# Interpretation of stratigraphical ages in orogenic belts

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## SUMMARY


This paper discusses some aspects of the dating of specified orogenic events, in terms of a stratigraphical scale, by various methods of correlation.

A standard stratigraphical scale is the common reference to which various data (structural, palaeontological, isotopic, etc.) and events interpreted from them are correlated. Lists of tectonic phases express age estimates of particular tectonic events and cannot usefully substitute for a standard scale.

Some datable elements in orogeny are defined. The direct relation between an orogenic event and a stratigraphical scale, as determined in different ways, yields an age which is limited in precision by distinct components of indeterminacy and uncertainty.

Correlation depends partly on diastrophic gradient which distinguishes the effects of tectonic events that are confined to the immediate neighbourhood from those at greater distance; few events have global effects (e.g., eustatic change). Correlation is generally effected, however, by relatively independent events, (e.g., biological, evolutionary, nuclear decay, climatic, magnetic reversals, etc.).

The primary purpose of dating orogenic events is to enquire into the distribution of earth movements in space and time. The results can be given in a number of ways (e.g., tectonograms, palaeotectonic and palinspastic maps, kinematic tectonic realms). Because the Earth's surface is a closed system a total synoptic stratigraphical study of many aspects of the time, direction and magnitude of movement becomes possible and is aided by new procedures of co-ordinated research, compilation, and automatic processing of data.


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## 1. Introduction

THE PROBLEM of dating orogenic belts stratigraphically can be resolved into three questions: (i) what standard or scale is to be used for dating?, (ii) what events are to be dated?, and (iii) how can orogenic events be correlated with a (stratigraphical) scale? There are two elements in the process of time correlation: positive and normative.

Correlation involves comparison and assessment of sets of observations. It employs all available means. In this field of positive science conclusions are in varying degrees uncertain and are expressed with varying degrees of confidence. This essential uncertainty in correlation applies whatever conventions are employed. The conventions should provide for a method of stating the uncertainty by a degree of confidence.

The normative element comprises the concepts and terminology for expressing opinions about correlation. They can be settled by decision; uncertainty here is thus unnecessary. Nevertheless concepts and conventions are in practice confused and so do contribute to the effective uncertainty in correlation, specifically by differences in definition or imprecision of usage, and more generally by the successive retailing of stratigraphical data when slight differences of usage are involved and successive restatements lead either to loss of available precision or to a spurious semblance of precision. This paper isolates and treats some aspects of conventional usage.

The purpose of interpreting stratigraphical dating of orogenic belts is primarily to enquire into the pattern of earth movement in space and time. How completely the pattern can be understood depends on the available record. Views about this have changed. Confidence in a continuous stratigraphical record punctuated only by short gaps representing diastrophism was characteristic of the earlier days of stratigraphy, but this yielded to an appreciation of the imperfections of the geological record. Evolution required a long time span represented only sporadically by strata and the 'time famine' (Holmes 1964) gave place to a rock famine. The imperfections of the record can be exaggerated, however, and the prospect of a representative record of the later part of earth history is continually being improved by the discovery or re-interpretation of successions throughout the world. Application of these stratigraphical developments to tectonic interpretation has lagged, and the implication that short synchronous movements divided geological formations has persisted; but whether earth history can usefully be divided by major and minor natural events is still a matter for investigation.

The methods employed in an investigation should be dictated by its purpose. If the subject of enquiry is the pattern in space and time of earth movements, then evidence used should be entirely free from assumptions concerning this pattern, whatever other assumptions are made during the investigation.

## 2. Rock, time and events

Stratigraphy is concerned with the interpretation of all rocks (not just sedimentary strata) as earth history, in a four-dimensional space–time framework which relates, supports, and is supported by all geological events, distributions, processes and environments. Stratigraphical procedure involves the investigation of successions or time sequences and their extension in space by time correlation. The purely chronological aspect of stratigraphy can be isolated, but the data of stratigraphy are derived from rock in space. Time is derived from a relativistic four-dimensional space–time model. In practice, then, it is impossible to separate time from space as long as a rock framework is its basis.

It is useful to distinguish dimensional aspects of stratigraphy as follows: (*a*) *rock* is described in lithostratigraphical or structural terms in studies that are essentially spatial; (*b*) *events* are interpreted from rock as concepts essentially in space–time; (*c*) *time* is a conceptual framework or scale for events and is expressed in terms related either to events or to rock. The terms can be standardized respectively either in relation to the duration of a year, hence the periodic unit scale of geochronology, or to points in rock, hence a standard stratigraphical scale. These will be considered briefly.

## (A) ROCK DESCRIPTION

A description of rock includes the following two procedures:

### (i) *Descriptive stratigraphy (lithostratigraphy)*

Clear descriptions of rock are needed for use as the basis for stratigraphy. Principles of procedure for this purpose as refined in successive stratigraphical codes are practically agreed (e.g. American 1961; Australian 1959; Norwegian 1961; Geological Society 1967). Successions should be described fully from all aspects (including palaeontological), divided, and labelled conveniently (groups, formations, members, etc.).

Most observations relating structure to stratigraphy refer to lithostratigraphical divisions. It is important that, whatever additional age interpretations may be attempted, the statement of these relationships should be preserved in terms of descriptive stratigraphy. Time correlation of strata can then be revised without loss of precision.

### (ii) *Descriptive tectonics (structure)*

Structural description is also a routine, though as yet not so standardized. Just as the lithostratigraphical division provides the basis for stratigraphical interpretation of age, of environments, and of other factors, so the structural description is the basis for tectonic interpretation. Some tectonic terms used in a time sense (e.g. orogenic phases), will need to be objectively based on specific structures designated after the manner of stratotypes.

## (B) EVENTS

Events are the elements of historical interpretation. They are limitless, but include events of actual and potential value for correlation as follows: (i) biological, (ii) diastrophic, (iii) magmatic, including volcanic, (iv) metamorphic, (v) magnetic reversals and polar wandering, (vi) climatic, and (vii) eustatic events. In varying degrees they also provide convenient sequences or scales of events. The biological evolutionary scale has long been the basis of most classical stratigraphical division and correlation and is now being rapidly supplemented by the others. Nuclear decay itself is a constant stream of events, but the events referred to isotopic age-determinations are the crystallization or thermal events that closed a system. An auxiliary scale of magnetic reversals is being rapidly developed with a distinct nomenclature. Diastrophic events are particularly relevant to this symposium and are considered in more detail in section 3.

### (C) TIME

Time can be expressed geologically as a duration or time-span; as an order or sequence; or as a point or specific moment. Combinations of these aspects are used to provide a scale or framework for the study of geological events.

Any of these aspects of time can be specified in terms of events, such as: the range or span of a defined organism; the (approximate) moment of a particular magnetic reversal; a structural sequence; or the span, sequence or moment of deposition with respect to a particular sedimentary formation. In correlation the concepts of synchronous, overlapping and diachronous events are used to relate in time any one set of events with any other. But all such events are interpretations of rock evidence and are liable to revision (Hedberg 1958). Indeed, it is a purpose of geological investigation to revise them. It is thus desirable to refer all kinds of events to a standard that will be, as far as possible, independent of interpretation and revision.

Two kinds of standard are in use. Each is being actively developed. Each has its advantages and limitations, and they are not in competition, for they supplement each other. The principle of each method is clear and only the application and nomenclature are difficult. These two standards are (i) the geochronological scale and (ii) the standard stratigraphical scale.

#### (i) *A geochronological scale*

A scale in units of duration (years) is the most obvious time-scale. Conceptually there is no problem here; however, an absolute quality is elusive (Holmes 1962), and there are two reasons for this. First, the conceptual scale is *relative* to an observed physical duration. The *Système International d'Unités* proposes to standardize all time units on the *second*, but the relative advantages of *year* and *second* are debatable and the *year* is likely to be retained for the time being in the earth sciences (Royal Society 1968). Additionally, and more important, the ages given by any method are interpreted as apparent ages, with errors stated and unstated, and as such are liable to adjustment. The use of quantities does not in itself give precision.

Isotope geochronology is a method for measuring the time elapsed since an event closed a system. Because igneous and metamorphic rocks have provided most of the better values, much of the dating of deep structural events depends largely on this method.

Only numerical values need be used for stating results. Nevertheless, for convenience of division of Pre-Cambrian time, schemes have been proposed with names for specified time-spans defined in years—e.g. Stockwell (1964), and Table 2. An early need is for a broad grouping of rocks, for mapping Pre-Cambrian terrains, that will be widely adopted.

Essentially geochronology is not so much a standard of reference as an attempt to calibrate any and all events in terms of years (e.g. Holmes 1959).

### (ii) *A standard stratigraphical scale*

The need for a stable objective scale for common reference is already met, to some extent, by the use of international time-stratigraphical terms (eras, periods, epochs, ages and chrons). These are generally understood in a broad sense but are not yet defined in such a way as to avoid ambiguity, or variation in terminology, or uncertainty as to exact boundaries. When it was necessary to define a complete sequence of Phanerozoic divisions for *The Fossil Record* (Harland *et al.* 1967; see also Table 1), as an interim solution the base of each division was defined by the base of a specified zone. This removed some larger ambiguities but still relied on the interpretation of biozones in terms of chronozones.

For some years now international effort has been directed towards agreeing a standard scale that, at the point of definition, shall be independent of interpretation (Hall 1891; Hughes 1891; Hedberg 1961, 1964; George *et al.* 1967). The concept of defined stratotypes for 'chronostratigraphical' divisions has been clarified by the recommendation to define them according to reference points identifiable in described, accessible rock successions (George *et al.* 1967, Hughes *et al.* 1967). The International Union of Geological Sciences has authority to decide on the locations of the points and on the names of the divisions they define. The Commission of Stratigraphy of the Union and its Sub-Commissions (to be reinforced by the International Geological Correlation Programme) are working towards this.

Each point in such a scale will define a point in time unambiguously. Time-stratigraphical divisions will then be defined as the spans between specified points. The object of such a standard is to allow estimates of the age of rocks and events anywhere to be expressed in a single language whose terms are known. This cannot, however, avoid the natural difficulties of correlating from other areas to those points.

The main advantage of such a scale is that, being defined in rock, any characters or interpreted events can be related directly to it. Any other calibration, valuable in itself for specific purposes, involves two variables instead of one and so lacks the quality of a standard; for example, the ages of biozones in years involve palaeontological and geochemical estimates, neither of which are stable. The preferred method is to calibrate biozones on the one hand and isotopic events on the other against agreed standards in rock.

Rocks selected for reference points should have an optimum potential for correlation. Volcanic rocks in fossiliferous strata may provide good opportunities for relating isotopic, magnetic and palaeontological data. Combinations of biological and climatic methods are also powerful, as in Quaternary correlation.

(iii) *The time-scale*

The combination of (i) and (ii) above, as has been successively attempted in refining the Phanerozoic time-scale (e.g. Holmes 1959; Harland, Smith & Wilcock 1964), best illustrates the respective limitations of geochronological and stratigraphical standards. The object is to estimate in years the boundaries of the stratigraphical scale (e.g. Table 1). Until the latter is standardized there are two sources of uncertainty, namely the stratigraphical position of division boundaries, and

TABLE 1: *Stages, etc., as defined in The Fossil Record* (Harland *et al.* 1967, pp. 5–9), *with age in m.y. of equivalent base as estimated in The Phanerozoic Time-scale* (Harland, Smith & Wilcock 1964, pp. 260–2).

| | Age of base (m.y.) | | Age of base (m.y.) |
|---|---|---|---|
| Holocene | — | Norian | — |
| Pleistocene | 1·5–2 | Carnian | [205] |
| Pliocene | 7 | Ladinian | — |
| U. Miocene | 12 | Anisian | [215] |
| M. Miocene | 18–19 | Olenekian | — |
| L. Miocene | 26 | Induan | 225 |
| U. Oligocene | — | Dzhulfian | — |
| L/M Oligocene | 37/38 | Guadelupian | 240 |
| U. Eocene | *c.* 45 | Leonardian | [265–268] |
| M. Eocene | *c.* 49 | Sakmarian | — |
| L. Eocene | 53–54 | Asselian | 280 |
| Palaeocene | — | U. Carboniferous | 290–295 |
| Danian | 65 | Moscovian | [306] |
| Maestrichtian | 70 | Bashkirian | [317] |
| Campanian | 76 | Namurian | 325 |
| Santonian | 82 | Viséan | 335–340 |
| Coniacian | 88 | Tournasian | 345 |
| Turonian | 94 | Famennian | 353 |
| Cenomanian | 100 | Frasnian | 359 |
| Albian | 106 | Givetian | — |
| Aptian | 112 | Eifelian | 370 |
| Barremian | 118 | Emsian | 374 |
| Hauterivian | 124 | Siegenian | 390 |
| Valanginian | 130 | Gedinnian | 395 |
| Berriasian | 136 | Ludlovian | — |
| 'Tithonian' | — | Wenlockian | — |
| Kimmeridgian | 151 | Llandoverian | 430–440 |
| Oxfordian | 157 | Ashgillian | — |
| Callovian | 162 | Caradocian | 445 |
| Bathonian | 167 | Llandeilian | — |
| Bajocian | 172 | Llanvirnian | — |
| Toarcian | 178 | Arenigian | *c.* 500 |
| Pliensbachian | 183 | Tremadocian | — |
| Sinemurian | 188 | U. Cambrian | 515 |
| Hettangian | 190–195 | M. Cambrian | 540 |
| Rhaetian | — | L. Cambrian | 570 |

their currently estimated age in years. The first can be settled by convention, leaving the estimate of age in years open indefinitely for progressive improvement both geochemically and stratigraphically. A time-scale of this sort is changeable and thus, being only an approximate standard, is inevitably a statement of a current estimate or hypothesis. It combines the whole range of geological interpretation and one example is given here, namely the interpretation of stratal thickness.

Maximum stratal thickness can be used to interpolate, extrapolate and supplement other data in constructing a stratigraphical scale. It is thus often an implicit factor in correlation. For detail or for particular problems it cannot be applied because the rate of sedimentation is highly variable and the net accumulation is seldom known (e.g. Hudson 1964). But the method has been apparently successful when long time-spans and averages have been used (e.g. Barrell 1917; Holmes 1947, fig. 3). The consistent averages that can be obtained (Kuenen 1967) are probably due to a similarity in maximum rates of net subsidence or oscillation (Belousov 1962). A local estimate of age or of correlation, in so far as it is based on stratal thickness, must not be used as a measure of rate of subsidence or of other tectonic process.

Facies curves (continental, littoral, shallow marine, etc.) are related through subsidence scales (oscillograms) to cumulative curves (Bubnoff 1963).

## 3. Tectonic sequences or scales

Tectonic geology is structural geology treated historically, and it is thus a structural extension of stratigraphy.

Stratigraphical divisions were originally decided by breaks in sedimentation or by unconformities conceived as catastrophic events or revolutions, and tectonic scales have this same pedigree. Early nineteenth century stratigraphy owed much to tectonic insight. Unfortunately assumptions of synchronous-global diastrophism (e.g. that of Cuvier) have persisted (e.g. via Stille) to the present day, as in a Soviet school of stratigraphy (Rotay 1960) and elsewhere. If natural divisions of earth history, largely tectonic, were to be accepted as a principle, then these divisions would need only to be correctly designated. Such natural divisions may, indeed, have existed, but to make this basic assumption stultifies scientific enquiry about them, and leads to stratigraphical and tectonic scales being equated in time without considering their relative space aspect. This in turn leads to ill-founded stratigraphical correlation by tectonic 'phases'. This problem has been surveyed many times, notably by Gilluly (1949, 1950); see also Stille (1950A, B).

Many tectonic or orogenic tables, lists, sequences, scales or diagrams have been published. These have usually been related to a particular region (e.g., Blackwelder 1914; Stille 1924; Rutten 1949; Gilluly 1967) but occasionally carry the implication of widespread synchronous events and thus of global application. In this sense a tectonic scale duplicates a stratigraphical scale, particularly if it be defined or calibrated in stratigraphical terms. Moreover, in an effort to make such a scale generally applicable, all manner of diastrophic effects, large and small, tend to be correlated as synchronous events when known only to be of approximately the same age. Tectonograms (in this sense the diagrammatic representations of diastrophic activity plotted against time, as in Bubnoff (1963)) almost invariably exaggerate the precision and reliability of orogenic dating. A good exception is seen in Gilluly (1967, pp. 310–311).

Although the above discussion refers to major orogenic events, the same principles apply to detailed structural sequences, e.g. *S*1, *S*2, *S*3, even in a hand specimen.

Two geochronological scales based on tectonic (metamorphic, igneous, diastrophic) events exemplify some of the preceding discussion: the division of Pre-Cambrian time by the Geological Survey of Canada already referred to (Stockwell 1964, see Table 2) and Phanerozoic 'orogenies and phases' (Roubault *et al.* 1967, see Table 3). Each of these scales is based on estimates in years of the age of tectonic events, but they serve different purposes.

TABLE 2: *Pre-Cambrian time-scale for the Canadian Shield* (*after* Stockwell 1964)

| | |
|---|---|
| PROTEROZOIC | 2390–600 m.y. |
| HADRYNIAN | 880–600 |
| HELIKIAN | 1640–880* |
| NEO-HELIKIAN | 1280–880* |
| Grenville | 945† |
| PALAEOHELIKIAN | 1640–1280* |
| Elsonian | 1370† |
| APHEBIAN | 2390–1640* |
| Hudsonian | 1735† |
| ARCHAEAN | ? –2390* |
| KENORAN | 2490† |

*mean age minus one standard deviation (K/Ar determination on orogenic micas).
†mean age of orogeny in millions of years.

The proposed convention dividing Pre-Cambrian time by relating boundaries to maxima of K–Ar ages of micas has the effect of giving names to given spans of years and so preferring names to numbers. The names will in effect refer to divisions based on years and so differ from the standard stratigraphical scale which is based on rock.

The age-estimate of traditional orogenic phases (in the sense of Stille, Table 3) converts the usual stratigraphical context of tectonic names to a geochronological context. The values are given with approximation signs to emphasize the uncertainty. There are two elements of uncertainty here: the uncertainty inherent in the interpretation of a named event from observed structures and the uncertainty concerned with evaluating the age in years. Such attempts at tectonic calibration are useful if the events are defined in terms of rock structure. Otherwise there is a danger that, lacking a precise reference in rock, the event comes to be conceived in years and consequently the scale of names serves as an alternative for a scale of years. This would be no better than making a tectonic scale duplicate points in a standard stratigraphical scale.

TABLE 3: *Scale of the principal orogenic phases, as they are defined by Stille and Brinkmann, and as dated by recent geological time-scales (in m.y.). From* Roubault *et al.* (1967).

ALPINE OROGENY
- ~2: Walachian phase
- ~7: Altic phase
- ~37: Pyreneic phase

LARAMIDE OROGENY
- ~65: Laramide phase
- ~80: Subhercynian phase
- ~100: Austrian phase
- ~140: Neocimmerian phase
- ~195: Cimmerian phase

HERCYNIAN OROGENY
- ~225: Palatine phase
- ~260: Saalian phase

HERCYNIAN OROGENY
- ~295: Asturian phase
- ~320: Erzgebirge phase
- ~325: Sudetic phase
- ~345: Bretonic phase

CALEDONIAN ORGENY
- ~395: Ardennes phase
- ~435: Taconic phase
- ~500: Sardinian phase

ASSYNTIC ORGENY
- ~570: Cadomian phase

A tectonic sequence or scale, like a time-scale, is a positive matter for research and will yield successive conclusions; but unlike a time-scale, which is universally applicable, separate tectonic time-estimates need to be given for specific points or regions in space. They are thus results, and not a method, and are mentioned again in section 11.

## 4. Definition of orogenic events

The case for, and nature and properties of, distinct tectonic terms are as follows:

(i) They should belong to specific regions or tectonic provinces where these are defined and should not be extrapolated for a global scheme. Each should be related *inter alia* to unconformities in the lithostratigraphically described successions that bracket it, recognizing that these unconformities change in time-span laterally. As with lithostratigraphical successions, so with tectonic sequences, the interest in dating is to compare with sequences elsewhere via a common reference scale. The evidence for a particular pattern of movements can then be explicitly stated.

(ii) An unconformity, tilted strata, or a complex deformation structure can be specified by name or names at a particular locality. This structure can then be referred to unambiguously whether or not its age be known. This procedure is convenient because, although the age is liable to revision, the structure retains its identity and has an objective reference value analogous to that of a lithostratigraphical formation.

(iii) A hierarchy of structural labels is often used and this may as well be explicitly recognized (e.g. orogenies and phases of Stille, see Table 3). But a hierarchy should be explicitly a terminological convenience to distinguish it from hypotheses of genetic significance which should be stated additionally. The concept of minor phases and climaxes within a major tectonic cycle has long been accepted. Individual structures may also be specified, as for instance metamorphic crystallization stages and, on a slightly larger scale, as fold phases. These may be grouped as an orogenic phase which in turn may be grouped into another still larger concept (as for example the Ny Friesland orogeny is grouped with the Svalbardian folding within the Caledonian orogeny.) These labels serve a useful purpose as long as they refer to structures which are identifiable, and are preferably defined and described from particular localities. It is important to define the smaller structures as from a more limited locality—for example, not *F*1 of the Caledonides but rather *F*1 of north-west Ny Friesland, since the latter may not be of the same age as *F*1 of central Ny Friesland.

(iv) To label structures by localities, as in lithostratigraphical procedure, could lead to a multiplicity of names but since these will not be of general application, only those frequently referred to in a general context will be remembered. In so far as time significance is intended the standard stratigraphical scale or the geochronological scale will be the common language.

The value of names need not be judged by ease of memory but by use in precise reference (as in biological nomenclature). Then, if $F1_x$, $F1_y$ and $F1_z$ later appear to be synchronous, *y* and *z* can be submerged in synonymy, whereas the alternative of using only *F*1 initially for many structures, without qualification or identification, could lead to an uncritical assumption of synchroneity and to loss of information if they prove to be diachronous. This logic applies even down to the crystalline scale where a detailed sequence of mineral changes may be discernible and may be correlatable with other tectonic events. Critical minerals should also be located in detail, even on particular slides. This is not to propose the erection of a vast nomenclature, but rather to encourage the relation of events to structures specified unambiguously (e.g. by map or slide co-ordinates).

(v) A tectonic sequence relates deformation structures, metamorphism, plutonism and mineralization to each other and as far as possible to surface stratigraphy. A tectonic scale, however, will generally apply to an intracrustal sequence, and a stratigraphical scale to a supracrustal sequence. This relationship is the question at issue in this paper and is the justification for naming distinct entities and making comparisons between them. Thus tectonic and sedimentological events can be interpreted, from both structural relations and strata, by reference *inter alia* to a common stratigraphical scale.

(vi) G. M. Kay has drawn my attention to a useful distinction, not always adopted, whereby, for instance, Taconi*c* be used for the place, Taconi*de* for the structure and Tacon*ian* for the time. The suffix-*oid* (as in Caledonoid) has also been widely used, and although this might confuse a simple direction with a genetic relationship, it is useful for specifying a palaeodirection without specifying its azimuth. A time-span (e.g. Taconian) should refer to that of the actual events producing the defined structure, and this may not be known in stratigraphical or geochronological terms. Herein is its value. The tectonic term refers to the exact time of the particular local structural development, whatever that was, and not to its interpretation in time-stratigraphical or geochronological terms.

(vii) A tectonic development may include, say, a geosynclinal stage as well as an orogenic stage if so specified. Thus the tectonic term is often applied to a preceding geosyncline because of its tectonic relationship. The context distinguishes two different uses of the term which are convenient. They have a common reference to the same rock.

## 5. Datable elements in orogeny

An orogenic or tectonic-magmatic cycle may last from a few tens of million years to as many as several hundred million years, as is seen from the evidence of isotopic ages (Cahen & Snelling 1966). These durations are analogous to those of sedimentary (geosynclinal) cycles (e.g. Compston, Crawford & Bofinger 1966). 'Thermal events' may span a greater time than their related tectogenesis because of slow-cooling and it is necessary to specify the event being correlated.

To avoid confusion some words used here are defined. *Earth movements* include seismic, tidal and other short-term perturbations, and also diastrophism which results in a long-term change of earth structure. *Diastrophism* here includes all deformation aspects of orogeny but not, for instance, petrogenetic nor erosional aspects. On the other hand it includes many earth movements not necessarily included in orogeny, such as uplift and subsidence, transcurrent movement (i.e. major strike-slip movements and not necessarily wrench faulting, still less tear faulting), and crustal extension (normal faulting and dyke swarms). *Deformation* refers to detectable rock strain and may be (secondary) tectonic, or (primary) sedimentary and igneous (flow structure). Tectonic deformation is included in *tectogenesis* with the development of structures not purely deformational (plutonic emplacement). *Orogenesis* or mountain building includes both the element of tectogenesis (structure building) and morphogenesis. It also includes mountain-root development modified by plutonic erosion or accretion. *Morphogenesis* (orographic or topographic development) includes uplift of the developing or completed structure and erosional sculpture (glyptogenesis) as well as the masking of structure by sediment (as in intermontane basins).

In detail the different stages of tectogenesis can be analysed and specified as already suggested ($F1$, $F2$, etc.) Where possible a further specification of tectonic regimes for particular parts of the structure is desirable, e.g. phase of axial extension at depth, or of superficial primary gravity movement (Harland & Bayly 1958). This is because the bulk movements of the lithosphere are easier to correlate in a wider sense than are specific fold phases within the structure, though the fold phases are likely to be easier to relate to mineralogical changes and so to isotopic ages. It is possible to work out a complex tectogenetic sequence and, by placing successive events in order, to provide for more accurate correlation elsewhere.

For correlation with surface strata, the events most likely to connect are uplift and erosion, and the generation of sediment and burial of the structure. Superficial tectogenesis may also be recorded in datable sedimentary sequences, as in the development of Wildflysch. When a stratal date for a particular structural phase is so obtained, however, this is not necessarily synchronous with deeper tectogenesis.

A time classification often used for orogenic belts is that of pre-, syn- and post-orogenic (Stille 1924). These terms are valuable but may be confusing unless tied to specific structures or to limited phases in the orogenic cycle. Tectogenic and morphogenic events, at least, need to be distinguished. If these terms are not related to specific events, the terms *early* and *late* orogenic are preferable. Further confusion has arisen because for European authors such as Aubouin (1965) a concept of orogeny is part of their geosynclinal scheme, yet to discover more about mountains and geosynclines requires that data be given without such presuppositions (Harland 1967).

## 6. Direct stratigraphical dating of orogenic events

Direct methods of correlating orogenic events are listed.

(*a*) The youngest deformed rocks of ascertainable age set an older age limit to the deformation.

(*b*) The oldest rocks in primary contact (igneous or sedimentary) with a deformation structure set a younger age limit to the tectogenesis.

The deformation may thus be post-(*a*) and/or pre-(*b*).

(*c*) Detached rocks indicating an ascertainable or related tectonic event may be in primary contact with later rocks of ascertainable age (adjacent or enclosed). For example, clasts in Miocene sediments were derived by erosion from discordant Alpine granites; and Argille Scagliose slides are found in normal sedimentary successions. In these cases the superficial movements are directly datable and the transported structures are at least older than the containing sediment. Moreover the 'primary contact' has been critical.

(*d*) Tectonic events may themselves serve to divide other events (tectonic or otherwise), in pre-, syn- and post-specified event, such as widespread deformation metamorphism, dyke-swarms. Their value for correlation depends on how intensive and how widespread they were. A faulted contact may not yield any relative age between the adjacent rocks, but it establishes that both are pre- some fault movement.

A critical discussion of these direct and more or less indirect methods could lead imperceptibly through the whole field of earth science, for in one way or another most events, situations and environments can be used to relate other events.

## 7. Precision and uncertainty of stated age

Statements about precision of correlation (which we cannot know) can usefully be converted to statements about confidence in particular correlations and/or about known degrees of uncertainty. Increasing correlation capability or precision is thus not necessarily matched by increasing precision in correlation statements if earlier estimates were over-confident. Estimates of the 'precision' of correlation have been made by taking stratigraphical time-divisions long enough to minimize the geochronological uncertainty of their limits with respect to their duration, and dividing by the maximum number of chronostratigraphical sub-divisions effective for regional or world correlation. Table 4 shows this kind of estimate based on *The Phanerozoic Time-scale* (Harland, Smith & Wilcock 1964).

Such studies suggest a progressive decrease in certainty with increasing age, as might be expected. To summarize:

(i) For Pleistocene chronology, correlation based on radiometric methods within the range of $^{14}C$ is generally most precise. The sequence of later human cultures yields slightly less precision. Otherwise correlation by short-term physical events, by climatological (often biostratigraphically based), eustatic and magnetic events, yields more precision than other radiometric or biostratigraphical methods, which, however, may also be needed to distinguish between similar physical events.

(ii) For Tertiary time the errors of the best isotopic dating are of about the same magnitude as for palaeontological methods. If magnetic methods later prove superior they will depend on the identification of reversals by other methods.

(iii) For Mesozoic and Palaeozoic time palaeontological correlation exceeds in precision that at present achieved by isotopic methods except in the direct correlation of thermal events.

(iv) For latest Pre-Cambrian time (except for thermal events) there is a transition between situations (iii) and (v).

(v) Most Pre-Cambrian correlation now depends almost entirely on isotopic geochronology, but there is no change of principle in dating rocks at the Cambrian–Pre-Cambrian boundary. Climatological and magnetic methods may in due course prove to be most precise if the events can be distinguished.

The comparisons above do not mean that one method should be preferred to another, for seldom is more than one method available, but when this happens they are superior in combination.

Isotopic errors contain a percentage element directly proportional to the age. Palaeontological precision depends on factors of evolution whose rate seems to vary greatly, and on environmental factors (e.g. temperature change) which can give great precision but can also introduce unknown hazards. Isotopic methods are ideally suited to igneous rocks and palaeontological methods to sedimentary rocks, with the unpredictable chances of closely bracketing one rock by ages from two others. In these circumstances volcanic rocks, with their added possibility of precise magnetic correlation, may combine many advantages (e.g. Evernden *et al.* 1964; Cox *et al.* 1968).

Any particular age-determination is componded of so many operations, each with its own limitations, that it is not useful to state an estimate of error without specifying to what it refers. These limitations are natural or artificial. The natural limitations of the record impose a degree of indeterminacy for a particular method. Human limitations impart various elements of uncertainty. These two factors are

TABLE 4: *Data in m.y., mainly from The Phanerozoic Time-scale* (Harland, Smith & Wilcock 1964)

| | TERTIARY | MESOZOIC | JURASSIC | CARBONIFEROUS | CAMBRIAN | PALAEOZOIC | LOWER PALAEOZOIC |
|---|---|---|---|---|---|---|---|
| (*a*) Estimated age of beginning | 65 | 225 | 190–195 | 345 | 570 | 570 | 570 |
| (*b*) Estimated age of end | 1·5–2·0 | 65 | 136 | 280 | c. 500 | 225 | 395 |
| (*c*) Estimated duration | 63 | 160 | 63 | 65 | 70 | 345 | 175 |
| (*d*) No. of divisions capable of world-wide correlation | 17 | 29 | 10 | 5 | 3 | | 11 |
| (*e*) No. of zones effective for distant correlation in favourable circumstances | 43 | 103 | 45 | 26 | 21 | | 67 |
| (*f*) $\frac{c}{d}$ to (*g*) $\frac{c}{e}$ | 3·7–1·5 | 5–1·6 | 6·3–1·4 | 13–2·5 | 23–3·3 | | 16–2·6 |
| (*h*) Radiometric experimental errors, e.g. as quoted by Holmes (1959). | ±2 | | ±5 | ±10 | ±20 | | |

not easy to distinguish, for natural limitations are subject also to human error and may be incorrectly assessed.

(a) *Indeterminacy* most obviously results from a complete gap in the record. At the site of orogeny this is bracketed by the youngest deformed and the oldest undeformed rocks in primary contact. Because the tectonism best defined structurally must be the least well defined stratigraphically the writer suggested the 'principle of tectonic uncertainty' by analogy with Heisenberg's principle (Harland 1956), but Eddington subsequently renamed it the 'principle of indeterminacy' and his statement makes a better model for the tectonic analogy because the ignorance is inherent in the evidence and is not a result of the method.

Similar but less obvious indeterminacy obtains throughout the concordant stratal record in which only a fraction of time can be represented by sediment. Even with rock of suitable age another limitation is set by lack of characters appropriate to a particular method. Alternatively this can be expressed as the degree of adequacy (time specificity or diachronic gradient) of particular characters.

(b) *Uncertainty* may be explicit or implicit and is also of the following kinds when attributable to man:

(i) Mistaken observations, as disclosed by repetition. These include idiosynchratic variations, misidentifications, standard error as expression of variation and observational limits.

(ii) Mistaken assumptions such as those relating to decay constants, or to the ranges of index fossils.

(iii) Avoidable uncertainty arising from the form of statement of stratigraphical age. Thus in a succession *XY*, a post-*X* age can only be certain if it is demonstrably post-part-*Y*—an obvious refinement that is seldom stated: if an event is demonstrably post-*X* formation and *X* formation is of *x* age it does not follow that the event is post-*x* age as is commonly inferred unless *X* formation and *x* age are co-extensive; again, where diastrophism is least distinct and an 'orogenic' phase is dated with relatively great stratigraphical precision (e.g. Stille's phases), unwarranted certainty is introduced when this name is applied to a major phase elsewhere with a wider stratal bracket.

Indeterminacy can be explicitly stated by giving stratigraphical bracketing limits. To express other uncertainty is more difficult. Stratal time-divisions need not be compounded in a hierarchy, but hierarchies can be used to express degrees of uncertainty. Thus a supposed mid-Jurassic event, with a large uncertainty as to date, may be stated as mid-Mesozoic. The same is possible but not so briefly stated for, say, end-Permian which could be mid-Phanerozoic, or late-Palaeozoic to early Mesozoic, and so on. Stratigraphical hierarchy, however, should not imply natural divisions of history.

## 8. Correlation with adjacent diastrophism

The rate of diastrophism or its gradient in time is considered elsewhere (Sutton, this volume, p. 239). The gradient in space implies the rate of change in tectonic facies over a given distance. A steep gradient probably favours stratal dating of adjacent diastrophism.

(*a*) *A vertical tectonic gradient* reflects the transition through facies with depth. It need not, as in *Stockwerke*, be gradual. It is related to a thermal gradient, with particular problems of sedimentation co-existing apparently with thermal events within a developing geosyncline. Inverted gradients, such as with superficial sliding or *décollement* over a different basement, present another problem (Rodgers 1964).

(*b*) A horizontal tectonic gradient evident at the level of exposure may be different at depth. Faulted margins to fold mountains often provide an abrupt front (as east of the Rocky Mountains) compared with a low gradient (as between the Zagros Mountains and Arabian Shield). If, as it seems, isostatic balance is generally maintained, relative stability can obtain adjacent to a mobile belt, but since the Earth is not a perfect fluid, uplift is often compensated by limited adjacent subsidence. This and other movements can result in tilt and obscure the tectonic gradient. Thus sediments on one side of a deformed block may obscure a continuation of that structure beneath them and so accentuate the impression of a steep horizontal tectonic gradient.

## 9. Correlation by effects of diastrophism

The influence of diastrophism on strata provides a further means of correlation.

(*a*) *Regional.* Stratal thickness is a measure of, or is related to, net subsidence (e.g. Belousov 1962). Cyclothems may reflect pulsatory diastrophism (e.g. Bott & Johnson 1967). Mobile tectonic environments yield characteristic unweathered, polymictic, pulsatory sediments (although by definition they are not eugeosynclinal without volcanism). Geosynclines also commonly comprise sediments characteristic of stable environments. Flysch and Molasse, etc., are proper names with particular stratigraphical and regional as well as tectonic and sedimentological connotations; if used out of context the quality referred to should be specified. Mineralization may recur in a particular tectonic environment and affect later sediments.

(*b*) *Global.* Most of the widely distributed effects of diastrophism in sediments are diffuse because they tend to average diastrophism by a bulk effect.

(i) Eustatic effects, although ocean-wide, are difficult to identify. Ignoring change of ocean volume as being too gradual to detect stratigraphically, and glacio-eustatic changes as being sudden but not clearly related, it would seem that the net effect of all orogenic activity is to accentuate the hypsographic curve and to lower the sea level. Conversely, gradational activity (especially denudation above sea-level and deposition below sea-level) will raise sea-level (Chamberlin 1909). Such effects can be established for Cainozoic time at least, and they provide a well documented measure of balance between total diastrophic and gradational activity. Briefly, Palaecene, late Oligocene, late Miocene and Pleistocene regressions (with a more complex pattern of intermediate stages) were times of widespread orogeny. Regressions might be expected also to reflect major horizontal movements such as ocean spreading, whose chronology is not yet clear unless the development of ocean rises and submarine volcanoes counterbalanced the effect exactly. This could account for the relative continental dominance of later Cainozoic time. Conversely, the maximum transgressions of say Middle Eocene and Lower to Middle Miocene, and to a lesser extent Pliocene time, correspond with relative orogenic quiescence. It has been common to attempt diastrophic/eustatic curves through time (e.g. Bubnoff 1963), but these often have only regional significance (e.g. Hallam 1963).

(ii) *Volcanism* associated with orogeny directly provides ash, bentonite or pumice horizons of precise significance in correlation, though compositions are seldom distinctive or very widespread. Claims have not been substantiated for a volcanic dust or $CO_2$ control of glacio-eustasy.

(iii) *Geochemical* effects are exceedingly diffuse and their interpretation is controversial (e.g. Brancazio & Cameron 1964). Atmospheric oxygen, maintained by photosynthesis, has been claimed to be reduced by the exposure by denudation of tracts of hypogene rock uplifted during orogeny; but there is little evidence that photosynthesis has not maintained a balance in the later part of earth history. $CO_2$ (atmospheric and oceanic) is supplied by volcanism and respiration, and is removed by photosynthesis. Arguments about distinctive deposits in more acid, early Pre-Cambrian waters have little specific tectonic application. Such long-term atmospheric and oceanic evolution (e.g. as reflected in sedimentary ironstones) probably reflects an over-all change in tectonic environment; but for later Pre-Cambrian and Phanerozoic time it is difficult to disentangle the related interplay of biological factors.

(iv) *Climate* is undoubtedly affected by topography and bathymetry. The average effect of low relief and high sea-level is to produce equable climates. Particular effects are debatable.

## 10. Correlation by relatively independent factors

Most factors used in correlation appear to be mainly or wholly independent of tectonic events, e.g.:

(i) *nuclear decay* is the best example of an environment-independent, time-dependent process;

(ii) *biological evolution* has a similar advantage in polarity and specificity, but is environment sensitive;

(iii) *magnetic reversals* are independent of lithosphere movements; *polar-wandering*, while related to these movements, and too slow for detailed correlation, is potentially useful for long-term discrimination—and, not least, in discriminating magnetic reversals;

(iv) *magmatic events*, volcanic rocks and dyke-swarms in particular, relate large areas, and relate superficial to deep rocks, also isotopic ages and magnetic polarity;

(v) *climatic fluctuations* are long- and short-term with biological, sedimentological and eustatic effects. These ramify to almost all aspects of geology.

## 11. Distribution of diastrophism in time and space

To work out the distribution of diastrophism has exercised innumerable authors and is a purpose of the *Data for Orogenic Studies* project. The results should be virtually the sum of tectonic knowledge. Each isolated observation and interpretation can be treated as an independent datum, and then grouped with other data according to successive concepts.

One recurring problem is to relate surface or epigene phenomena (that are more easily stratigraphically related) to hypogene or deep tectonic processes at the same place and time. Cross-cutting dykes and related volcanism provide one connexion.

The simplest way of showing the distribution in (space and) time is to plot in tabular form, against a stratigraphical scale, independent columns giving stratal hiatus and/or tectonograms. These are analogous to stratigraphical correlation charts and each serves a specified region.

Successive palaeotectonic (palinspastic) maps and sections provide the skeleton for kinematic models and these can be objective on a large scale when identifiable rock units are depicted. On a smaller scale data can be abstracted to map the boundaries between different degrees of mobility, i.e. at steep tectonic gradients. This defines a tectonic province at any one time. Through time, different tectonic sequences at different places would identify a changing tectonic province. This evolving four-dimensional shape (tectonic realm, Harland 1965), provides a convenient envelope to contain and relate the many kinematic events. For example, an enlarging and migrating geosyncline might give place to orogeny that might terminate or bud-out into an extended mobile realm somewhat displaced in position. Within the orogenic realm the successive strain regimes at the surface and at depth fit together in detail in the same way that the realm itself fits the adjacent immobile realms, like a kinematic '3D' jig-saw puzzle. This is distinct from a palinspastic model in which boundaries should preserve their identity in rock, and exhibit net motion rather than degree of motion. These are two ways in which structural and stratigraphical data can be synthesized. They provide an independent check on other models such as tectonic or chelogenic cycles, mantle convection, or patterns of climaxes of major and minor intensity.

Orogenic belts, more than most structures, provide evidence of diastrophism, often through great spans of geological time. In contrast to current evidence from oceans, in particular, they provide a principal source for earth history. Compression whether crustal or purely stratal, impresses a record in the rock so providing for its preservation and exposure.

## 12. Synoptic study of a closed system

Earth history is interrelated. An answer to one problem is a question, method, or assumption for another problem with an indefinitely expanding feedback and interplay of information. The lithosphere may be regarded as a closed surface and its kinematic history is therefore more accessible through synoptic study. Given knowledge of the limits within which the Earth's radius may have changed, and given that strain in consolidated rock yields observable structures, all movement has repercussions elsewhere. Orogeny here, strike-slip there, and extension elsewhere may be the result of deep-rooted movements, but the surface movements must also be related in some way. In this context strata everywhere provide critical evidence of mobility or relative stability. Knowledge of magnitudes and rates of subsidence, uplift or horizontal movement is critical, as is knowledge of timing or of movements of known direction and sense. Even doubt about horizontal movements of the lithosphere in one direction is not complete ignorance, for there may be little doubt about stability or movement in another direction. If the lithosphere moves in undisturbed segments separated by mobile zones, the problem is soluble.

Synoptic study requires a synthesis of the whole field of evidence which has hitherto been first inadequate and then too difficult. The data are rapidly becoming adequate to disentangle earth history backwards from the present situation (surveyable in all aspects), through Pleistocene time with detailed chronology and fitting of tectonic and stratigraphical events, and through Tertiary time with a workable knowledge of many parts of the earth. Now, through this co-operative investigation, the data can be sifted and assembled, and with help from automatic processing it is reasonable to plan for a kinematic-stratigraphical framework of earth history in which orogenic studies can only prosper.

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