such as corroid plates
- involves the precipitation of minerals in pore spaces to make a denser more solid structure
- infilling material may be the same as the original hard parts, or different
- the process of permineralization is commonly accompanied by recrystallization or mineralization of the original hard parts

c) Leaching

- dissolution and complete removal of soluble skeletal minerals can leave behind a void (cavity) the same shape and size as the original fossil

- the enclosing sediment that was in contact with the fossil forms a mould that reflects surface features of the original fossil
- d) Leaching and later precipitation
- moulds produced by leaching (if not closed by compacting) can be later filled by precipitation of new minerals, to produce casts or pseudomorphs of the original fossil

TYPES OF FOSSILS

- 1) Original or altered hard parts
- 2) Carbonized remains (carbon films) and impressions of organic hard parts and soft-bodied organisms
- 3) Trace fossils such as tracks, trails, burrows that represent the activities or organisms, commonly without the organisms themselves being fossilised

Reasons For Non-Preservation

- 1) lack of hard parts (in an example of a modern temperate sea floor environment with a range of gravel, sand and muddy sediments, 190 species had preservable hard parts, while 240 species lacked hard parts)
- 2) conditions are unsuitable for preservation of even hard parts (e.g. in high energy beach environments, shells are rapidly broken, abraded and eventually destroyed)
- 3) destruction by erosion, igneous activity, metamorphism, long after deposition and lithification of enclosing sediments.

TRACE FOSSILS (ICHNOFOSSILS)

Definition: sedimentary structures resulting from biological activity ("biogenic" sedimentary structures)

Living mobile organisms carry out several main trace-forming activities:

- moving on or across a substrate (locomotion or feeding)
- resting temporarily on or in a substrate
- burrowing or boring into a substrate (feeding or dwelling)

The study of trace fossils is called ichnology, and is a very important contribution to sedimentology -- the behaviour of organisms in response to substrates provides a variety of important paleoenvironmental information.

A. Organism activities and types of trace fossils

Five main activities (1-5) were recognised in early trace fossil studies as responsible for forming most trace fossils.

1. Walking (to form traces called Repichnia) - tracks or trails left by mobile benthic organisms as they moved across a substrate, using feet or other types of movement controlled by muscles.
e.g. Diplichnites -- sets of marks left by vertebrates, or arthropods (e.g. trilobites), as they walked over the sediment
2. Resting (to form traces called Cubichnia) -- marks produced by a mobile organism resting temporarily on the sediment. They are commonly shallow depressions excavated by the organism and represent efforts to hide by scavengers and suspension feeders.

- eg. *Rusophycus* -- bilobed excavations produced by the paired limbs of trilobites.
3. Surface-grazing (to form traces called *Pascichnia*) -- trails produced by mobile deposit - feeders during feeding. The marks represent surfaces from which food has been selected (e.g. grazing of algae).
eg. *Nereites* -- bilobed surface trace representing a systematic exploitation of the food resource on the sediment surface
 4. Deposit-feeding (to form feeding burrows called *Fodinichnia*) -- organisms penetrating the substrate in search of food produce simple or complex systems of burrows in exploiting food sources beneath the surface (process analogous to underground mining). The burrows in addition hide and protect the organism.
eg. *Chondrites* -- complex, downward-radiating, branching burrow system.
 5. Dwelling (to form dwelling burrows called *Domichnia*) -- organisms penetrating the substrate (hard or soft) primarily in search of permanent shelter. They commonly obtain their food from outside the burrow as suspension feeders, scavengers or predators.
eg. *Skolithos* -- single vertical burrow or boring
Arenicolites -- U - shaped vertical burrow or boring.

Several additional activities (6-9) result in more specialised and less common types of trace fossils, and were defined in more recent trace fossil work.

6. Farming (to form feeding traces called *Agrichnia*)
eg. *Paleodictyon* -- elaborate tunnel systems that possibly represent galleries excavated to grow and harvest bacteria.
7. Predation (to form feeding traces called *Praedichnia*)
eg. tooth marks on Mesozoic ammonite shells, that correspond to the tooth patterns of contemporary swimming reptiles
boring through clam shells (known to be formed by modern gastropods and octopi)
8. Escape (to form *Fugichnia*)
eg. vertical escape burrows formed by sedentary benthic animals that were suddenly buried by sediment.
9. Death throes (to form *Taphichnia*)
eg. tracks or markings representing the death throes of organisms that find themselves in toxic environments (eg. arthropods associated with surface markings in black shales -- representing pelagic animals that sank into anoxic environments).

B. Preservation

Surface traces (walking, resting, grazing)

- preserved by being rapidly covered by a thin layer of new sediment
- many are best preserved as casts on undersurfaces of overlying sediment, e.g. on the base of a sand layer deposited over a mud layer with surface traces -- the sandstone is more resistant than shale and preserves the traces as "hyporelief".
- preservation on the original substrate is referred to as "epirelief".
- Subsurface traces (burrows)
- Open burrows -- produced by forcible penetration or by removal of sediment from burrow to surface. Preservation depends on sediment properties such as firmness and cohesiveness, and on whether the organism re-enforces the burrow walls by producing a burrow lining (e.g. burrow wall made more cohesive by a mucus lining)

- Once the organism has left a burrow in unconsolidated sediment (or a burrow with no reinforced burrow lining), the burrow will typically be collapsed by compaction. The traces may either:
 - disappear if the sediment is uniform above and below the burrow, or
 - be preserved if they are at a boundary between different types of sediment
- Burrows with burrow linings or in partly consolidated sediment may remain open long enough to be:
 - filled by later sediment, or
 - filled by precipitation of mineral cement from ground water
- Back-filled burrows -- produced by sediment "mining" by the organism. sediment is either:
 - passed through the gut to accumulate as solid back fill (undigested mineral grains), or
 - as food is selected from the sediment, the remainder is pastured on burrow walls or packed into the tunnel behind the animal.
- The layers of sediment fill are referred to as "spreiten", literally material "spread" or plastered into the burrow (singular "spreite")

C. Names and significance

Most trace fossils can be produced by a variety of different organisms, e.g. simple vertical dwelling burrows can be produced by certain worms, by brachiopods, by bivalves, by arthropods, and by other organisms.

- It is commonly not possible to identify precisely the type of organism that produced a trace unless it is fossilised with the trace.
- Trace fossil genera and species are generally not time- significant because of this (except for certain forms such as distinctive traces produced by trilobites which occur only in the Palaeozoic).
- Trace fossils are given genus and species names for convenience, but these names do not correspond to real genera and species (commonly called ichnogenera and ichnospecies to distinguish them).
- The same organism may be able to produce several different traces as it conducts different activities, e.g. a single trilobite can produce:
 - walking traces (Diplichnites)
 - resting traces (Rusophycus)
 - grazing traces (Cruziana)

D. Environmental significance

Trace fossils are records of organism activity; organism activity is strongly controlled by environmental factors; therefore distinctive assemblages of trace fossils are produced in particular environments.

A distinctive distribution relative to depth, and depth - related environmental factors has been recognised. Major environmental changes with depth:

- energy levels related to waves and currents generally decrease with depth, affecting:
 - rates and continuity of sedimentation
 - particle size deposited (sediment firmness, consistency)
 - amount of food available (eg. kept in suspension or deposited?)
 - oxygenation
 - light levels decrease with depth, affecting:

- photosynthesis, therefore primary producers available for grazing
- vision, therefore predation, escape, etc.
- temperature decreases with depth below the zone of mixing due to wave action (effects on trace-forming activities less obvious)

E. Generalisations

1. Littoral and shallow subtidal environments (higher energy):
 - physical protection is important (from drying, high energy), therefore:
 - animals are mobile, using sediment as a means of protection or escape from environmental stress.
 - predominance of shallow excavations (temporary resting traces) and deep vertical burrows (permanent dwellings)
 - rates of sedimentation are more variable, therefore:
 - burrowers must cope with rapid burial or rapid exposure by erosion
 - microscopic food particles are maintained in suspension with higher energy, therefore suspension feeders predominate.
2. Deeper and calmer subtidal shelf environments (low energy)
 - food particles settle out of suspension, therefore:
 - deposit feeders are much more important
 - surface-grazing traces and feeding burrows are much more common
 - burrows are much more horizontal, following sediment layers rich in organic detritus ("mining" the layers)
 - environments are still somewhat photic, therefore:
 - hiding is still an advantage
 - vertical dwelling burrows and resting traces are present but subordinate
3. Deep sea environments
 - aphotic, therefore hiding is less of an advantage and dwelling burrows are unimportant
 - food settles out of suspension in low energy conditions, therefore exploitation of food resources is predominantly by vagile benthos, producing surfaces grazing traces, and by shallow burrowing organisms, producing elaborate horizontal feeding burrows.
 - weak circulation, therefore muds become anoxic, burrows very limited in depth, and surface grazers predominant.

Walking traces are less diagnostic of particular environments, and are found at many depths.

Ichnofacies [= assemblages of traces characteristic of particular environments] Nine recurring ichnofacies are currently recognised. They are designated by the names of diagnostic trace fossils, and characterised by assemblages of similar associated traces.

	SOFTGROUND	FIRMGROUND	HARDGROUND	WOODGROUND
Fresh water (aquatic)	<u>Scoyenia</u>			
Mixed marine/non-marine (terrestrial)	Psilonichus			

Marine	high energy	<u>Skolithos</u>	Glossifungites	Trypanites	Teredolites
	intermed	<u>Cruziana</u>			
		<u>Zoophycus</u>			
	low energy	<u>Nereites</u>			

underlined names -- 5 originally designated softground ichnofacies
others -- ichnofacies subsequently defined

Seilacher (1964, 1967) recognised that many trace fossils do not occur randomly in the sedimentary record, but strongly reflect environmental factors, chiefly those controlled by depth. Five recurring facies based on trace fossils were originally recognised in rocks of various ages:

1. Scoyenia ichnofacies is typical of non-marine aquatic environments.
2. Skolithos ichnofacies represents marine, peritidal softgrounds (found in sandstones, dolostones)
3. Cruziana ichnofacies represents shallow subtidal shelf softgrounds (found in siltstones, shales limestones)
4. Zoophycus ichnofacies represents deeper subtidal shelf softgrounds (found in shales, limestones)
5. Nereites ichnofacies represents softgrounds at bathyal (slope) depth (found in turbidites)

Four other recurring ichnofacies were subsequently defined (see Pemberton et al. 1992):

6. Pylonichus ichnofacies is developed in mixed marine and non-marine soft substrates, and consists largely of the surface tracks, trails and burrows of terrestrial invertebrates and vertebrates.
7. Glossifungites ichnofacies consists of burrows developed only in firm, semi-consolidated marine substrates.
8. Trypanites ichnofacies consist of boring in, and scrapings on the surfaces of, bully lithified marine substrates.
9. Teredolites ichnofacies consists of boring in woody substrates.

The recognition of depth control on certain ichnofacies has important implications in paleoecology. Paleoenvironments have now been worked out in many sequences of largely unfossiliferous rocks, including some Precambrian formations.

Summary: trace fossils are important for the information they can provide about ancient environments with respect to:

- relative depth
- geographic position
- energy level
- substrate characters (food sources, burrowing medium)

ABSOLUTE AGES: RADIOCHRONOLOGY

Fossils provide useful tools for determining relative ages of rocks and geologic events. Accurate method for determining absolute ages of rocks began about 1896 when Henry Becquerel (french physicist) showed that uranium has the ability to spontaneously emit rays that cause fogging of photographic plates in total darkness-radioactivity.

Basic principles of estimating absolute ages.

The age of a radio of a radiogenetic mineral is usually calculated from the measured ratio of a parent radionuclide to a daughter product in the mineral, using the known decay rate of the parent material.

The decay rate is measured in the laboratory by special counters and is commonly expressed as the half life of the radioactive isotope(i.e.the time required for one half of the parent material to decay to daughter product). Table 18.5.

Radiometric methods for calibrating the Geologic Time Scale

Radiochronologic methods have limited application to direct estimation of ages of sedimentary rocks because the minerals in these rocks are terrigenous minerals that when analysed yield the age of the parent rock, not the time of deposition of the sedimentary rock. Much of the geologic time scale has been calibrated by indirect methods of estimating ages of sedimentary rocks on the basis of their relationships to igneous or metamorphic rocks whose ages can be estimated by radiochronology. Table 18.6.

Direct Radiochronology of Sedimentary Rocks

Only materials in sedimentary rocks that can be used for direct radiochronology are organic remains (wood, calcium carbonate fossils and other such remains) that were deposited with the sediment and authigenic minerals that formed while the sediment was still on the seafloor or shortly after burial.

Methods for direct Radiochronology of Sedimentary Rocks are:

1. Carbon-14 Method- For organic materials.

Applied to materials such as wood, peat, charcoal, bone, leaves and the CaCO_3 shells of marine organism. Used extensively for estimating ages of archaeological materials. Carbon-14 decays rapidly with a half-life of only 5 730 years and therefore can only be used for materials less than about 40 000yrs old, as older material has less carbon to be determined by standard analytical methods.

Successful for estimating ages of very young sediments in cores of deep sea sediments and unravelling recent glacial History by analysis of wood in glacial deposits.

Limitation

Limitation application owing to the very short useful age range of the method- little value in calibrating the geologic time scale except for the very recent quaternary events.

2. Potassium-40/Argon-40 and Rubidium-87/Strontium-87.

Radiochronology of Glauconites.

Glauconites-a group of green clay minerals, all of which are complex potassium-Aluminium-Iron Silicates that commonly occur in sediments as small rounded grains or pellets.

Radioactive ^{40}K is incorporated into the glauconite grains as they evolve by alteration process on the sea floor.

Measurement of the $^{40}\text{K}/^{40}\text{Ar}$ ratio in the glauconite grains thus allow the age to be determined.

Half-life of potassium -40 is 1 300 million years; therefore rocks ranging from 50 000 to the age of Earth can be determined.

Limitation-loss of Argon yields 10-20% too young ages and too old ages in some cases where radiogenic Argon is already in the sediment.

3. Rubidium-Strontium method.

Radioactive rubidium (^{87}Rb) is incorporated into glauconites as they form along the potassium-40.

Rubidium-87 decays to strontium-87(^{87}Sr), with a half life of 47 000 million years.

The long half life limits Rb-Sr method to rocks older than about 5 million years.

Limitation-ages are 10-20% too young

Analytical problems and uncertainties makes this method unfavourable in contrast to Potassium-Argon method.

4. Thorium-230 and Thorium-230/Protactinium-231

Method for estimating ages of Recent sediments.

Uranium-238 decays through several intermediate daughter products including Uranium-234 to Thorium-230.

Thorium-230 is an unstable isotope and itself decays with a half-life of 75 000 years to still another unstable daughter product, Radium-226.

Sediments taken from the ocean floor exhibit a measurable decrease in ^{230}Th contact with increasing depth in the cores.

Assuming that sedimentation rates and the rates of precipitation of ^{230}Th have remained fairly constant through time the concentration of ^{230}Th should decrease exponentially with depth.

The ages of the sediment at various depths in a core can be calculated by comparing the amount of remaining ^{230}Th at any depth to the amount in the top layer of the core(surface sediment).

Method can be applied to the dating of sediments younger than about 250 000 years making the method useful for bridging the gap between maximum carbon-14 ages and minimum potassium-argon ages.

Protactinium-231, is the unstable daughter product of uranium-235 & itself decays with a half-life of about 34 000years to Actinium-227.

Protactinium-231, like Thorium-230, precipitates quickly from sea water and becomes incorporated into sediments along with Thorium-230.

Because Protactinium-231 decays about twice as rapidly as Thorium-230 the age of the sediment at any depth in the core is determined by comparing the $^{231}\text{Pa}/^{230}\text{Th}$ ratio at that depth to the ratio in the surface sediment.

Method can also be used measuring the ratio of these daughter products to their parent isotopes Uranium 238 & 235 in the skeletons of marine invertebrates such as corals.

Limitation-reliability of ages determined rests on the assumption that Protactinium-231 & Thorium-230 are produced everywhere in the ocean at constant rate and the starting ratio of the two isotopes in surface sediment is constant throughout the ocean.

Method cannot be applied to estimating ages of skeletal materials that have undergone recrystallisation (recrystallisation opens the closed system and allows escape of daughter isotopes or parent isotopes.)

SEQUENCE STRATIGRAPHY AND SYSTEMS TRACTS

Introduction

- For more than 100 yrs. earth scientists (geologists) have accumulated geologic evidence indicating fluctuations in mean sea level during Phanerozoic time.
- Some early workers (Suess, 1906) remarked on the apparently synchronous episodes of deposition of nondeposition of marine strata in different parts of the world and suggested that rises and falls of sea levels may be eustatic (global) in origin.

Why Study Sea-Level Fluctuations?

- Have important implications for organic productivity of oceans and sediment distribution patterns along the continental margins and in interior basins. Therefore is of prime interest to hydrocarbon exploration.
- Fluctuations in sea level are also thought to control hydrographic climatic patterns, and, indirectly, biotic distribution patterns as well. So important in deciphering paleoceanographic conditions.

Contribution Of Seismic Stratigraphy

- Developments in seismic strata during 1969's and 1970's led to recognition that primarily seismic reflections parallel stratal surfaces and unconformities (sec. Vail et al., 1977)
- On this basis, Vail et al. (1977) proposed that sediment package (depositional sequences) bounded by unconformities and their correlation conformities represented primary units with chronostratigraphic significance.
- Vail et al. (1977) used stratal geometries and patterns of on lap, develop, truncation, and basinward shifts of coastal on lap to interpret sea level histories a long various continental margins. The "apparent" synchronicity of sea level falls in widely separated basins led them to generate a series of charts showing global cycles of relative changes in sea level.
- (see Fig. 1 for terms and sequence stratigraphic concepts)

Problems With Use of Seismic Stratigraphic Onlap Curves of Vail et al

Note: The original coastal onlap curves were largely based on interpretations of seismic sections with paleontological age control from well data.

Main Criticisms of the Sea Level Curves are:-

1. Lack of adequate corrections for local and regional subsidence and thus the potential error in estimating the magnitude of sea level rises and falls.
2. Questions concerning timing and global synchrony of some of the major events and their significance to events in the deep sea.
3. Need for updating sea level curves in view of recent and refined of time scales.
4. Non publication of supporting evidence (much of which was considered proprietary).

Sequence Stratigraphy - Terminology

Sequence: refers to succession of sediments deposited during (Hag's definition) a complete sea level cycle (i.e., from a sea level fall to subsequent rise and ending with next fall).

Sequence Stratigraphy is broadly defined as branch of stratigraphy that deals with depositional sequences or successions of genetically related strata deposited during the different phases (low stand, transgressive, and highstand) of sea level cycles.

Note: Stratigraphic sequences and system tract as defined in sequence stratigraphy are lithostratigraphic concepts and as such interpreted in sedimentologic terms.

Sedimentologic analysis is the most appropriate way to reveal the primary controls behind a certain feature of sequence stratigraphy. This, in turn, allows one to assess the role of sea level and other factors in a building the sequence record.

The Sequence Boundary

Despite the subdivision of sequences into systems tracts and the recognition of other surfaces (max. flooding surface-unfs), the "unconformable sequence boundary" has remained the key element in sequence stratigraphy. The limited resolution of seismic profile very often does not allow one to identify the systems tracts. Generally, one can recognise sequences and sequence boundaries as unconformities and sediment packages with internally coherent bedding patterns.

Mitchum (1977) p. 531 defines sequence and sequence boundaries as:
From Mitchum (1977, p. 531 of Vail et al., 1977)

Sequence: a stratigraphic unit composed of a relatively conformable succession of genetically related strata and boundaries by unconformities on their correlative conformities.

Seq. Boundaries: observable discordance in a given stratigraphic section than shown evidence of erosion on non deposition with obvious stratal terminations, but in places they may be traced into less obvious paraconformities recognised by biostratigraphy or other methods.

Seismic unconformities: represent changes in the pattern of sediment input and dispersal in the basin.

Note: Although sea level is an important control on input and dispersal patterns, so are tectonics changes in sea-floor topography, tectonics changes in interland (drainage patterns) changes in ocean environment, are antocyclic processes in sedimentation.

- A growing number of basin studies reveal a rather complex interplay of eustasy, regional tectonics and sedimentologic process as control on depositional sequences (eg., Underhill, 1991).

Note: Van Wagoner et al. (1988) restrict the term unconformity and sequence boundary to surfaces that induce significant subaerial exposure.

This burdens term with a genetic connotation that is often difficult to verify in field and namely impossible to verify in seismics.

If also "defines away" any alternative to sea level in the interpretation of sequences and sequence boundaries.

Sequence Stratigraphy Terminology

Parasequences are the building blocks of sequences.

Parasequences are shoaling-upward bedsets bounded by marine flooding surfaces. these boundaries are used for local correlation of time and facies.

Parasequence sets are stacked parasequences; can be progradational, retrogradational, and aggradational in nature, and are recognised in well logs and well-log cross sections.

Correlations of these sets commonly result in significantly different correlations than conventional lithostratigraphic correlations. They are building blocks of sequence.

Sequences can be subdivided into systems tracts based on objective criteria including types of bounding surfaces, parasequence set distribution, and position within the sequence.

Two types are recognised in rock record:

- 1) **Type - 1 sequences** are bounded by unconformities marked by erosional truncation and a basin ward shift in facies, and their correlative conformities.
- 2) **Type- 2 sequences** are bounded by unconformities marked by a downward shift in coastal on lap in the coastal plain. But not by erosional truncation or a basin ward shift in facies, and their correlative conformities.

Sequences are interpreted to form the interaction of eustasy, subsidence and sedimentation.

Systems tracts are defined as a linkage of contemporaneous depositional systems and can also be characterised by geometry and facies associations.

Depositional systems are defined as three-dimensional assemblages of lithofacies.

Four systems tracts are recognised:

- lowstand, shelf margin, transgressive, and highstand systems tracts.
- lowstand and highstand are descriptive terms that refer to position within the sequence; when referring to systems tracts these terms do not indicate a period of time or position on a eustatic or relative cycle of sea level.

(see Table III for the various terminologies).

DEPOSITIONAL SEQUENCES

Sequence-informally used to refer to any grouping or succession of strata.

- formally used to refer to any distinctive stratigraphic units that are commonly bounded by unconformities.

Depositional sequence-extended and redefined by Mitchum, Vail and Thompson (1977) as "stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities (stratal surfaces or bedding planes)

- Generally range in thickness from tens to hundreds of meters. Sequences-distinct, related groups of depositional sequences superposed one on another.
- Sequences are not primarily dependent for recognition upon determination of rock types, fossils or depositional processes.

Criteria for Recognition of Sequences.

1. Time significance-all sequences have time -stratigraphic significance being deposited during a broad interval of time although the age range of individual strata within the sequence may differ from place to place.
 - hiatus represented by unconformities may be million to hundreds of millions of years.
 - the physical surfaces that separate groups of strata or individual beds and laminae within sequences were produced during a relatively short period of time and are essentially synchronous.
 2. Internal Relationships-strata of depositional sequence may be either concordant(i.e. parallel to the sequence boundary) or discordant(i.e. lack of parallelism with respect to the sequence boundaries).
 - concordant relations occur at both upper and lower boundary of a sequence.
 - discordant is the most important physical criterion used in determining sequence boundaries:
 - Two types recognised based on the manner in which the strata terminate against the sequence boundaries.
- i. Truncation: the lateral termination of strata owing to being cut off from their original depositional limits by erosion.
 - occurs at upper boundary of a sequence
 - can be local or regional in extent.
 - ii. Lapout-the lateral termination of strata against a boundary at their original depositional limit.
 - divided into Baselap and Toplap depending on the specific nature of the discordant relationship with the upper or lower sequence boundary.
- a. Baselap: occurs at the lower boundary of a depositional sequence; two types:-
 - Onlap- is baselap in which an initially inclined stratum terminates downdip against an initially horizontal or inclined surface.
 - Onlap and Downlap indicate nondepositional hiatuses & not erosional breaks in deposition.
 - b. Toplap-is lap out at the upper boundary of a depositional sequence e.g. the internal termination updip of the foreset beds of a deltaic complex.
 - is also evidence of non depositional hiatus
 - results from a depositional base level, being too low to permit the strata to extend further updip, thus allowing sedimentary bypassing and possibly minor erosion to occur above base level while prograding strata are deposited below base level.

IDENTIFICATION OF DEPOSITIONAL SEQUENCES

- can be identified in outcrops & subsurface sections.
- in subsurface, well logs (e.g. electric logs that measure resistivity of rock units) & seismic data to locate and trace unconformities, truncations, and lapout relationships.
- can be identified on basis of physical stratigraphic relationships but
- fossils can be used to determine geologic ages.