6 THE FOURTH DIMENSION—CHRONOLOGY

6.1 STRATIGRAPHY/HISTORICAL GEOLOGY

This chapter should be regarded as being no more than a preface to further stratigraphic study. Here we deal with the generalities of classifying rock strata and have no time to go in detail into the myriads of properties (lithology, fossil content, time of formation, geophysical properties, etc.) used in stratigraphic studies. In dealing with strata the distintive aspect of classification involves the vertical and lateral arrangement of the layers. Besides the geometrical consideration, time relations—our fourth dimension—are crucial in our attempt to understand geological histories from maps. However, not all university courses follow a logical progression (for staffing, timetable, historical, etc., reasons) and some readers may well be in a system that completes the map analysis section before any stratigraphy is given. This chapter is mainly aimed at such unfortunates, though the more stratigraphically enlightened may benefit from an alternative presentation. The latter perhaps might like to test their grasp of stratigraphic principles by following the arguments (scientific discussion) about Cambrian stratigraphy in part of the USA (*Geology*, **13** (9), 663–8, 1985). First-timers in stratigraphy might like to try the same test having read this chapter.

Even a cursory survey of the present-day earth reveals a vast array of tectonic settings: ongoing continent/continent collision along the Alpine–Himalayan chain, active subduction of oceanic lithosphere at continental margins (Central and South America), island arcs marking the zone of convergence between oceanic plates, conservative plate boundaries where the elements of the plate mosaic slide past one another (San Andreas Fault system), rifting at various stages from incipient (East African Rift Valleys) to mature (Atlantic Ocean) and many more. At our present level of understanding of earth dynamics, we are at the same time starting to see some order in the pattern of geological processes within a plate tectonic framework and beginning to appreciate the complexities of the system we are investigating. Each tectonic setting is characterized by different processes and products. Particular sedimentary, structural, metamorphic, and igneous styles typify the different regimes, but significantly it is the contemporaneous variation within each of these styles that is most diagnostic. In many island arcs, the lavas and intrusives vary in composition according to distance from the trench. Also in the same subduction zones, heat flow and hence metamorphic effects are very different in the trenches and in the volcanic arcs. Sedimentary environments within single tectonic settings show the greatest variety, but their lateral and vertical arrangements are diagnostic for each tectonic process. A rifted continental margin at any one time displays a regular progression from coastal plain through littoral environments across the shelf to slope and rise conditions.

Most tectonic settings also show characteristic evolutionary sequences. Again using continental margins as the example, the first signs of break-up are rift valleys that contain fluvial and lacustrine sediments controlled by active faulting. In addition most rift valley systems have a chemically distinctive (peralkaline) volcanic contribution to the rift infill. Minor marine incursions may flood the rift zone as pull-apart proceeds, but the major change takes place at eventual separation and generation of new oceanic crust. By this time the edge of the continent is considerably thinned and, as it moves away from the zone of sea-floor spreading, it cools and subsides. The result is a marine transgression along the entire edge of the continent cutting across the earlier rift structures and sediments which are superimposed by a kilometres-thick succession of shelf, slope and rise sediments. For one region, on a continental margin several thousands of kilometres long, the local sequence of events—a relative chronology—is established using some very basic principles that can be applied in all situations to delineate a geological history. Along the whole margin the major events in the evolutionary process occur in the same order but from the relative chronology approach we cannot say if the stages took place at the same time. In fact the generation of one continental margin involves very different timings from place to place for rift initiation, first formation of oceanic crust and marine transgresstion, thus providing vital information on the nature of the tectonic machinery.

To understand and document this tremendous tectonic diversity throughout earth history requires an ability to make time correlations. An ideal but unobtainable goal of **historical geology** would be to chart continuously through time the distribution of continents and oceans, and all their varied tectonic settings. There are sizeable problems in achieving this aim for even the last 100 Ma, and further back in time we rapidly have to learn to live with limited success. Only tiny fragments of ancient oceans are preserved and inferred plate distributions of around 250 million years (250 Ma) ago are speculative, degenerating to wild guesses for around 600 Ma ago, and in the Archaean (>2500 Ma) we are not even sure what tectonic processes were operating. In dealing with the material that survives tectonic recycling, sedimentary successions provide the most complete record of the earth's history. Other results of tectonic processes are generally more discrete in their time-span; in the birth, growth and death of an ocean there are long periods, in most parts of the system, without deformation, metamorphism or igneous activity, whereas sedimentation is much more continuous. It is, therefore, not surprising that studies of strata—**stratigraphy**—have dominated historical geology. The purists would say that stratigraphy is solely the study of the geometry and time relations of bedded sedimentary rocks and even exclude consideration of sequences of lava flows. The literal translation of stratigraphy, writing about strata, would include sedimentary petrography and sedimentation but these now have a separate identify as the discipline of sedimentology. From an outsiders' point of view it appears that common usage has just about closed the gap between stratigraphy and historical geology acknowledging the very strong bonds created by much common ground. Codes of stratigraphic nomenclature issued by many countries always include sections on non-stratified plutonic and metamorphic terrains showing a willingness to embrace the wider history-of-the-rock-record approach. The basic principles of stratigraphy expounded in **every** text include some methods that can only be applied in non-stratified rock, further illustrating the close interrelation between stratigraphy and historical geology. Most undergraduate courses labelled stratigraphy deal with earth history. Whilst accepting that historical geology and stratigraphy are not strictly synonymous to some authors, they will be used interchangeably in the following discussion. At first glance the definition of stratigraphy quoted below is restricted to layered rocks but modern interpretations make sweeping reference to grand scale layering of the crust and thus include virtually all comers in their brief.

> **Stratigraphy**—Definition. The science of rock strata. It is concerned not only with the original succession and age relations of rock strata but also with their form, distribution, lithologic composition, fossil content, geophysical and geochemical properties—indeed with all characters and attributes of rocks as strata. . . . *Glossary of Geology* . (Bates, R. L. and Jackson, J. A. 1980. Second edition. American Geological Institute.)

6.2 GEOCHRONOLOGY

The time factor is the most distinctive feature of geology and it is at the heart of our 4-D understanding of geological maps. Our analysis of geological time will follow similar lines to the historical development of the subject. At first we shall deal with methods that lead to the construction of local sequences of events and then move on to the thorny problem of establishing time equivalence. Both topics come under the umbrella of **geochronology**, the science of dating and determining the time sequence of events in earth history. There are many methods that can be used to establish the section or slice of geological time to which a particular rock or event belongs. Subdivisions of geological time were identified and labelled long before the duration of the units in years could be measured but this did not invalidate the recognition of time equivalence or sequence. The quantitative measurement of geological time, expressed in years, is **geochronometry** and unfortunately careless usage in geological circles has led to only this specific activity being referred to as geochronology. Other facets of geochronology seemingly have been swamped by a massive explosion of mass spectrometry work on isotope systems to give dates for rocks and geological events.

The basic rules of relative chronology were developed very early. The most basic is the **principle of superposition**, first published in 1669 by Steno, which states that older rocks are found beneath younger rocks (Figure 6.1a). For a tectonically undisturbed region, this may seem self-evident to us, but in an age dominated by non-scientific ideas about earth processes it was a major advance. Because of the cryptic nature of some 'disturbed' regions, we now very rarely rely only on the basic principle to determine which is the oldest and youngest part of a sequence of layers. Many small-scale sedimentary structures tell us which is geological top and bottom and give way-up or younging (Figure 6.1a). Collectively such structures are referred to as geopetal. Younging is still extremely important data in analysing the sequence of units and internal geometry, and can be key information in determining tectonic displacement directions. Presentation of younging data on maps is very varied (see Appendix 2, Symbology) but is usually related to the dip and strike symbol of layering. I suspect that there are still many areas in the external parts of orogenic belts where the layers are assumed to be right-way-up which are in fact upside-down, suggesting that insufficient attention has been paid to recording younging in the past. Palaeontological data are also used to determine the younging direction.

The **principle of inclusion** is sometimes useful in confirming the younging of a layered sequence (Figure 6.1b). If a bed includes fragments of another bed, then the unit containing the inclusions is the younger. By implication an erosive contact must exist between the two beds which may or may not represent a significant time-gap. The same principle has more general applications in establishing sequences of events. If an igneous (or sedimentary) intrusion breaks off fragments of country rock (Figure 6.1c), then again the rock with the inclusions is the younger. A third principle, that of **cross-cutting relationships**, is commonly applied to events other than sediment deposition. Its statement is that a rock body (or structure) that cuts across another rock body (or structure) is the younger of the two (Figures 6.1c, d). This approach is classically applied to igneous intrusions. Irregular masses of granite or tabular sheets (dykes) cutting layering in the country rock sediments are both younger than the host. Two dykes generate cross-cutting relationships, the second cutting the first, as do fault structures (fractures). These are very simple notions but very effective in building up the geological history of an area from a published map. Applying the above principles in the field may be another matter where you have to contend with patchy exposure, the vagaries of the weathering process, metamorphic and deformational overprints, hydrothermal alteration and lots more.

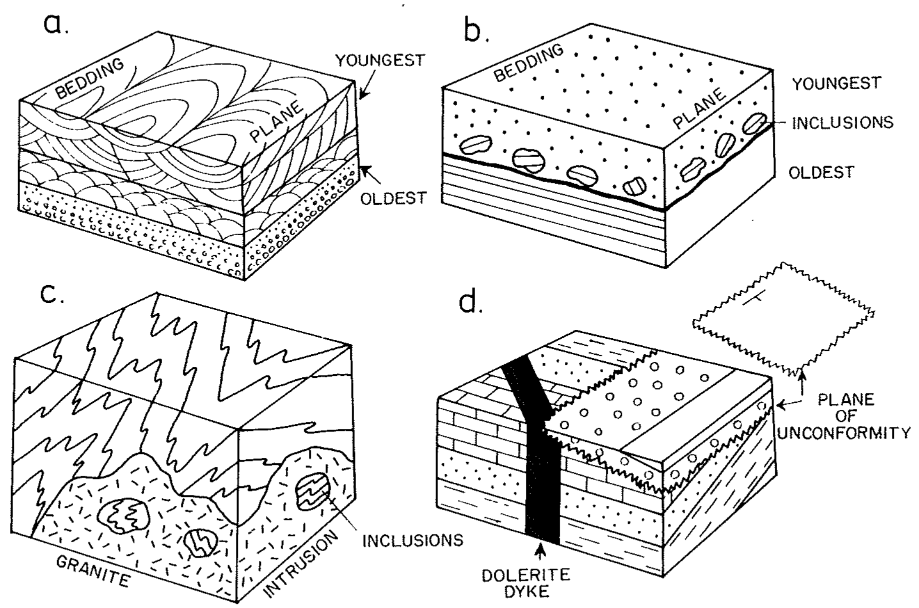

Fig. 6.1 (a) Principle of superposition for an untectonized region where older rocks lie beneath younger rocks. Because some deformation events are cryptic it is wise to check the younging direction indicated by sedimentary structures (e.g. graded bedding, truncated cross-lamination) or other features (pillow lavas). Many Geological Survey maps and besides giving dip and strike of layering give younging data (see Appendix 2). (b) Principle of inclusion—the unit containing the inclusions is the younger. (c) The principle of inclusion may also be applied to intrusive igneous bodies. (d) Principle of cross-cutting relations. The dolerite dyke is younger than the lower sedimentary succession which it truncates—both are truncated by the unconformity which is an erosional surface

Until now the discussion has centred on successions of parallel sedimentary layers deposited without major interruptions. A noticeable gap in the geological record is referred to as an **unconformity** and the clearest example is where there is a difference in attitude between the older and younger layers (Figure 6.1d). The surface of unconformity is then a cross-cutting feature establishing the order of evens. Some unconformities divide younger and older beds with parallel layering, either being marked by a zone of minor erosive activity or by a perfectly planar contact. Unconformities play such an important role in historical geology that they are the subject of a whole chapter once folding and faulting have been discussed.

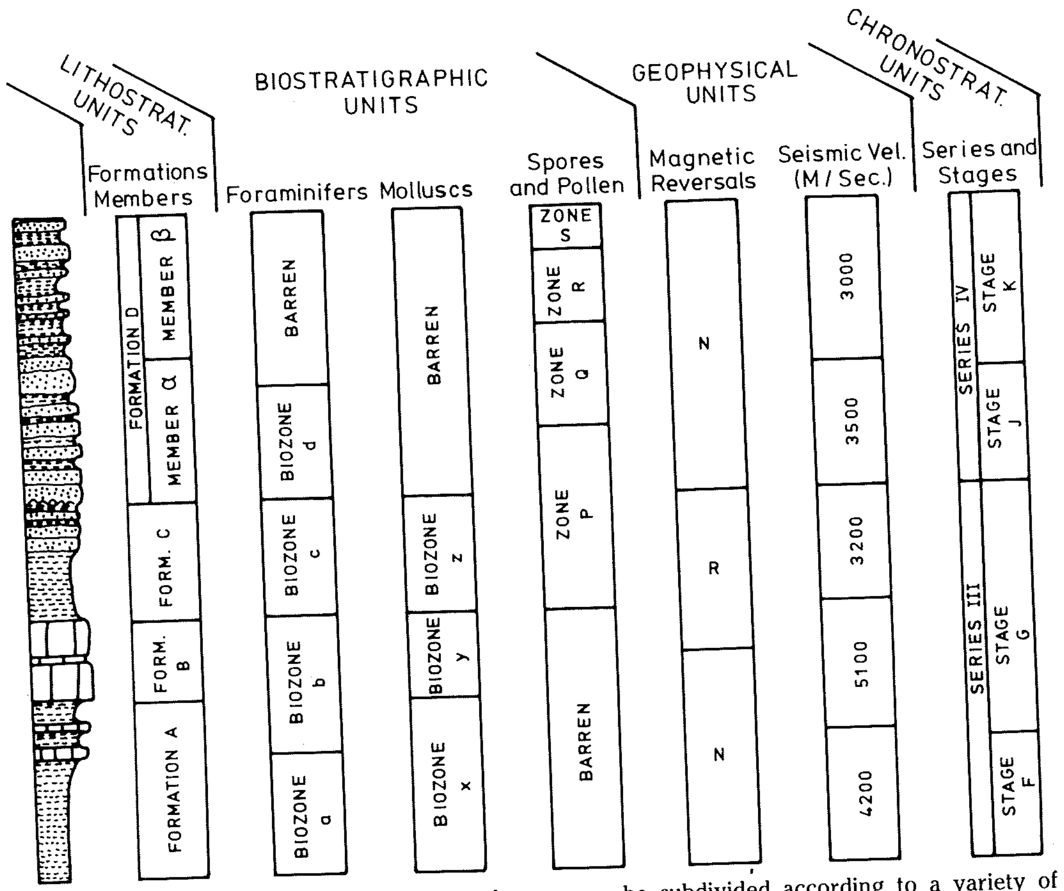

Fig. 6.2 A vertical stack of sedimentary layers may be subdivided according to a variety of characteristics. Lithostratigraphy classifies on lithology. Biostratigraphy classifies on fossil content and schemes will be different depending on the group of organism used. Geophysical units can be based on properties like seismic velocity or magnetic polarity (normal or reversed). Chronostratigraphy is a time-rock classifiation

6.3 STRATIGRAPHIC PROCEDURES

Stratigraphic procedures can readily be considered under a number of distinct headings which are dictated by the various properties of strata that are useful for classification (Figure 6.2). The major subdisciplines are based on lithology (**lithostratigraphy**), fossil content (**biostratigraphy**) and time of origin of an interval of strata (**chronostratigraphy**). Magnetic polarity, geophysical characteristics, chemical composition and mineralogy, have also been used for classification in a stratigraphic context. Of all the bases for classification, lithology is probably the most objective but not completely so as the following discussion explains.

The primary aim in geological mapping is to document the distribution of different rock types. Clearly individual beds cannot be represented on maps with scales smaller than about one to one hundred, and, even at this detailed scale, laminations in a siltstone or shale could only be schematically portrayed. It follows that virtually all maps involve a compromise in portraying the distribution of lithologies. Scale dictates the amount of compromise, and the first stage in a mapping campaign is to decide what groupings of layers are (1) distinctive enough to be recognized from place to place, and (2) can be represented at the scale of eventual publication. The results of these assessments define **formations**, the basic lithostratigraphic unit. That formations are so dependent upon scale has led to criticisms of their worth, but a reasonably objective description of the lithologies in the geological column is a fundamental first step in any stratigraphic study. Figure 6.3 is an example of the sort of choices that have to be made when first studying a region at the start of a mapping campaign. Air photographs are the medium of illustration in this case, but the same process is employed where vertical photography is unavailable or of limited use because of extensive soil and/or vegetation cover. Ten formations have been delineated (S_1 to S_{10}) as natural groupings of the strata. For example, S_9 consists of nearly 20 layers that can be identified at the scale of photography yet the overall coherence of the package of layers readily defines a formation. Formation S_7 is a thin, very well laminated unit but again is a good candidate for an easily recognizable, and thus mappable, unit. It is worth pointing out that some formations show significant variations in their expression, particularly S_3 from the north side of the fold to the south. In part, such variable units are recognized by their stratigraphic position relative to other more constant units.

Stratigraphic procedure requires that each formation be defined at a type locality as a reference point where its boundaries (top and bottom), and characteristics, are well displayed. Formation names and details are usually approved and recorded by a central committee in each country typically run by a national geological society or geological survey; the names are then regarded as being formal. Without such coordination the same name might be given to different lithologies from different places and the confusion would be unbearable. The smallest lithostratigraphic unit is a **bed** (e.g. a thin but widespread air-fall tuff layer) and, between this and a formation, a **member** may usefully be recognized under some circumstances (e.g. lenses of one lithology surrounded by another). Several formations with some connection are linked in a **group** and at the top of the hierarchy allied groups form a **supergroup** (Table 6.1). As an example of this process in operation, a tectonic element in Western Australia called the Pilbara Craton contains the Pilbara Supergroup which comprises the Warrawoona Group, the Gorge Creek Group, and the Whim Creek Group. Eighteen formations have been recognized within the Supergroup including the Duffer Formation and the Honeyeater Basalt. The example is mainly presented to show how the nomenclature is used and to indicate the style of capitalization. Lithostratigraphic unit names must contain a part derived from a geographic feature local to the type area together with a term appropriate to its rank (group, formation member, bed) (e.g. Newark Group) or a term describing the dominant rock type (e.g. Compton Schist) or both (e.g. Burlington Limestone Formation). The unit term (formation, group, etc.) of a formally defined lithostratigraphic unit should be capitalized, a practice which is extended to all parts of formal names (e.g. Spiti Shale). The above conventions are sufficient for introductory work but I would recommend readers, as soon as they can, to study, Owen, D. E. 1987; Commentary: Usage of stratigraphic terminology in papers, illustrations and talks. *Journal of Sedimentary Petrology*, **57**, 363 – 72.

6.4 STRATIGRAPHIC CORRELATION

We now move on to the more intricate conceptual aspects of traditional stratigraphy mainly centred on time-correlation. Disputation is so rife in this domain that the

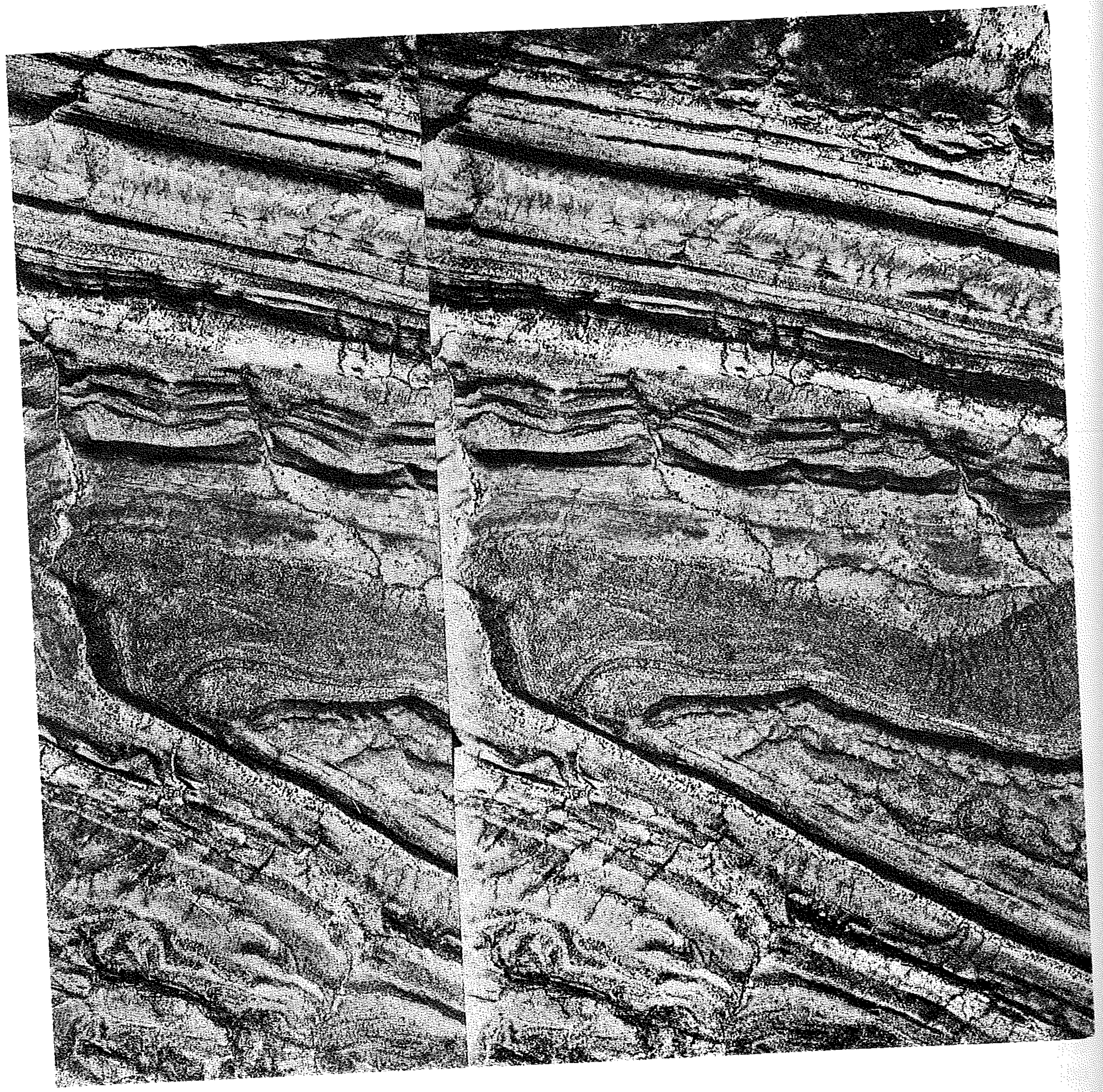

Fig. 6.3 A stereopair of vertical air photographs of a folded sedimentary sucession. The first question in mapping is 'what are the mappable units?'—the formations—the basic units of lithostratigraphy. Formations have some unifying aspect that outlines a distinct package of layers. The interpretation shows the formations that most practising geologists would adopt though, in a detailed study, smaller units might be employed. A large fold structure has caused a repetition of several of the formations and different dips on either side of the fold largely account for the variation in outcrop width (in map view)

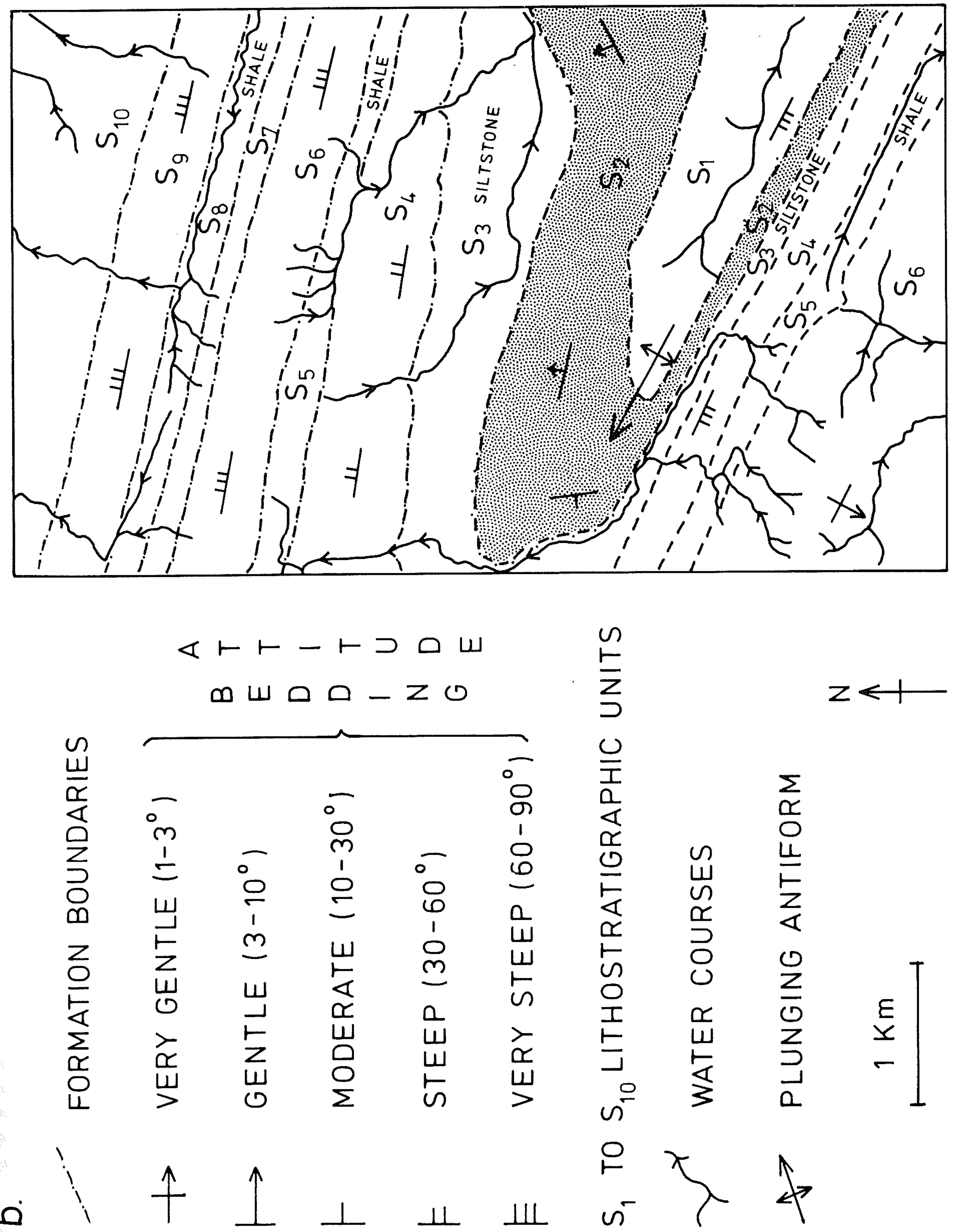

Table 6.1 Conventional hierarchy of formal lithostratigraphic terms

LITHOSTRATIGRAPHY
Supergroup — two or more groups
Group — two or more formations
Formation — primary unit of lithostratigraphy
Member — named lithological entity within a formation
Bed — named distinctive layer in a member or formation

fundamentally different concepts of biostratigraphy and chronostratigraphy are to some authors so similar they should not be distinguished separately. Much stratigraphic practice has evolved from studies of rocks formed in the last 600 Ma where the attempts to establish time equivalence have heavily relied on palaeobiological criteria (biostratigraphy). The method is totally dependent on the fact that species, genera, and groups, evolve, reach peaks, and become extinct. The trend of these patterns may be followed in single sections to determine younging and comparison of the patterns from place to place leads to palaeontological-correlation and indirectly to time-correlation. By the time reliable radiometric ages (geochronometry) became available, the latest 600 Ma of earth history had been elaborately subdivided (Figure 6.4), on the basis of the fossil content of the rocks, into **geochronologic units** (Table 6.2) of varying lengths of time (eras>periods>epochs> ages). Without radiometric techniques the actual length in years of these subdivisions could only be estimated by fairly crude methods (e.g. sedimentation rates). However, the advent of geochronometry had no influence on the palaeontologically established subdivisions of time, and even today there is much debate about the absolute age of many of the biostratigraphically defined units though the range of estimates is generally narrowing. The greatest uncertainty relates to the base of this part of the column, that is, the time of explosive evolution that marks the start of the Cambrian Period placed variously between 530 and 580 Ma ago.

The biostratigraphic method of correlation says that two sections of sedimentary rock contain equivalent fossils. To make the jump and claim that this means the same age is an assumption that can never be proved. Under favourable circumstances the assertion may be subject to little uncertainty, but the more steps and complications in the correlation process the more dubious the correlation becomes. Biostratigraphic correlation is usually based on the overlap of the ranges of several taxa (species, genera, families, etc.) forming a concurrent range-zone named after two or more diagnostic components. The pessimistic view of such a comparison highlights the problems. A new species evolving in one area may take considerable time to migrate to other regions. At the present there are many biogeographic provinces defined by latitudinal constraints and physical barriers. Taxa distribution is commonly strongly influenced by warm or cold ocean currents, rain belts or rain shadows, all of which lessen the latitudinal controls. Also within each province, many elements of the flora and fauna are restricted to particular environments. Intercontinental correlations in the ancient record normally require several steps each between somewhat isolated biotas such that at every alternate step there may be no species or genera in common across the intervening province. The uncertainties of biostratigraphic correlation, which extremists claim to be as much as a quarter of a period, validate the current chronostratigraphic approach (Table 6.2). The base of each major chronostratigraphic unit (systems) will eventually be defined by international agreement at a particular place in a selected sequence of well-exposed sedimentary rock with as continuous as possible a record of sedimentation. The definition of

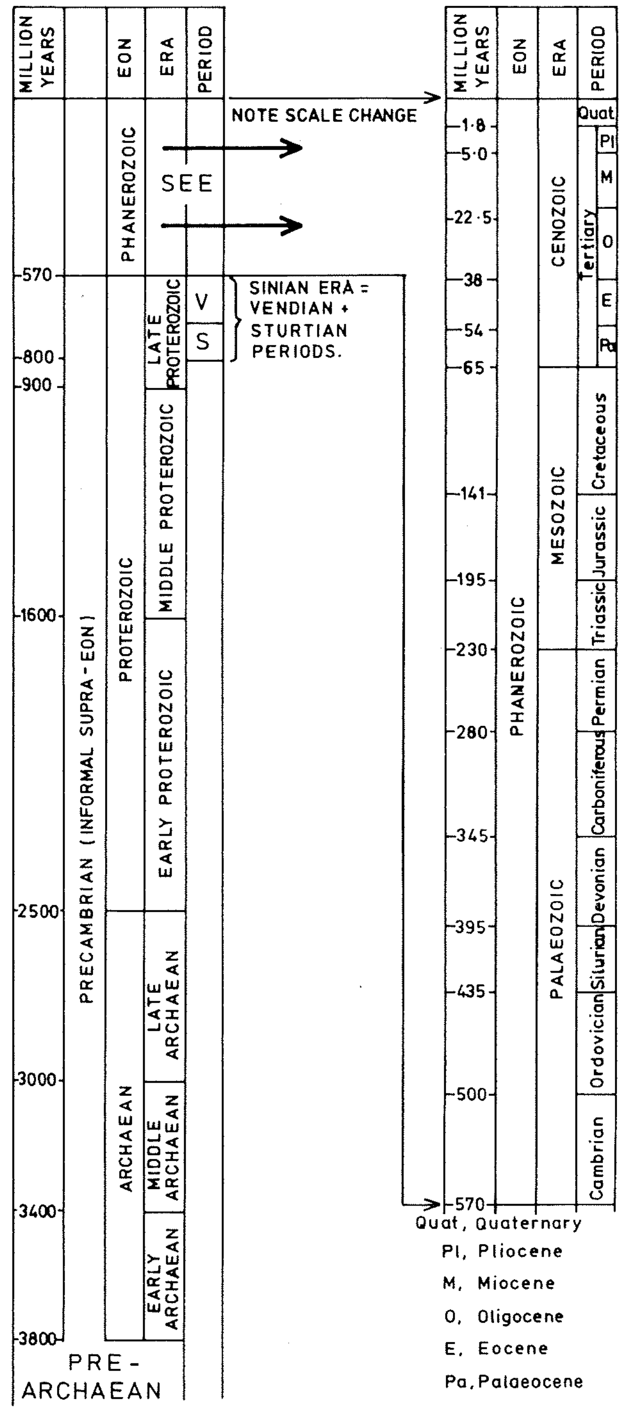

Fig. 6.4 The geological time-scale showing the major divisions. Not many geologists know all the smaller subdivisions into ages, but if you work for some time on rocks of a particular period the details should be known. The left-hand column shows earth history on a linear scale. The Phanerozoic is expanded on the right to represent all the major units in this more favoured part of the column

Table 6.2 Conventional hierarchy of chronostratigraphic and geochronological terms (Hedberg, 1976). Names in brackets are examples of each category

Chronostratigraphic (time-rock units)	Geochronologic (geological time units)
Eonothem (not often used)	Eon (Phanerozoic)
Erathem (not often used)	Era (Mesozoic)
System (Cretaceous)	Period (Cretaceous)
Series (Upper Cretaceous)	Epoch (Late Cretaceous)
Stage (Campanian)	Age (Campanian)

Remember — **Geochronometry** gives ages in years.
Note: Upper + Lower relate to rock units; Late + Early relate to time units.

Cambrian and younger systems will be on biostratigraphic grounds at specified biozones but recorded in terms of an actual sedimentary layer. The task then is, on a world-wide basis, to identify this same time horizon as closely as possible. We will never know, for example, how closely the chosen base for the Silurian in China corresponds to that in Wales. They may well be somewhat diachronous because of errors in the biostratigraphic correlation. The only known point is the defined base in the rock at Moffat in the Southern Uplands of Scotland. This then is the **time-rock** link that is crucial to chronostratigraphy.

The process has been criticized by some authors who state that chronostratigraphy is only as good as the biostratigraphy employed in its definition and they question the necessity of introducing another category of stratigraphic divisions. Chronostratigraphy is necessary because of the uncertainty in all of the methods for establishing time equivalence which generates the need for reference/anchor points around which arguments involving assertions and assumptions can rage.

Care is needed in applying stratigraphic terms and many practising stratigraphers are horrified by the lax use amongst the general geological population. The following passage demonstrates the nuances of nomenclature that have to be observed. The Cretaceous Period is a well-defined span of time in the relative time-scale (geochronologic unit). During this time rocks of the Cretaceous System were formed. Thus it would be correct to state that the Gingin Chalk (a lithostratigraphic term) belongs to the Cretaceous System but that pterodactyls flew (or glided) during the Cretaceous Period. The primary aim of the nomenclature is communication. Because there are myriads of local lithostratigraphic names each geologist will only retain a tiny subset in memory; however, any geologist will understand a colleague who says he is working on the Cambrian of an area.

In the above discussion on time-correlation very little was said about the detailed methodology of biostratigraphy which organizes strata into units based on their fossil content. A biostratigraphic unit (biozone) is a thickness of sedimentary rock characterized by one or more diagnostic fossils. Many types of biozones may be defined and there has been some discussion as to which is best for correlation. The simplest type of zone is based on the **range** of a single taxon (Figure 6.5a) both vertically in a stratigraphic sequence and horizontally (lateral extent). A concurrent-range-zone (Figures 6.5b, c) is formed by the overlap of the range-zones of two or more selected taxons. Oppel- and lineage-zones are more subjective styles of range-zone and little used in correlation. An acme-zone is a body of strata representing the maximum development of a taxon, but as this may be environmentally controlled its time significance is questionable. Of the many remaining biozones the assemblage-zone defined by a natural association of taxa is frequently discussed in

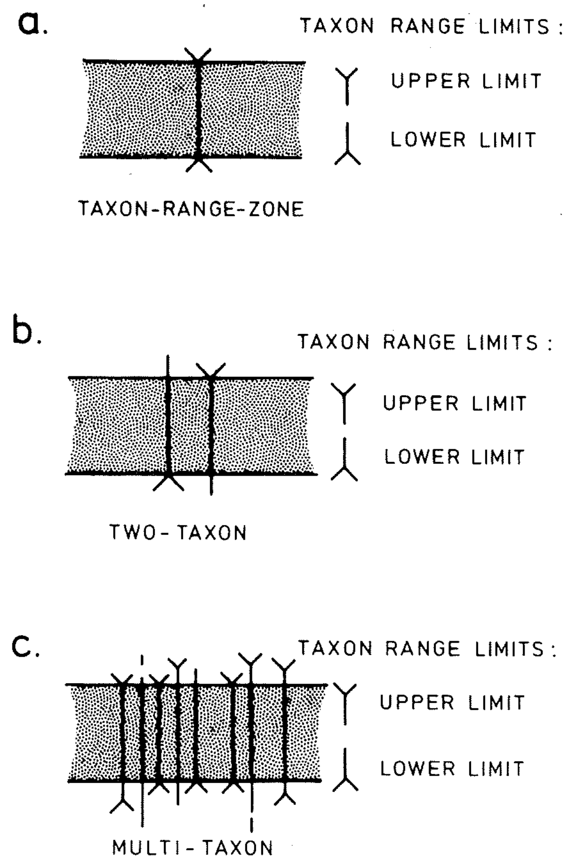

Fig. 6.5 There is a great variety in the type of biozones recognized. The simplest is based on the incoming and disappearance of one taxon. Greater definition is achieved by including more than one taxon

biostratigraphic theory, but is again more likely to reflect environment than time and is not used for correlation. Whichever zonal scheme is chosen the selected fossils need to have most of the following characteristics to be useful: (1) existence as a clearly identifiable taxon for a short time-span; (2) occurrence in several lithologies; (3) widespread distribution; (4) abundance and easy preservation.

Biostratigraphy is now being applied with some success in the latest Precambrian (approximately the last 200 Ma) in which chronostratigraphic units may be defined in the near future (Figure 6.4). Apart from this, the Russians have claimed that stromatolites are useful for much of the Proterozoic in defining fairly large biozones but this has been hotly disputed, mainly by the Canadians. The negative case is largely based on evidence for a strong environmental influence on the morphology of stromatolites such that particular forms more reflect factors like tidal range, frequency of storms, degree of protection from open sea, etc., rather than an evolutionary period. Also stromatolites are restricted to intertidal and shallow subtidal carbonates making them very limited in occurrence.

The question remains of what to do with the bulk of geological time, the 80 per cent of earth history from 800 Ma age to the creation of the earth at about 4600 Ma (Figure 6.4). Despite the overall international coordinating body recommending a chronostratigraphic solution for all of geological time, the Subcommission on Precambrian Stratigraphy has adopted subdivisions based on geochronometry and the time-rock concept does not figure in their deliberations (Plumb, K. A. and James,

H. L. 1986, Subdivision of Precambrian time: recommendations and suggestions by the Subcommission on Precambrian Stratigraphy. *Precambrian Research*, **32**, 65 – 92). This departure from the well-tried methods of the Phanerozoic has some bizarre consequences. When the Great Dyke of Zimbabwe was studied in 1977 its radiometric age of 2514 ± 16 Ma placed it in the Archaean as defined geochronometrically. However, a revision of the decay constants changed the date to 2461 ± 16 Ma and this major intrusion lurched into the Proterozoic. The oscillation of rock units from eon to eon could have been prevented if the time-rock or in-the-rock philosophy had been applied. By nominating the crystallization (cooling) age of the Great Dyke as being the Archaean/Proterozoic boundary would anchor this major divide-in-time in-the-rocks. Critics of chronometric subdivision claim that it is not based on stratigraphy but the subcommission in a spirited defence states that it is taking the broad view of stratigraphy by using the best attribute for classifying Precambrian strata and including all petrographic styles (sedimentary, igneous and metamorphic).

6.5 LITHOLOGIES THAT TRANSGRESS TIME (DIACHRONOUS)

A fundamental concept to be grasped is that lithological boundaries are rarely parallel to surfaces representing equal time horizons. Almost all formation boundaries are, therefore, diachronous. In conformable sequences where depositional slopes are low the angular differences between the two surfaces (time and lithology) are typically very small but when traced regionally they became significant. Continental shelves and abyssal plains, the most extensive depositional areas, have average slopes of 1 in 500 and 1 in 1000 respectively. The narrow continental slope has an appreciable gradient of 1 in 15 (4°) and the apron at the foot of the slope, the continental rise, has inclinations around 1 in 40. Locally more pronounced topography creates abrupt lateral changes in lithology particularly in submarine canyons and barrier reefs.

A brief consideration of almost any small region on the present-day earth will emphasize the difference between time surfaces and rock unit boundaries. Across many shorelines there is a wide range in the types of contemporaneous environments, perhaps from fluvial and aeolian through beach, lagoonal and barrier islands to offshore conditions in open seas (Figure 6.6a). The deposits formed in each of these environments are different and the term **facies** is used by many geologists to refer to the coexistence in time of many disparate lithologies. To such workers a facies boundary is a junction or transitional zone beween different rock types that were formed at the same time; to be specific this should be referred to as a **lateral facies change**. Recently the emphasis on the definition of facies has changed and qualifiers are now recommended to specify the exact meaning intended. Examples include lithofacies, biofacies, mineralogic facies, volcanic facies, marine facies, etc. Lithofacies in this usage is simply a particular lithology without the implication that it had to have formed at the same time as another unit.

To create a sheet of sand (the commonest geometry) from, for example, the barrier island depositional process (Figure 6.6a), we need a substantial period of either transgression or regression. Transgression is illustrated in Figure 6.6a where for some time either sea-level has risen (glacially or tectonically driven) or the land has fallen for tectonic reasons. Sediment supply may be an important control on which process happens as large amounts of input into a subsiding basin could bring about a regression. During a transgression the position of the beach moves towards points fixed within the hinterland and the belts of lagoons, barrier islands and offshore conditions follow suit. At any one time all of these environments coexist such that in vertical drilling at two places different distances out to sea (1 and 2, Figure 6.6a), the equivalent lithologies could not have formed at the same time. Time equivalence is oblique to the lithological contacts with the beach sands (A) at site 1 having been deposited at the same time as the barrier sands (B) at site 2.

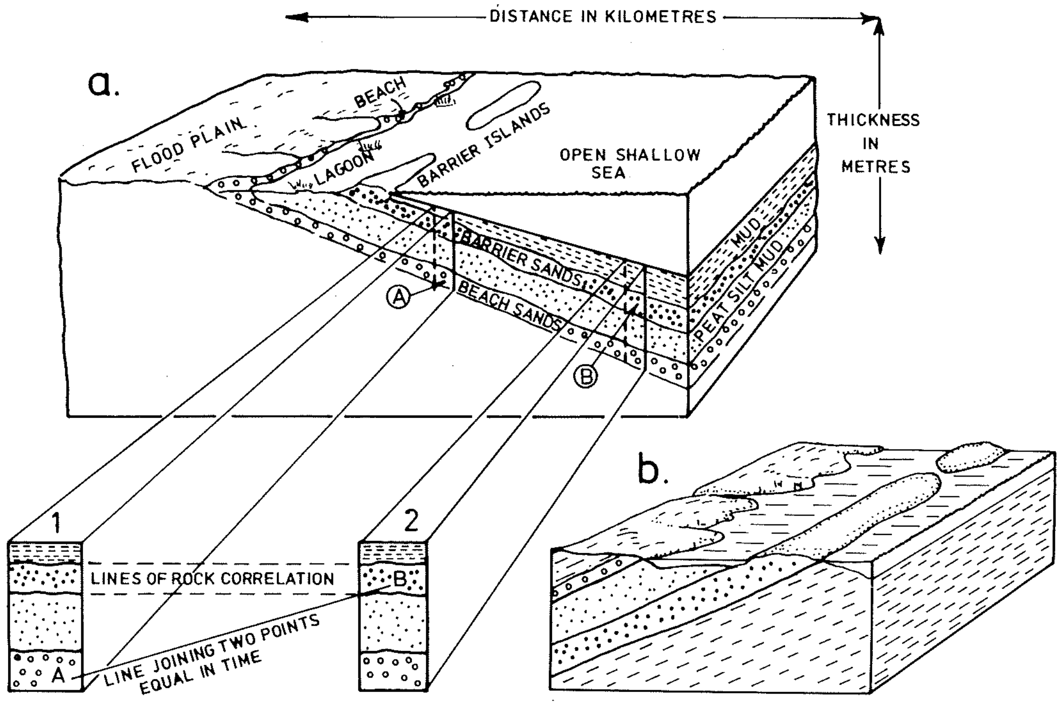

Fig. 6.6 (a) A marine transgression leaves a characteristic vertical stack of lithologies/lithofacies. At any one time the flood plain, beach, lagoon, barrier island and open-sea deposits coexist such that lithological boundaries cannot be equal time horizons. Vertical drill-holes at localities 1 and 2 will have similar sequences, but the beach rock at 1 formed at the same time as the barrier sands at 2. The vertical axis has been greatly exaggerated to make the point and angles between time planes and lithological boundaries are typically less than a degree or so. (b) Regression reverses the vertical stack of lithologies/lithofacies

Because of the normal low depositional slopes, the diagram (Figure 6.6a) has had its vertical dimension grossly exaggerated (several hundred to one) to clearly show the discordance between time surfaces and lithological/formation boundaries. From the time of deposition of the sediments, the angular discordance in fact is reduced by compaction which induces a 70 per cent vertical shortening in shales and around 25 per cent in sands. Compaction decreases the vertical thickness of the sediments without changing the horizontal dimensions of the layers and this deformation changes shapes and modifies angular relations (see Chapter 7). Any surfaces, except vertical ones, inclined to the horizontal, have their dip reduced during compaction, hence time surfaces and lithological contacts converge. Another example of a massive vertical stretch for cartographic clarity is shown in Figure 6.7. Such exaggeration is typical of lateral facies relationship diagrams yet it is invariably forgotten or not fully appreciated by observers (and ?authors). Even in regions with dramatic initial topographies such as carbonate reefs, an exaggeration of several hundred to one is needed to highlight the lateral facies variations (Figure

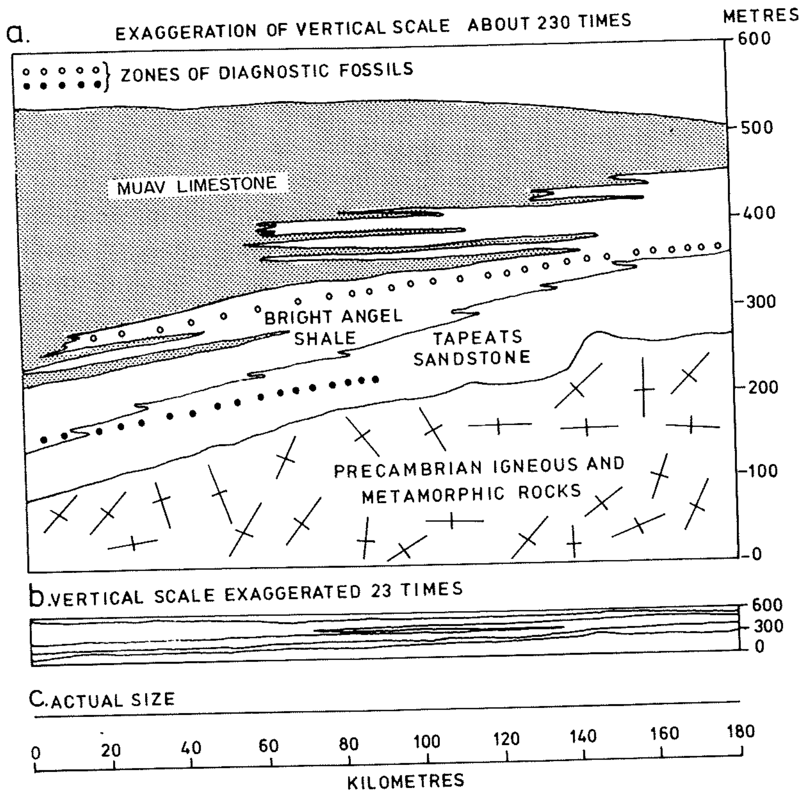

Fig. 6.7 A typical example of lateral facies changes which are gradual over tens of kilometres such that gross vertical exaggeration (a) is required for clear display. Even a large exaggeration (×23 in (b)) obscures the lateral relationships. When drawn to true scale (c) nothing can be resolved because the thickness (600 m) is so much less than the horizontal distance (180 km)

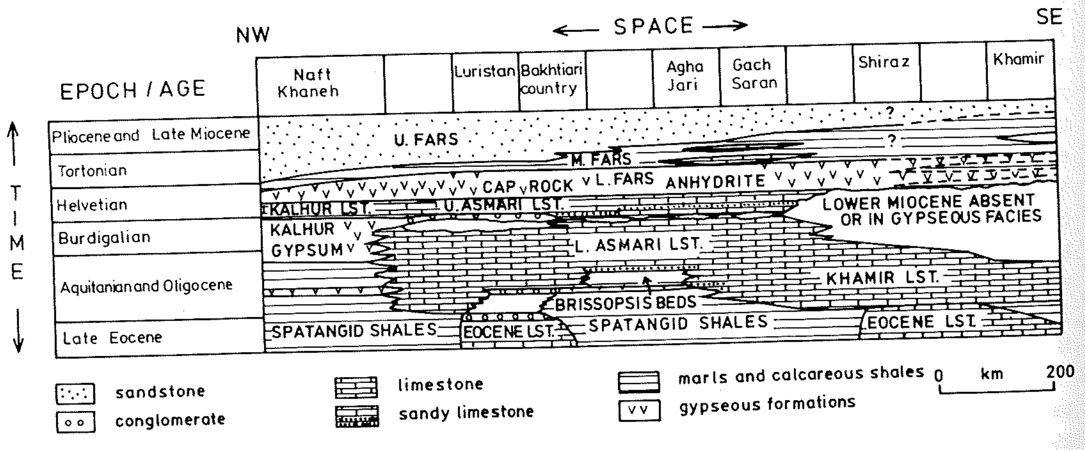

Fig. 6.8 A time-space plot draws attention to lateral facies changes, but remember the vertical axis has nothing to do with stratigraphic thickness. Gaps in the rock-record are also highlighted by these diagrams. This example shows relations between units that developed in a shelf setting in what is now the Zagros area of Iran

6.8). In this Tertiary succession palaeontological control is good and biostratigraphy provides well-defined time horizons through the different lithologies.

The lateral migration of different environments through time creates a stacking of different lithologies and vertical facies changes. Sedimentological analysis makes considerable use of these vertical varitions in interpreting palaeoenvironments. At its simplest this approach can distinguish between transgressions and regressions. Compare the vertical facies changes of Figures 6.6a and b. In a regression (Figure 6.6b) the finer offshore muds are overlain by the barrier islands sands, lagoon muds, beach sands and perhaps by continental deposits. The reverse vertical stack is generated by transgression (Figure 6.6a) with the fine offshore muds on top.

Having emphasized the generality of diachronous lithological contacts, it is now appropriate to mention the isochronous exceptions. Major catastrophic eruptions like that of Toba, 75 000 years BP, pour vast quantities of pyroclastic material (up to 2000 km^3) over large areas in a geological instant (days or weeks). The Toban event produced 400 times more ash than the better-known Krakatoan eruption with presumably devastation approximately in proportion. The Toba Tuff was deposited on land, and in shallow shelf waters over the whole range of environments in such regions. This tuff and the many equivalents in the ancient record provide geological time surfaces and are very useful in constraining biostratigraphic correlations in some areas. Instantaneous units of this nature are commonly referred to as **key beds**, though again the term has several meanings and to some workers key beds are distinctive layers not necessarily deposited everywhere at the same time.

6.6 STRATIGRAPHICAL INFORMATION ON MAPS

The standard geological survey product is a coloured map. The key to the colour scheme is on a lithostratigraphical basis (formations, groups, etc.) with geochronological (time) information (eons, periods, epochs, etc.). A wide range of conventions exists and even within one survey, through the years, the style of presentation will have evolved. The simplest key is a set of coloured boxes, labelled with formation names, arranged in order from oldest at the bottom to youngest at the top (Figure 6.9a). Sedimentary and volcanic rocks are always treated in this way but intrusives may appear (1) grouped together at the bottom of the key (2) in their correct stratigraphic position or (3) kept separate from the stratified rocks. If style (1) or (3) is adopted for intrusives, within this grouping, they are still arranged from oldest at the bottom to youngest at the top. In addition to colour coding, most keys provide a letter code which is helpful when there are so many units that colour differentiation may become difficult. In making a sketch-map of part of the published map to illustrate a report it is useful to follow the letter code.

The next most informative approach is a set of boxes with brief lithological descriptions for each formation (Figure 6.8b). A slight variation on the above two methods is to join up the boxes in a vertical stack which creates a schematic stratigraphic column—our example of this style (Figure 6.9d) was published in combination with a more detailed representation of the stratigraphy. The latter is achieved as a columnar portrayal of the formations showing thicknesses to scale with variable amounts of commentary on the lithology (Figure 6.9c). The thicknesses may be averages for the map area or those seen in one small part of

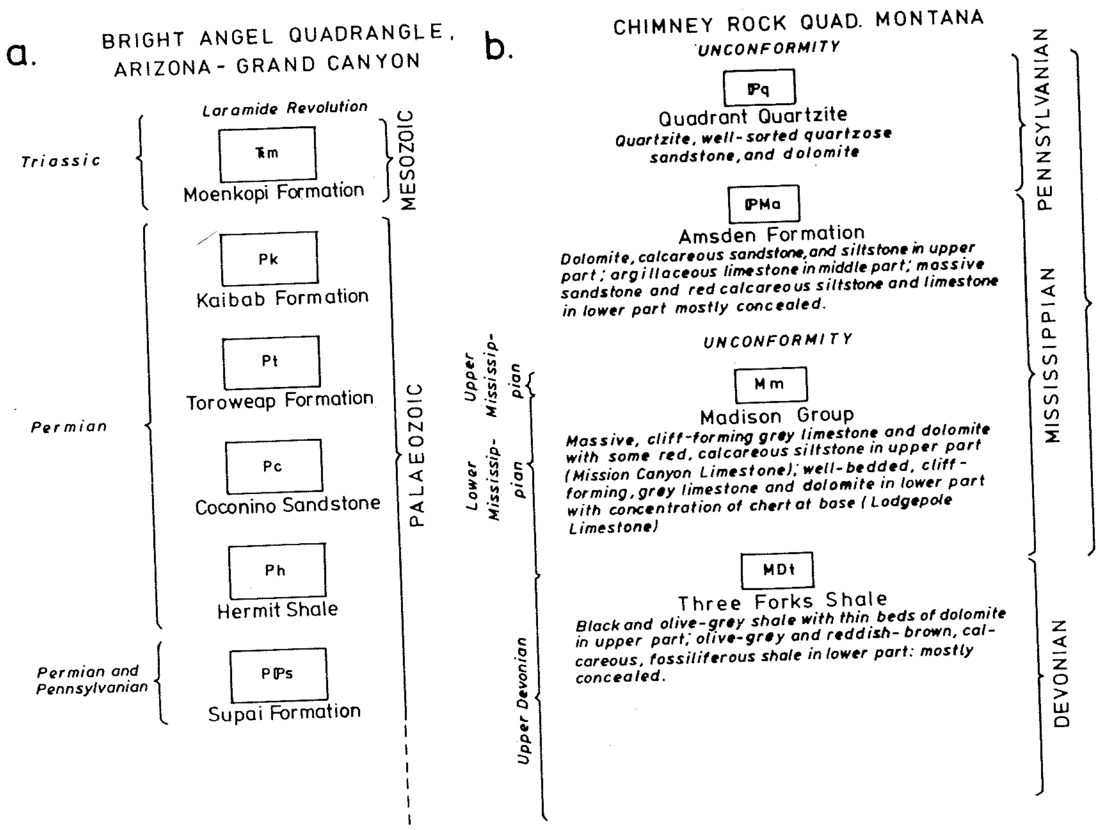

Fig. 6.9 a,b

the area. This style allows lenticular units to be identified and also for graphic presentation of major facies boundaries or angular unconformities. A thumb through one issue of a geological journal revealed a bewildering array of names given to the columnar style of stratigraphic representation, viz. schematic columnar sections, stratigraphic sections, columnar section and generalized stratigraphy and stratigraphic columns. The British Survey somewhat misleadingly calls them generalized vertical sections.

Detailed information on lithologies is seen on only a few maps. Beginning students are often unaware of the variability in lithology that is sometimes lumped together and called a mapping unit—a formation (see e.g. Figure 6.3). Bearing in mind the requirements of scale and mappability, some formations are very mixed lithologically. The style of Figure 6.9e allows us to see that the single colour on the map for the Mauch Chunk Formation from Pennsylvania is a mixture of shale, sandstone and limestone, with no one dominant lithology. Further details (Figure 6.10), in terms of a graphic, measured or sedimentary log, is rarely seen on published maps. Even Figure 6.9e does not show all beds, whereas graphic logs typically can represent beds down to a few tens of centimetres though scales again may vary to suit the aim of the project and publication constraints. Graphic logs usually give information on sedimentary structures and fauna in addition to lithology. The horizontal scale on modern examples relates to grain size, though older examples give a more fuzzy weathering profile with less information.

Several variations on the above themes are possible. Maps of a large region may cover very different domains that evolved together, for example, an island arc and

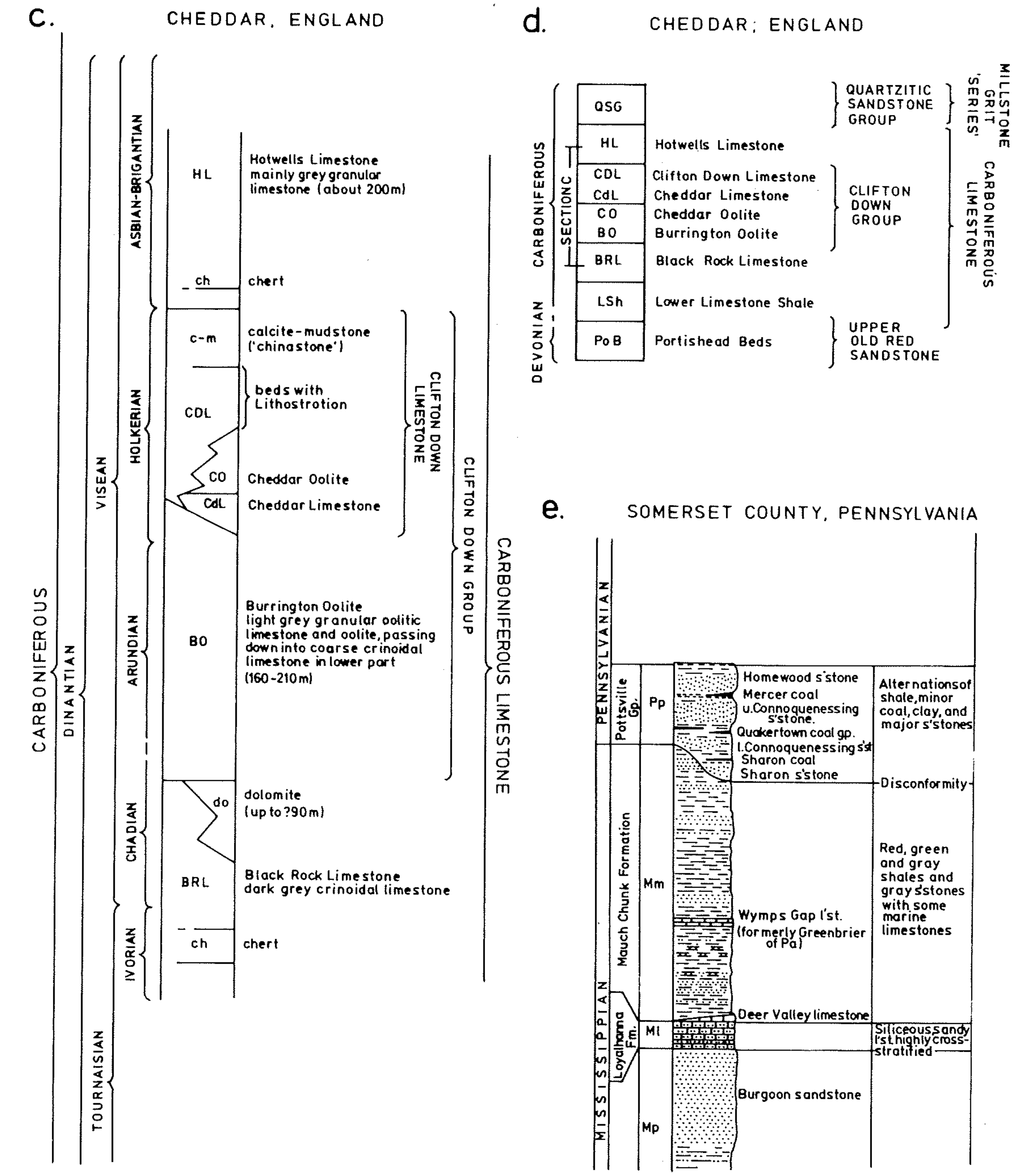

Fig. 6.9 (a) The simplest and least informative method of representing a stratigraphic key/legend on a geological map. Formations are named, colour coded and lettered but no lithological data are given. Geological time units are also given. (b) A move in the right direction in that a reasonable amount of lithological information is provided in addition to (a). (c) A stratigraphic column with some lithological commentary and a good graphic portrayal of lenticular units (lateral facies). At a glance this style gives relative thickness which may be averages for the map area so variations will still have to be analysed on the map. (d) This standardized representation is similar to (a)+(b) and the amount of lithological information given varies considerably. As a stand-alone version this would rate poorly in data transfer, but it was published as a summary diagram in combination with a more extensive stratigraphic column which is partly shown in (c). (e) It is rare to see on published Geological Survey maps this amount of detail. From the pictorial style of the stratigraphic column a good idea can be gained of sand/shale, etc., ratios within each formation. Such information is useful in an analysis of depositional environments, but often such crucial information is in limited supply

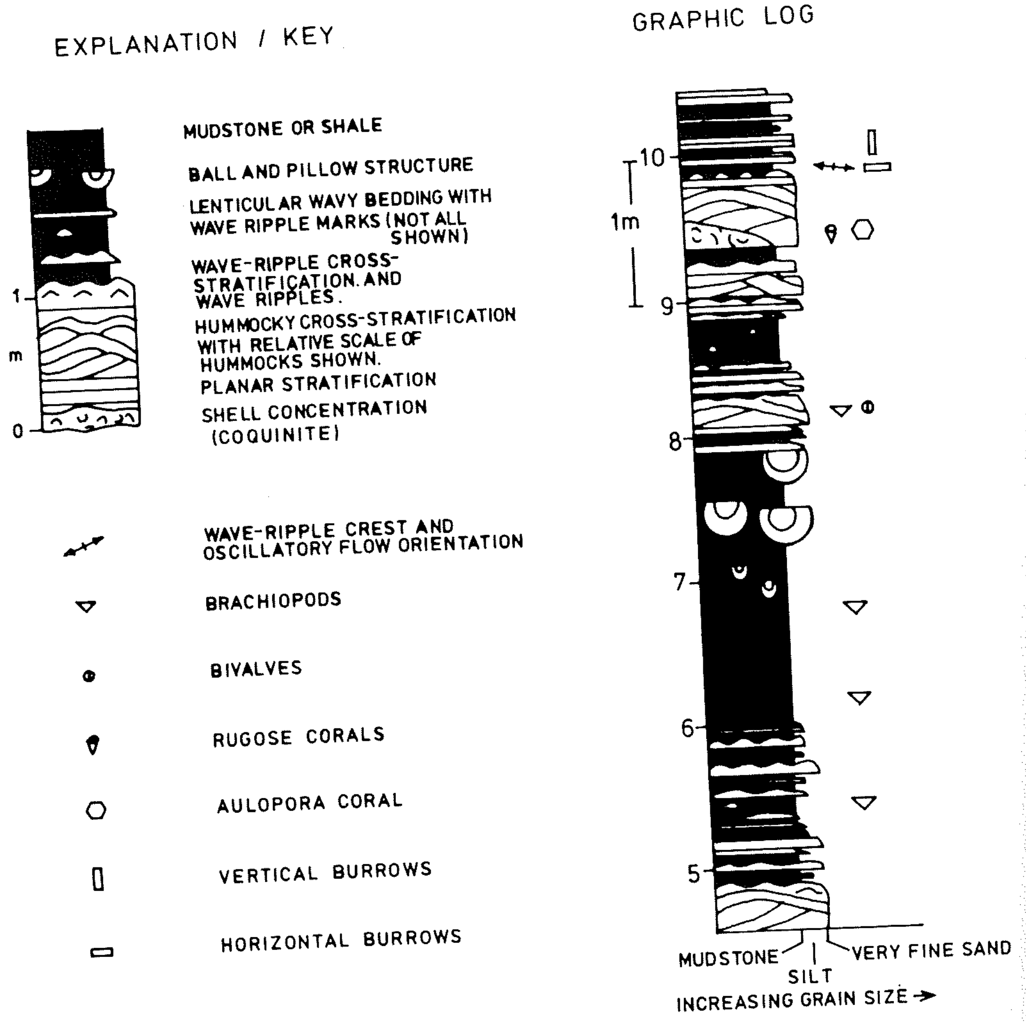

Fig. 6.10 This is a graphic, measured or sedimentary log which at its most detailed records every bed, gives grain size, fossil content, sedimentary structures and palaeocurrent direction. The same style can also be very effective on a smaller scale to give overall trend in stratigraphic columns kilometres thick. This very detailed style is normally found in reports, memoirs or published papers, whereas Figure 6.9e is a small-scale example which is not as rigorous about representing grain size

an adjacent marine region (see Figure 10.17). The pronounced lateral facies contrasts may require two separate stratigraphic columns placed side by side to show interpreted correlations. If the two disparate regions are then linked by a later more widespread unit, this may be shown diagramatically. On tectonic maps, a time-space plot may be used in a similar fashion but containing more information on structural and metamorphic events, and tectonic style. A welcome modern trend is to provide rock relationship diagrams (Figure 6.11) which schematically give the stratigraphic relations between the mapping units. In contrast to a cross-section, this diagram involves all units not just those found on the section line. These diagrams give a very quick way of assessing the structural style, lateral variations in lithology, sequence of events, nature of unconformities, intrusive styles, etc.

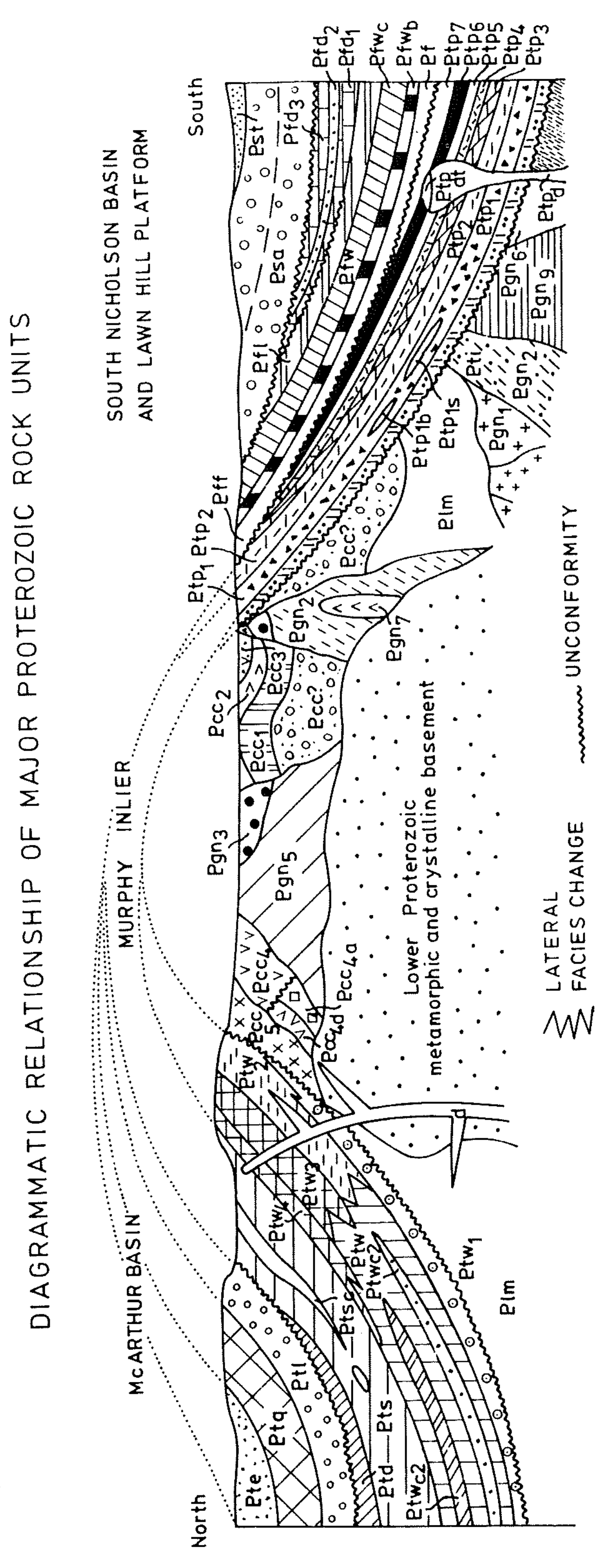

Fig. 6.11 Rock-relationship diagrams are a powerful means of conveying the essential interrelations of most of the units on a map. Key overprinting, intrusive or lateral changes are brought to your attention and then their expression on the map can be more easily detected. Modern maps typically have several styles of summary diagrams (e.g. block diagrams) to speed the process of data transfer

6.7 FURTHER READING AND IMPORTANT SOURCES OF INFORMATION

Eicher, D. L., 1976, *Geologic Time* (2nd edn) Prentice-Hall, New Jersey, 150 pp.

Hedberg, H. D., 1976, *A Guide to Stratigraphic Classification, Terminology and Procedure*. International Subcommission on Stratigraphic Classification of the International Union of Geological Sciences Commission on Stratigraphy, John Wiley, New York, 200 pp.

7 DEFORMATION BASICS

7.1 GENERAL COMMENTS

Stratigraphic methodology established the fundamental principles of superposition, original continuity, horizontal deposition, etc., but the many departures (exceptions) demanded the birth of a new discipline—**structural geology**. Fine-grained sediments dipping at high angles were clearly not in their original state and **displacement** had to be invoked. Displacement in this context simply means a change in position. In fact it is the analysis of displacement that is the distinctive aspect which distinguishes structural geology from other branches of geoscience. If displacement has occurred, then structural geologists are interested and the following questions are asked: What is the nature (type) of displacement? What is the amount (quantification)? What caused it? What mechanisms allowed it to occur? A good definition of structural geology is:

> 'The branch of geology concerned with the description and mechanism of displacement.'

In geological terms displacement and deformation are synonymous though the *Concise Oxford Dictionary* defines the latter as 'disfigurement, a change for the worse'. Most stratigraphers would sympathize with these sentiments because original features which they like to study are modified or obscured and complications arise, but many deformation structures are strikingly aesthetic, i.e. they can be admired despite the problems (challenges) they pose.

It is fairly common for geologists to consider structural geology to be small-scale tectonics. I do not share this view because tectonics is a much more wide-ranging subject as is hopefully conveyed in the following definition:

> 'Tectonics is the study of the thermal and mechanical history of the lithosphere.'

Tectonics is very much concerned with the consequences of the mechanical behaviour of the crust and immediately underlying mantle. For example, large-scale differential movements of the lithosphere commonly create sedimentary basins; the sedimentation pattern and history become important in the tectonic analysis, but this is a far cry from the structural heartland of studying displacement.

We will now briefly consider the causes of displacement and the nature of the processes within rocks that allow deformation to occur. The earth is a heat engine and this creates an active planet. At depth, heat production may be fairly uniform, but transfer is by the markedly heterogeneous mechanism of convection and therefore concentrated by cells into zones of upwelling and sinking. Important by-products of this activity are variations in the magnitude and orientation of forces being applied to the outer skin of the earth. Geologically it is usual to work in terms of forces normalized per unit area to facilitate comparisons from place to place and time to time. After normalization the forces are referred to as **stresses**, and despite the