PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Unconformities of the North Atlantic [and Discussion]

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Unconformities of the North Atlantic

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Lowstands of sea level produce significant unconformities, both on the continental shelves as subaerial unconformities and on the ocean basin slopes and floors by submarine erosion and shifts in depositional patterns. This report utilizes seismic data from the eastern Atlantic off Africa and the western Atlantic off the Blake Escarpment to illustrate the recognition and dating of deep sea unconformities.

Twenty-eight major and minor deep sea unconformities are identified on these seismic data and tentatively dated by means of well control and a chart showing global relative changes of sea level. The major unconformities identified are basal Sinemurian, basal Callovian, basal Valanginian, basal middle Aptian, basal middle Cenomanian, basal Thanetian, basal upper Ypresian, basal middle Chattian, basal Burdigalian, basal middle Tortonian, and basal Messinian.

Unconformity identification and correlation on seismic data from the deep sea is useful for building a stratigraphic framework for palaeoenvironmental studies and correlating deep-sea stratigraphy with the stratigraphy of continental shelves and interior basins.

1. Introduction

The principal purposes of this report are: (1) to illustrate how unconformities can be recognized and dated in the deep sea by using seismic reflexion and well data and (2) to encourage the use of unconformity correlation in the deep sea, rather than individual reflexion correlation, for initially subdividing seismic sections into intervals representing chronostratigraphic units. A secondary purpose is to propose global relative changes of sea level as a possible cause of the deep sea unconformities. Such global sealevel changes would be a major factor influencing the palaeoenvironments of the ocean basins, and would provide a practical method of global correlation.

Studies by Vail *et al.* (1977*a*, parts 3 and 4) on global cycles of relative changes of sea level conclude that lowstands of sea level produce interregional or 'global' unconformities. Evidence from the North Atlantic, including Joides deep sea cores, shelf wells, and reflexion seismic sections, tends to support this conclusion.

Recognition, correlation, and accurate dating of the unconformities and related strata are critical in showing their interregional extent and similarity over large regions and from one region to another. Seismic sections documented by well control are ideal for this type of analysis. In general, the greater the fall of sea level, the more easily the unconformities can be detected on seismic data. The commonest and most widespread seismic criteria are onlap, downlap, and truncation.

Global unconformities appear to be produced on the continental shelves and in interior basins by subaerial erosion and lapout of coastal deposits; and on the ocean basin slopes and

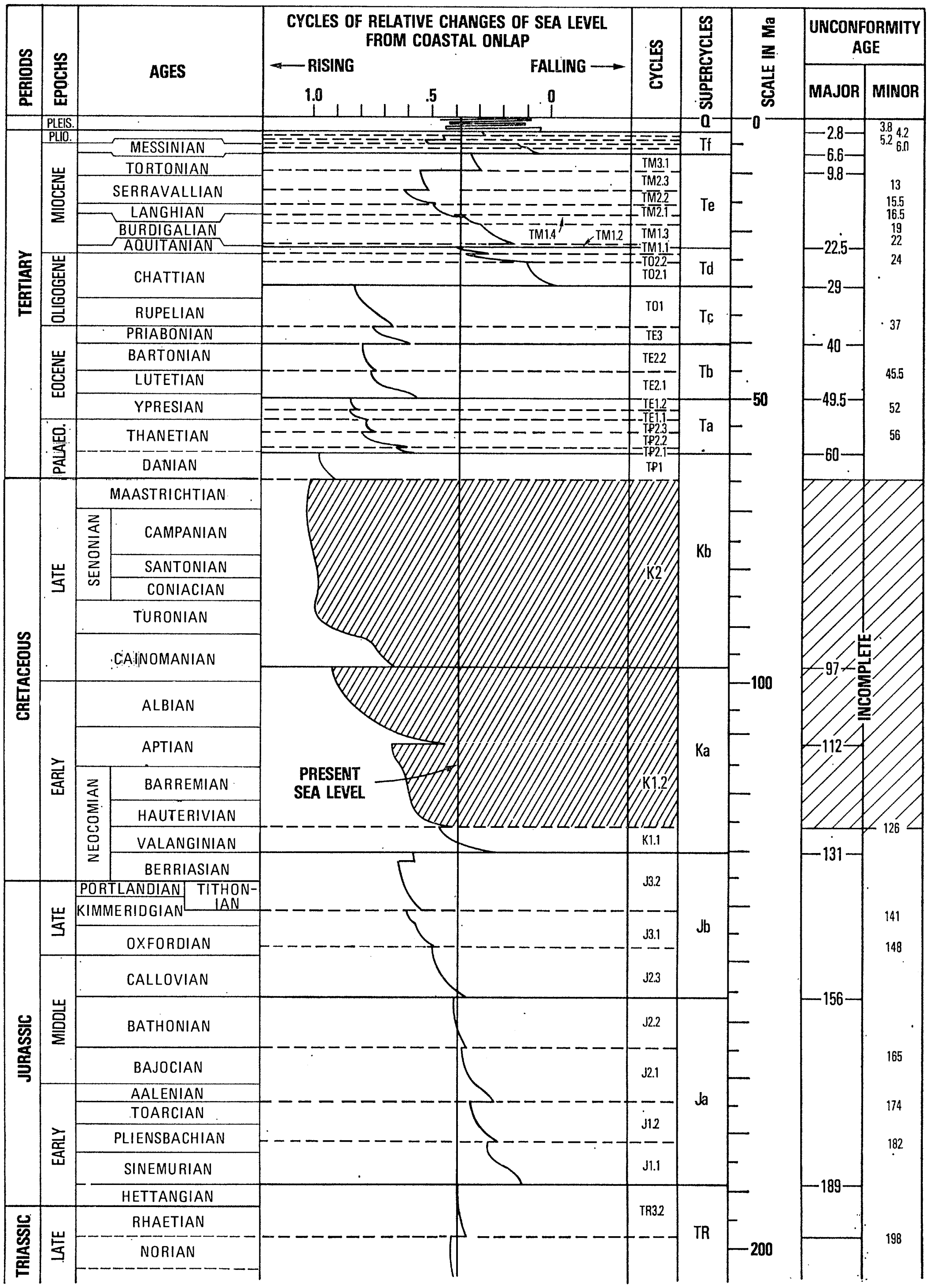


FIGURE 1. Chart of global relative changes of sea level since the Triassic and ages of major and minor global unconformities (modified from Vail *et al.* 1977*b*, p. 85).

floors by submarine erosion, shifts in depositional patterns, and nondeposition related to starved conditions in the deep oceans. Unconformities are best dated by establishing ages of overlying and underlying strata at points of minimum hiatus along the unconformities or where conformity is approached. Essential for accurate dating are detailed palaeontologic studies of wells tied carefully to seismic sections.

Examples of deep sea unconformities are shown on two seismic sections from offshore West Africa and the Blake Continental Margin. These sections show how unconformities can be recognized and used to subdivide the stratigraphic section into genetically related intervals or 'sequences' that provide a regional framework for interpreting depositional environment, lithofacies, and structure. In addition, they illustrate how the use of global unconformities provides a global system for chronostratigraphic correlation that can be used to relate the stratigraphy of the deep sea to the stratigraphy of the continental margins and interior basins.

2. Global unconformities

Vail *et al.* (1977*a*, parts 3 and 4) conclude that lowstands of sea level produce interregional or 'global' unconformities. Each unconformity can be related to a fall of relative sea level as shown on a chart of global relative changes of sea level (figure 1). This chart is updated slightly from Vail *et al.* (1977*a*, part 4, figure 2). The ages (Ma) of the Jurassic, Tertiary, and some of the Cretaceous unconformities are listed in figure 1. Designation of major and minor unconformities is based on the magnitude of the relative fall of sea level in figure 1. Relative falls of 0.1 or greater are considered major; relative falls of less than 0.1 are considered minor. The relative scale is based on a high level of 1.0 in the late Cretaceous and a low level of 0.0 in the late Oligocene (Vail *et al.* 1977*a*, part 4). In general, the major unconformities are the most easily recognized on seismic data, while minor unconformities are usually only identifiable in areas of rapid deposition.

Cycles of relative changes of sea level appear asymmetric, with a gradual relative rise, a period of stillstand, and a rapid relative fall of sea level. In detail, one gradual cumulative rise characteristically consists of a number of smaller scale rapid rises and stillstands, 'paracycles'. These smaller scale events are not commonly detected with seismic data, but are more readily recognized with data observed in outcrops, cores, and well logs. A cycle of higher order called a supercycle consists of a set of several regional or global cycles with a distinctive pattern consisting of successive rises to higher relative positions of sea level, followed by one or more major relative falls to a lower position. The falls of relative sea level at or near the ends of the supercycles commonly cause the major global unconformities. The sea level falls occurring during an overall rise are commonly, but not always, smaller, causing only minor unconformities.

3. Ages of North Atlantic unconformities

Each of the regional unconformities identified in the North Atlantic appears to be related to one of the relative falls of sea level shown on figure 1. Although unconformities are identified on seismic lines worldwide, this report deals exclusively with two seismic lines from offshore West Africa and from the Blake continental slope off the southeastern United States. The ages of several unconformities in the Blake Continental margin area have been determined by direct correlation or projection to Joides deep sea cores. In the West Africa area, many ages have been

Table 1. Ages of North Atlantic unconformities identified in this report

estimated age		magnitude of uncon- formities	method of dating		approximate deep sea reflexion equivalent
name	age/Ma		West Africa	Blake continental slope	
basal Upper Pleistocene	1.7	—	not identified	D.S.D.P. 102 projected	—
basal Calabrian	2.8	—	not identified	D.S.D.P. 102 projected	—
basal Upper Piacenzian	3.8	—	not identified	D.S.D.P. 102 projected	—
basal Tabianian	5.2	minor	not identified	D.S.D.P. 102 projected	—
basal Messinian	6.6	major	good correlation to shelf well	D.S.D.P. 102 projected	—
basal Middle Tortonian	9.8	major	fair correlation to shelf well	D.S.D.P. 104 projected	M
basal Upper Serravallian	13.0	minor	not identified	D.S.D.P. 104 projected	—
basal Serravallian	15.5	minor	not identified	estimated from sea level chart	—
basal Langhian	16.5	minor	good correlation to shelf well	estimated from sea level chart	X
basal Upper Burdigalian	19.0	minor	not identified	estimated from sea level chart	—
basal Middle Burdigalian	22.0	minor	estimated from sea level chart	estimated from sea level chart	—
basal Burdigalian	22.5	major	good correlation to shelf well	estimated from sea level chart	—
basal Aquitanian	24.0	minor	not identified	estimated from sea level chart	—
basal Upper Chattian	26.0	minor	not identified	estimated from sea level chart	—
basal Middle Chattian	29.0	major	good correlation to shelf wells	correlated with D.S.D.P. 105 and 391	A_u
basal Upper Ypresian	49.5	major	projected from shelf and D.S.D.P. wells	estimated from sea level chart	A_c
basal Thanetian	60.0	major	good correlation to shelf wells	projected D.S.D.P. 105 and 391	A*
upper Cretaceous	—	—	correlation with shelf wells	—	—
basal Middle Cenomanian	97.0	major	not identified	estimated from sea level chart	—
basal Middle Aptian	112	major	projected from shelf and D.S.D.P. wells	good correlation with D.S.D.P. 105 and 391	Beta
basal Hauterivian	126	minor	correlation with shelf well	estimated from sea level chart	—
basal Valanginian	131	major	good correlation to shelf wells, pro- jected from D.S.D.P. wells	fair correlation with D.S.D.P. 391	—
basal Tithonian	141	inter- medi- ate	projected from shelf wells	projected from D.S.D.P. 105	—
basal Oxfordian	149	minor	tied to shelf well	not identified	—
basal Callovian	156	major	tied to shelf wells, projected in deep sea	estimated from sea level chart	—
basal Bathonian	165	minor	estimated from sea level chart	not identified	—
basal Aalenian	174	inter- medi- ate	estimated from sea level chart	not identified	—
basal Middle Pliensbachian	182	minor	estimated from sea level chart	not identified	—
basal Sinemurian	189	major	estimated from sea level chart	not identified	—
basement	—	major	reflexion character	D.S.D.P. 105 and reflexion character	—

determined by direct correlation with shelf wells and projection to JOIDES deep sea cores. In the absence of well correlations, ages are estimated by comparison with the global sealevel curve, figure 1. Table 1 lists the North Atlantic unconformities identified in this report and summarizes data sources for determination of unconformity ages.

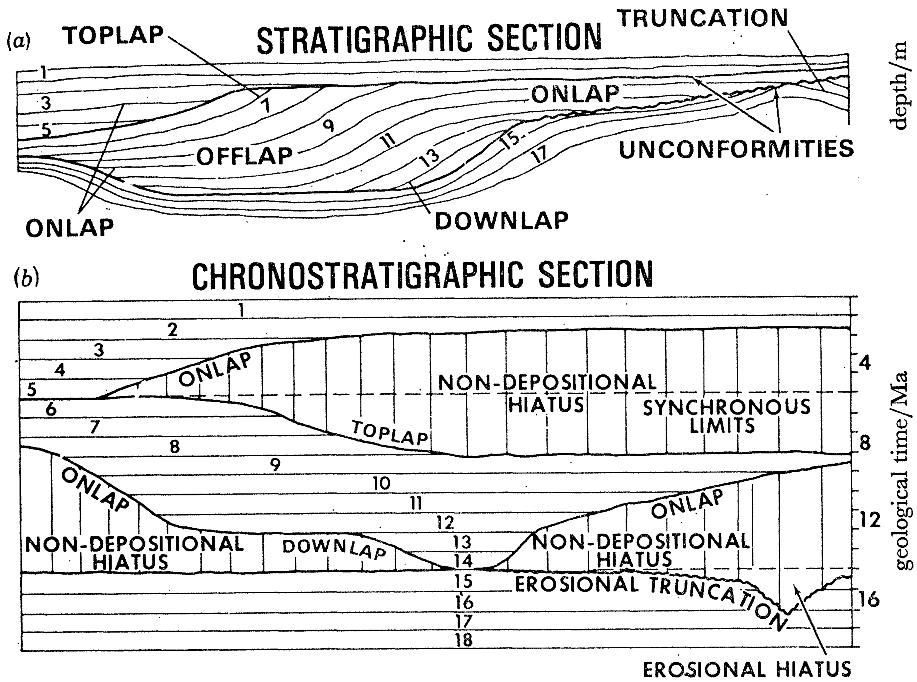


FIGURE 2. Concepts of unconformities and hiatuses developed from stratal patterns (modified from Vail *et al.* 1977*b*, p. 54).

4. SEISMIC RECOGNITION OF UNCONFORMITIES

Reflexion seismic sections which are controlled by well information are ideal tools for analysing unconformities. Unconformities are surfaces of erosion or non-deposition that separate younger strata from older rocks and represent a significant geological time gap (Gary *et al.* 1974). Rocks above and/or below the unconformity surface commonly occur at an angle to the surface, although they may be concordant over relatively large areas. Angular relationships of the underlying strata are commonly due to erosion and truncation of these strata at the unconformity, although sedimentary bypass may produce a similar effect called 'toplap' (Vail *et al.* 1977*a*, part 2). Discordance of the overlying rocks with the surface is related to sedimentary lapouts or terminations of overlying strata. These are called onlap or downlap, depending upon whether they lap out in an updip or downdip direction, respectively (figure 2*a*). All these angular relations are observable on high quality seismic data. Because seismic reflexions are largely produced by stratal surfaces and unconformities with significant velocity–density contrasts (Vail *et al.* 1977, part 5), reflexion patterns portray stratal configurations within the limits of seismic resolution. The recognition of regional unconformities by using seismic onlap, downlap, and truncation patterns is discussed in detail in Vail *et al.* (1977*a*, parts 2 and 6). Toplap commonly defines unconformities that may be local in extent.

In general, the greater the discordance between the strata overlying and underlying an unconformity, the easier the recognition of the unconformity. In areas where palaeotopography and/or structuring are significant, zones of onlap and downlap on seismic data tend to be more obvious, thus making unconformities more easily defined. Also, the greater the magnitude of the relative fall of sea level, the easier it is to detect an unconformity on seismic data by these depositionally related criteria. The relative falls tend to intensify processes that produce onlap, downlap, and erosional truncation by submarine currents or fluvial channelling. Erosional truncation is also more easily recognized where underlying strata have been structurally tilted before erosion.

An ideal situation for observing unconformities is in an area that is undergoing long-term gentle structural deformation. A rapid relative fall of sea level superposed on this long term structural movement may produce an unconformity with erosional truncation of folded strata in a relatively short time. Several unconformities showing truncation may be produced by several cycles of sealevel rise and fall in an area subjected to long-term structural movement. Many geologists tend to relate the unconformities to several short spurts of structural movement rather than to sealevel changes. A good example of this phenomenon is the multiple unconformities related to the Jurassic Cimmarian structural movements in the North Sea (Vail *et al.* 1977*b*).

On a seismic section, the expression of angular unconformities in terms of resultant reflexion character is controlled by a combination of the difference in dip of the strata above and/or below the unconformity, and the velocity–density contrasts which exist both at the unconformity and at the individual stratal surfaces.

A reflexion will not be generated at an unconformity if there is no significant velocity–density contrast across the surface. However, even when there is no reflexion from the unconformity, in many cases it can be located on seismic data by the discordance between the overlying and underlying reflexions. The underlying reflexions will show truncation and/or the overlying ones will show onlap or downlap.

If there is a significant velocity–density contrast across the unconformity, the unconformity will have a reflexion which is either continuous or discontinuous. It will be continuous if the reflexion coefficient at the unconformity is significantly strong or is in phase with concordant reflexions above or below the unconformity. It will be discontinuous if the underlying and/or overlying reflexions are discordant to the unconformity and have reflexion coefficients similar in magnitude to that of the unconformity. Under these conditions, the unconformity reflexion will go in and out of phase with the discordant reflexions and appear as a discontinuous reflexion.

A strong reflexion along an erosional surface may produce a ‘follow-cycle’, or second peak on the waveform, beneath the principal reflexion. Unless removed by processing, the ‘follow-cycle’ may mask underlying reflexions so they appear to terminate against it, rather than against the primary reflexion originating from the unconformity. The actual surface of the unconformity should be defined at the top of the unconformity reflexion. To avoid choosing the ‘follow-cycle’ as the principal reflexion, the unconformity is commonly more correctly positioned by using onlap or downlap of the overlying reflexions rather than truncation of the underlying reflexions.

Unconformities which have large hiatuses in some areas such as along basin margins usually extend laterally into areas where deposition has been more nearly continuous. The hiatus associated with the unconformity gradually decreases as the unconformity approaches conformity (figure 2*b*). A conformity is a stratal surface that separates younger strata from older strata where there is no identifiable geologic time gap. Although the surface is not an unconformity, it is a chronostratigraphic horizon and must be traced with its correlative unconformity in order to define completely the depositional sequence it bounds. In this way, the three-dimensional sequence framework bounded by unconformities and their correlative conformities is completely defined for subsequent seismic facies and structural analysis (Vail *et al.* 1977*a*, part 7).

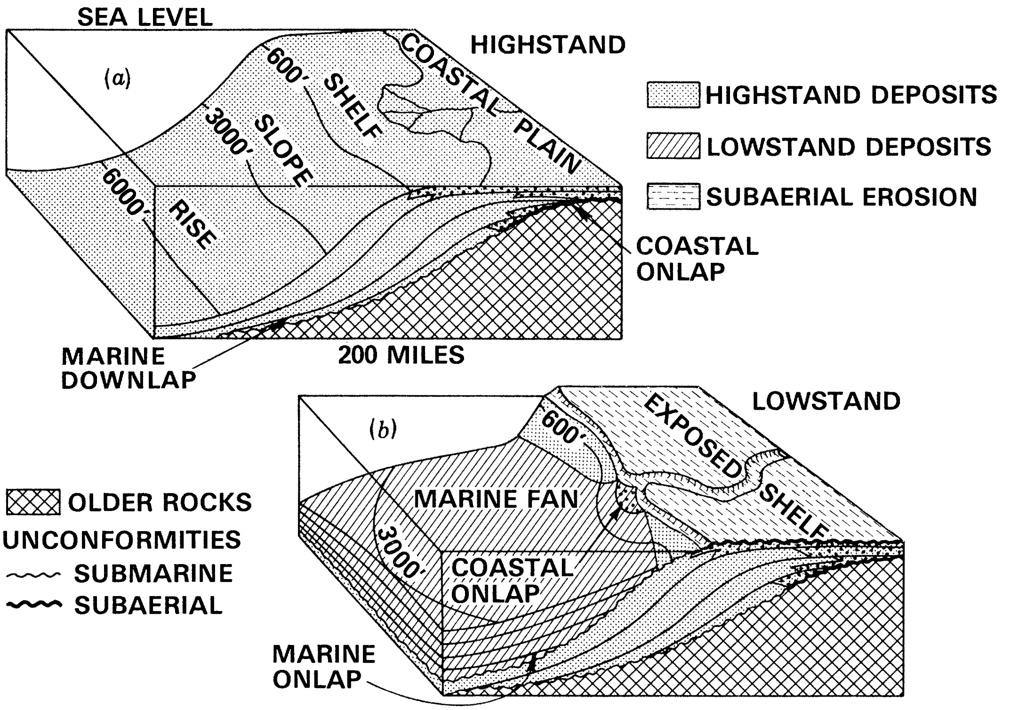


FIGURE 3. Depositional features associated with highstands and lowstands of sea level (from Vail *et al.* 1977*b*, p. 73).

In many cases an unconformity cannot be recognized directly from seismic data when both the overlying and underlying strata are apparently parallel (concordant) to the unconformity. Under these circumstances, well data are needed to demonstrate missing section. Commonly, a concordant unconformity has a significant reflexion produced by the constructive interference of the unconformity reflexion and the reflexions from the adjacent concordant strata. Such reflexions may have an above average amplitude and continuity, and commonly can be correlated over large areas.

Correlation problems exist related to tracing individual unconformities from areas where they have merged. These problems are discussed in §6.

5. Development of deep sea unconformities

Deep sea unconformities are caused by nondeposition and/or erosion by submarine currents. In a general way, highstands of sea level are times of reduced sedimentation in the deep sea, while low and intermediate stands of the sea are times of higher rates of sedimentation (Worsley

1978). According to Worsley's data, this is true for both land-derived clastic sediment and biogenic material. Rona (1973) has illustrated widespread lack of oceanic sediments during early Oligocene and early Palaeocene time. These are, in part, examples of non-deposition during highstands. We believe that during highstands the shelves tend to be flooded and trap sediments, thus reducing the supply to the oceans; during low and intermediate stands the shelves are more exposed and sediments are more readily carried to the ocean basins (figure 3).

In addition to the variations in rates of sedimentation, there is commonly a significant change in depositional facies between highstand and lowstand deposits (figure 3 and Vail *et al.* 1977*a*, part 3). Along the margins of ocean basins, highstand deposits commonly consist of sediments that have prograded across the shelf into deep water. In the basins, highstand deposits are typically hemipelagic, and characteristically drape over the underlying topography. Contourites also appear to be related to highstands. Lowstand deposits commonly occur as marine fans characterized by onlap of thick marine shales in a landward direction and downlap in a seaward direction. Many examples of these changes in depositional facies are shown in §8.

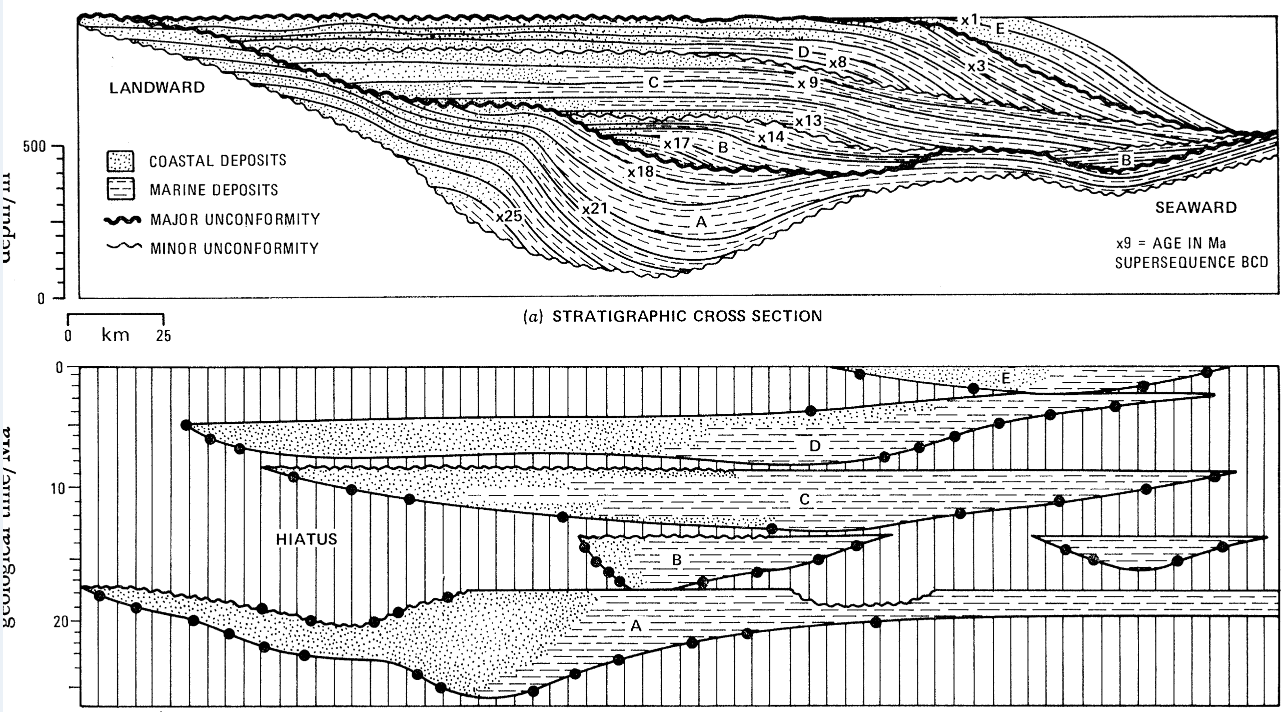
Major submarine erosional unconformities which are marked by truncation are common phenomena along the borders of ocean basins. The submarine erosion appears to be caused not only by downslope turbidity currents, but by major deep ocean boundary currents (Tucholke 1978; von Rad, this volume).

Seismic stratigraphic evidence indicates that most of the erosion along major submarine unconformities, such as those described in this report, takes place during geologically short periods of time (on the order of one million years). These periods of major erosion appear to coincide with the relative lowstands of sea level on figure 1, although not enough well data are available at this time for positive proof. The basal middle Chattian (29 Ma) unconformity discussed later in §8 and shown on tables 1 and 2 is a good example.

6. Dating unconformities

The geological time significance of an unconformity is that all the rocks below the unconformity are older than the rocks above it. The ages of the strata above and below the unconformity will vary, of course, if the areal extent of erosion or non-deposition varies with time. As discussed in Vail *et al.* (1977*a*, part 5), seismic reflexions are produced primarily from stratal surfaces and from unconformities with sufficient velocity–density contrasts to cause coherent seismic reflexions. Stratal (bedding) surfaces represent ancient surfaces of deposition and therefore are essentially time synchronous. The duration of the hiatus associated with an unconformity is variable, but the unconformity itself is a geologic time boundary because it separates rocks of different ages and does not cross other chronostratigraphic surfaces. Although time lines merge along an unconformity, none actually crosses the unconformity. For these reasons, unconformity reflexions are not diachronous. By carefully correlating unconformities, a sedimentary section can be subdivided into genetic depositional sequences that have chronostratigraphic significance (see Vail *et al.* 1977*a*, part 2). Reflexions derived from hydrocarbon or other fluid boundaries, or diagenetic surfaces, may be diachronous.

An unconformity is most accurately dated by establishing ages of overlying and underlying strata at points where the hiatus along the unconformity is least. Ideally this point is where the surface becomes a conformity. In many cases, however, conformity is not reached and the point of minimum hiatus is used. A hiatus is the total interval of geologic time that is not represented by strata at a specific position along a stratigraphic surface. The hiatus may be attributable either to erosion or to non-deposition of strata or to both. The distinction is based on whether the strata below the unconformity terminate by erosional truncation or whether the strata above the unconformity terminate depositionally by onlap or downlap (figure 2*b*). Successive terminations of older to younger strata by onlap or downlap above the unconformity produce an increasing depositional hiatus in the direction of termination. Conversely, successive terminations of older to younger erosionally truncated strata below the unconformity produce a decreasing erosional hiatus in the direction of termination.



(*b*) CHRONOSTRATIGRAPHIC CHART

Figure 4. Methods of dating and naming unconformities (modified from Vail *et al.* 1977*b*, p. 78).

Special dating problems occur when several unconformities coalesce into a major one with a large hiatal gap (figure 4, the unconformity below B). In order to date the major unconformity, the ages of the individual merged unconformities must be known. Therefore, the major unconformity must be traced to an area where the stratigraphic section is most continuous and the individual unconformities can be separated and dated. Once the ages and lateral stratigraphic relationships of the involved unconformities are known, the dating procedure for the merged unconformity varies, depending on whether the study area is on the landward or seaward side of the area of most continuous stratigraphic section.

Basin margin areas characteristically have many unconformities that merge landward from the area of the most continuous stratigraphic section, as illustrated in figure 4. In such basin margin areas, the most areally restricted sequences (sequence B in figure 4) are the first to pinch out depositionally by onlap in a landward direction, causing their bounding unconformities to coalesce, and increasing the magnitude of the hiatal break associated with the resulting unconformity. Similarly, other more widespread sequences (C and D) may pinch out landward, increasing the hiatus even more. Erosional truncation associated with the unconformity may cause the unconformity to coalesce with underlying older unconformities, also increasing the hiatal break along the merged unconformity. As these unconformities coalesce in a landward direction, the major unconformity is designated and named as the one that occurs at the base of the most restricted sequence (sequence B of figure 4). Unconformities that coalesce with the major unconformity due to onlap are considered minor (figure 4).

Ocean basins are starved basins and commonly have many unconformities that merge seaward from the thick sedimentary sections bordering the continental shelves, as illustrated in figure 4. Characteristically, the thickest stratigraphic sections also have the greatest number of unconformities. In most cases the minor unconformities are only recognizable in areas of thick sediments. Durations of hiatal gaps along unconformities increase in a seaward direction owing to non-deposition, submarine erosion, and coalescence of unconformities. As several unconformities coalesce into one major unconformity in a seaward direction, the major unconformity is designated on the same basis as the unconformities that extend landward, i.e. as the one at the base of the most areally restricted sequence on the landward side of the area of the most continuous section. This makes the determination of major and minor oceanic unconformities difficult when several have coalesced, since the data commonly are not available to trace them from the ocean basins to shelf areas.

The problem is magnified because the distal (seaward) depositional lapout of the individual sequences is controlled largely by sediment influx, whereas the landward lapout is controlled largely by the relative position of sea level (see Vail *et al.* 1977*a*, part 3). Because of the variability of sediment influx, the seaward pinchout of a depositional sequence is much less predictable than the landward pinchout. Some general characteristics, however, aid in separating major and minor unconformities. Most major unconformities along the borders of ocean basins are characterized by truncation caused by submarine erosion and are overlain by submarine fans exhibiting deep marine onlap and downlap. Minor deep marine unconformities are characterized by downlap and more subtle onlap associated with sediments that have prograded across the shelf into the ocean basins. These minor unconformities tend to coalesce with the major unconformities.

Pitfalls in correlation and dating exist when individual unconformities and reflexion events are traced away from the area where they are merged, especially in deep sea deposits where extensive onlap and downlap are present. Without well control, it is difficult to determine ages of individual minor unconformities or strong reflexions as they 'split off' the major unconformity in the direction of thickening. The commonest seismic correlation error, in our experience, occurs when an unconformity reflexion is traced laterally to a prominent reflexion which onlaps the unconformity and the correlation surface is then carried onto the onlapping reflexion rather than on the underlying unconformity. In such cases, seismic loop correlations will close because no reflexions have been crossed, but the dating of the underlying strata is incorrect. An example of this problem can be illustrated on figure 4. Suppose the basal B unconformity (underlying sequence B) has been identified by well control near the seaward (right) edge of figure 4. This unconformity can be traced landward past the position where a thin distal part of sequence B pinches out against a small palaeotopographic high. It is a common mistake to then correlate the basal C unconformity with the similar basal B unconformity at the point where sequence B reoccurs landward of the palaeotopographic high. For proper

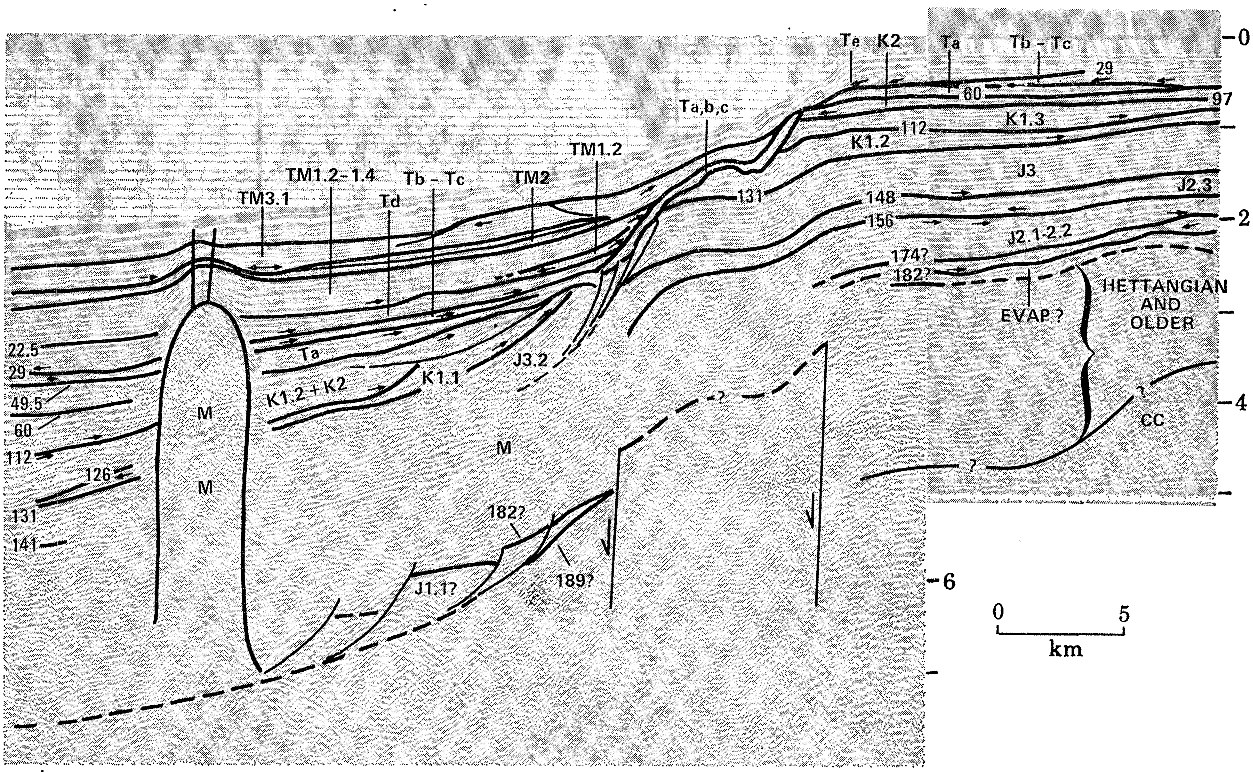


Figure 5. Eastern Atlantic African continental shelf and slope 24-fold c.d.p. seismic section showing deep sea unconformities. See figure 1 for identification of interval and unconformity age notations.

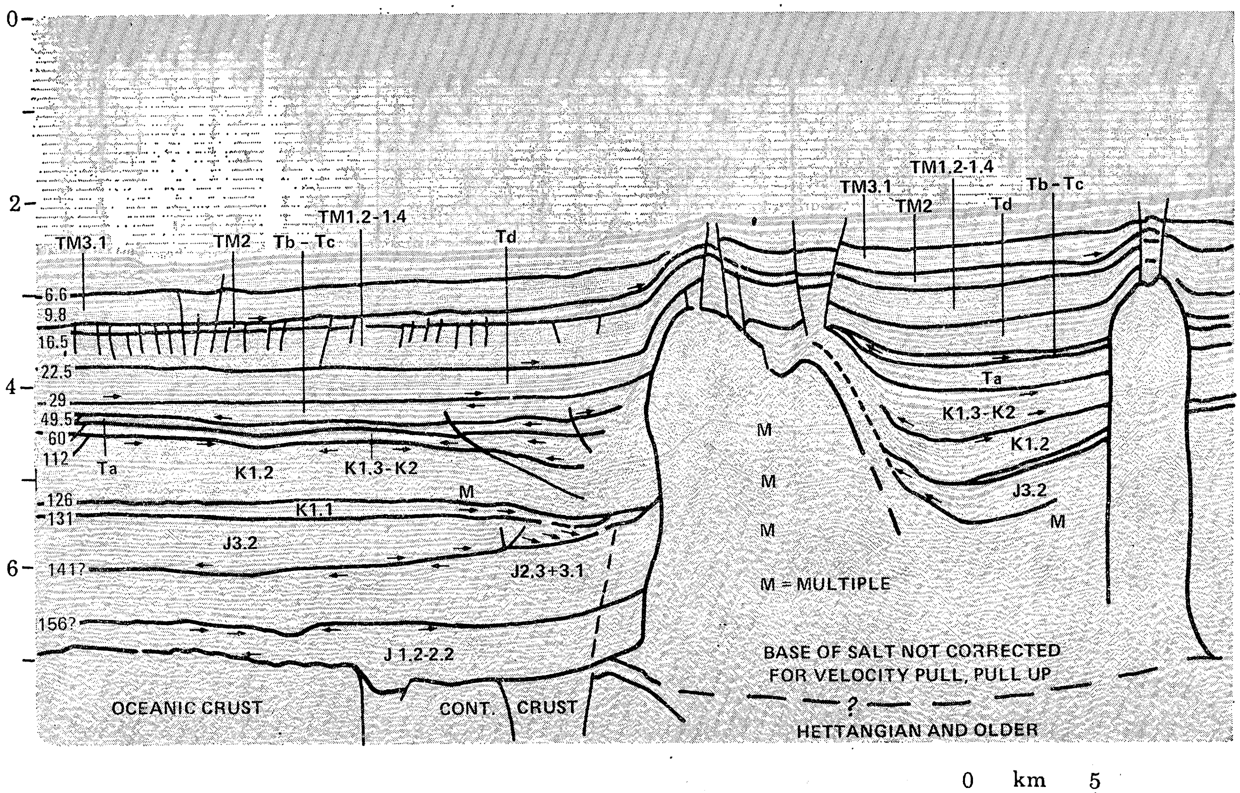


Figure 6. Eastern Atlantic African continental rise 24-fold c.d.p. seismic section showing deep sea unconformities. See figure 1 for identification of interval and unconformity age notations.

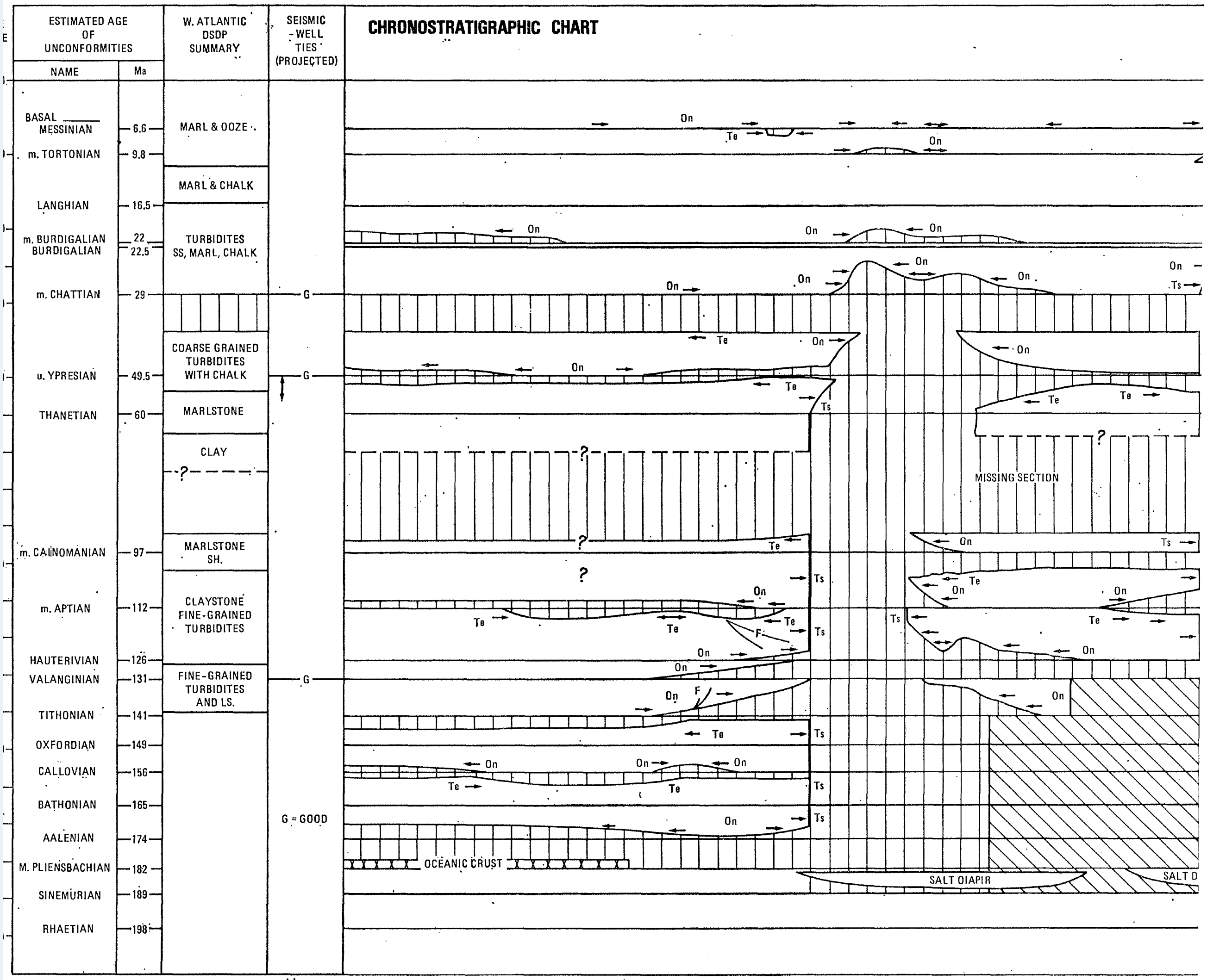


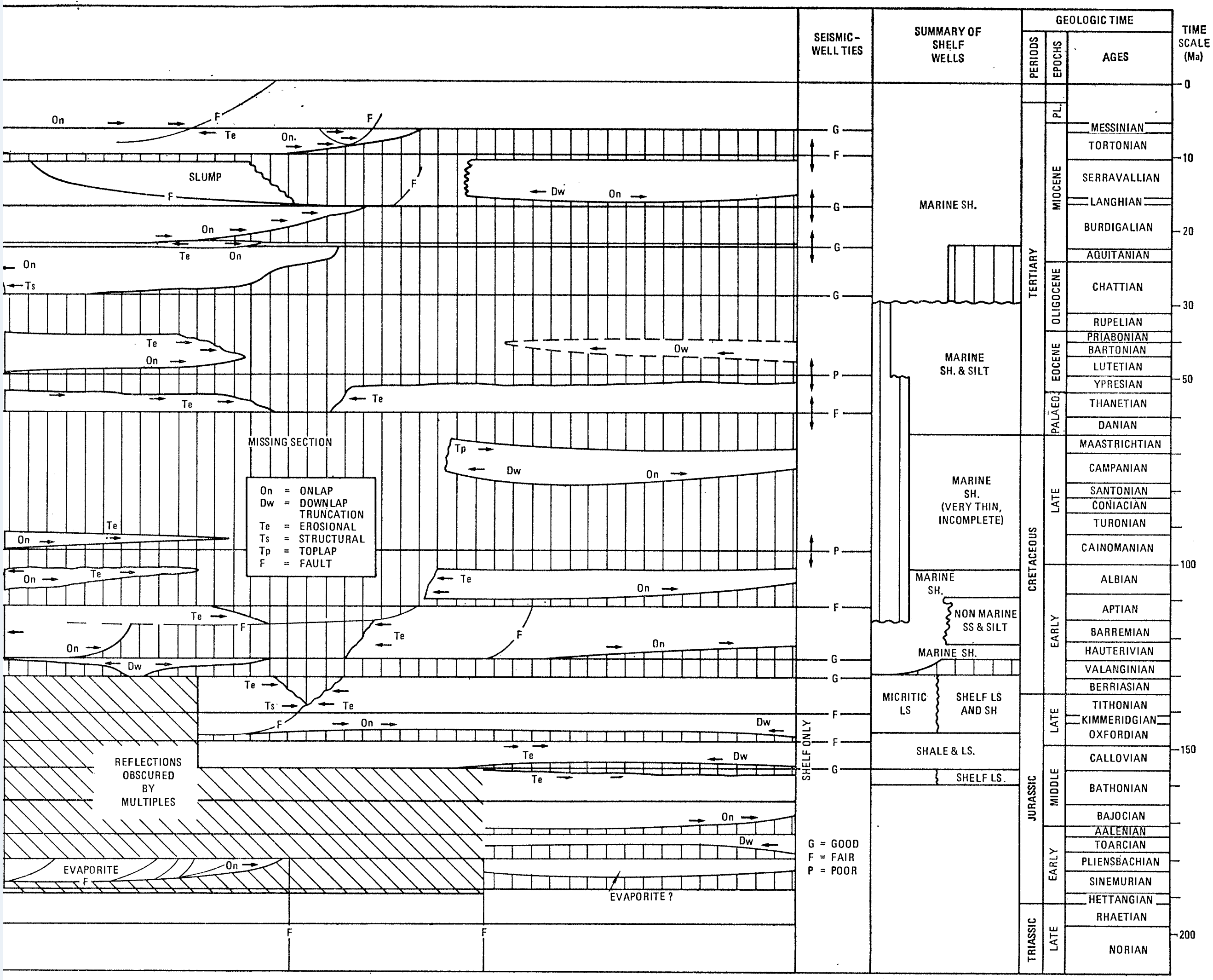
FIGURE 7. Chronostratigraphic chart constructed from seismic sections shown on figures 5 and 6.

correlation the basal B unconformity should be carried below the onlapping and downlapping reflexions of sequence B.

An example of this problem is thought to occur just beyond the seaward end in figure 9. Shipley & Watkins (1978) traced the β reflexion southwestward from D.S.D.P. 105 to the seismic line on figure 9. Their correlation of β was higher on this line because it appears they correlated from the basal mid-Aptian unconformity to the top of an onlapping sequence of Aptian–Albian age.

In our opinion the best way to avoid this correlation problem is to identify all the unconformities on the section and determine if they are major or minor. In this way, the addition of new unconformities can be recognized and problems with reflexion character correlations can be sorted out.

When dating unconformities it is very important to tie the wells to the seismic sections as accurately as possible. The best possible palaeontologic control should be obtained at least to



the level of ages in the pre-Tertiary and to the planktonic zone level in the Tertiary. Small errors at the well can cause major correlation errors away from the well as the intervals thicken and thin.

7. Seismic stratigraphic nomenclature

A major problem being discussed by deep sea stratigraphers is how to name the seismic–stratigraphic surfaces, intervals, and facies. Our experience is that names or colours for specific horizons and intervals, such as the deep sea seismic symbols listed in table 1 or the interval names sued in Shipley *et al.* (1978), are useful on a preliminary basis. However, once the geologic ages of the strata causing seismic reflexions are known, we believe the most information is precisely conveyed by naming the unconformities after the oldest strata above the unconformity (e.g. the basal Valanginian unconformity), and informally naming the intervals between the unconformities with symbols (e.g. J 3.2), as shown in figure 1 and described in Vail *et al.* (1977*a*, parts 4 and 8). Unconformities are designated on the seismic sections by age in millions of years (Ma).

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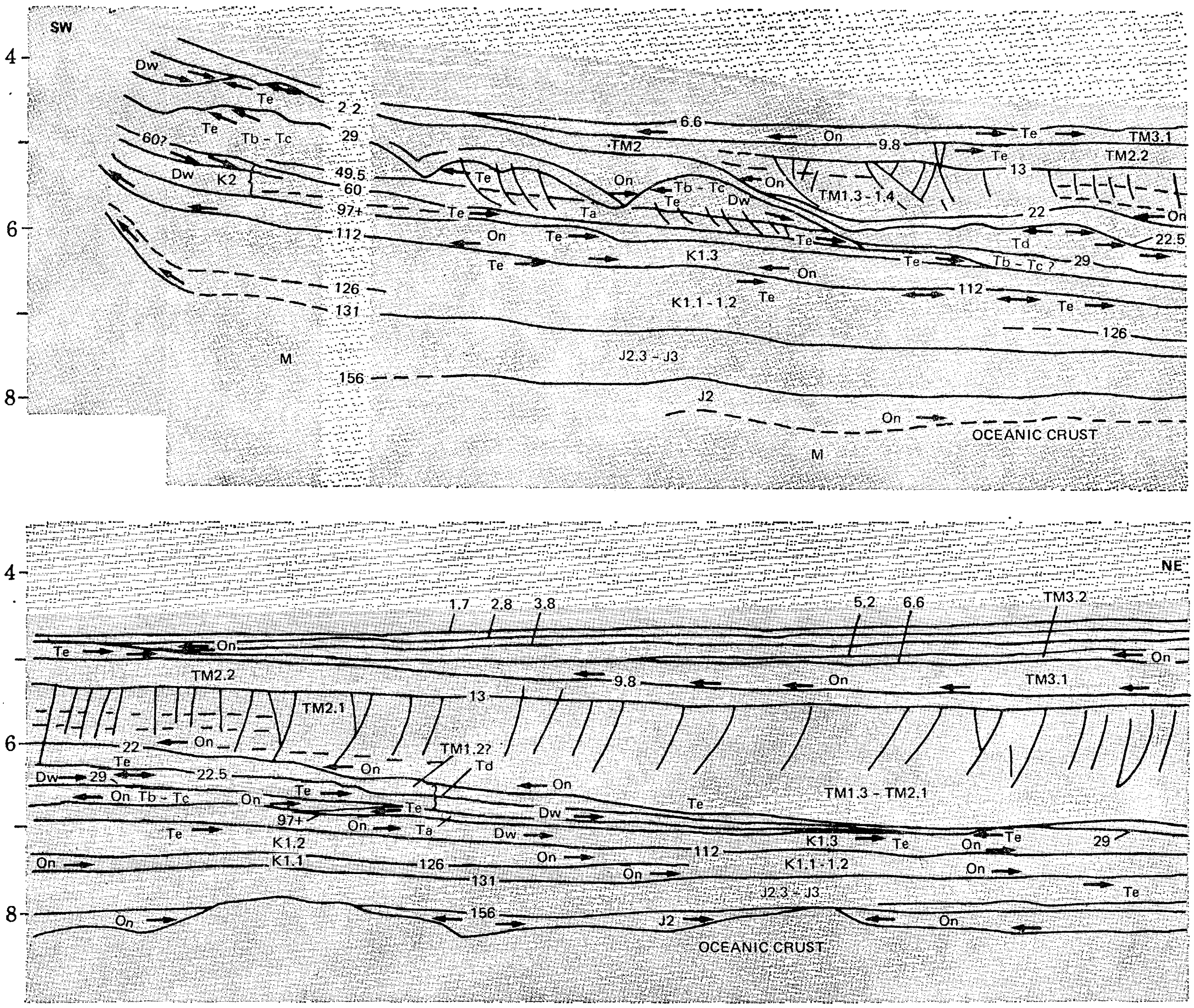

FIGURE 8. Western Atlantic Blake 12-fold c.d.p. seismic section showing deep sea unconformities. See figure 1 for identification of interval and unconformity age notations.

Our experience also indicates that when interpreting geologic facies from seismic data, it is very important to define first the particular seismic parameters making up a given seismic facies from which geologic facies are to be interpreted. These seismic criteria are objectively defined and presumably identifiable to other interpreters. Interpretation of geologic facies from seismic facies is more subjective (see Vail *et al.* 1977*a*, parts 6, 7, 9 and 10). Certain characteristic geologic facies, such as the Albian–Aptian black shale or Neocomian limestone, can be referred to by age and rock type.

Formal formation names for the deep sea stratigraphy from D.S.D.P. cores of the western Atlantic are currently being proposed by Jansa *et al.* (1978). These formal names may serve a useful descriptive purpose, but it must be remembered that formations such as the Blake–Bahama Formation are lithostratigraphic units and may transgress time. This may lead to serious interpretation errors if not recognized (see Vail *et al.* 1977*a*, part 5).

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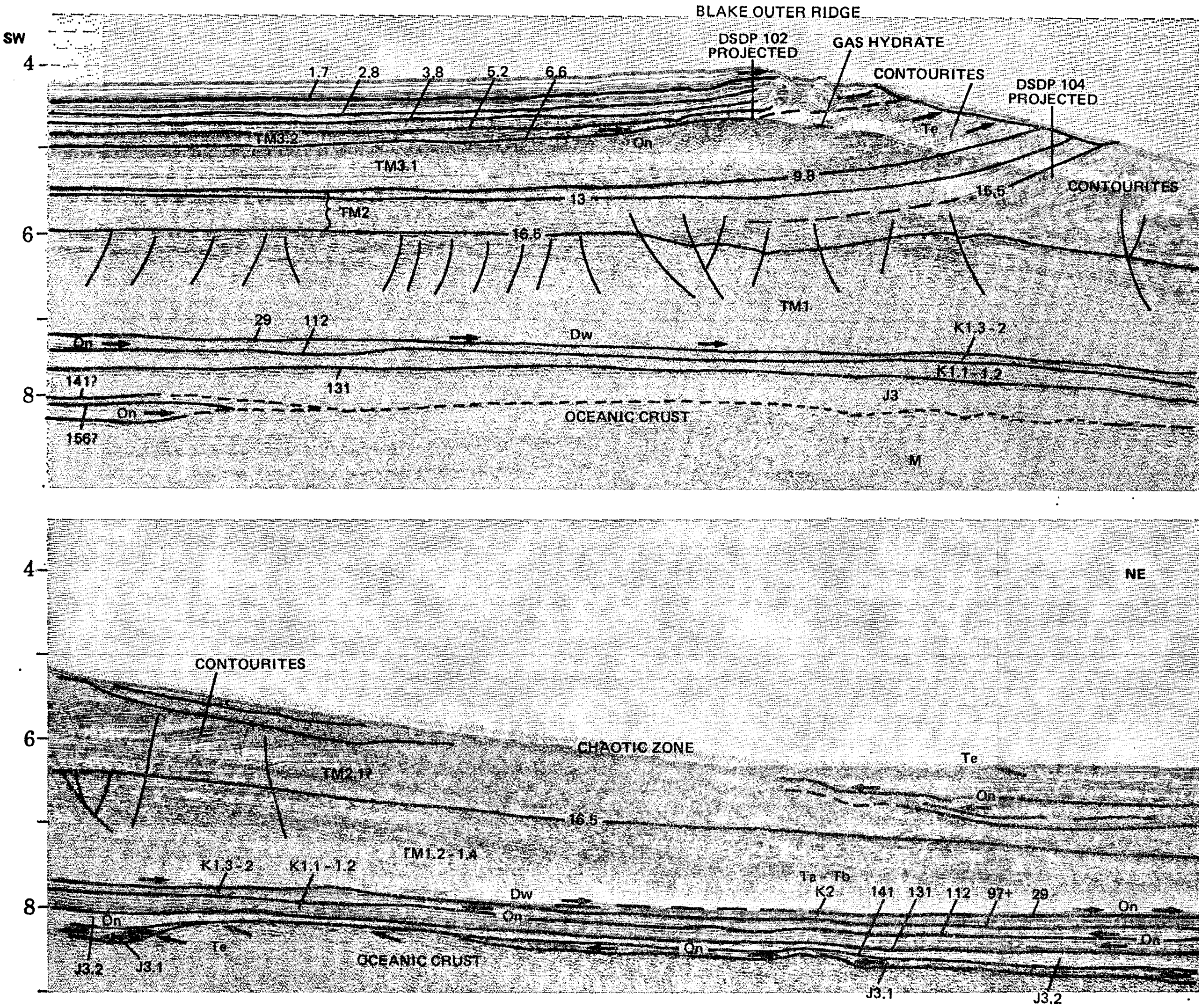

FIGURE 9. Western Atlantic Blake outer ridge 12-fold c.d.p. seismic section showing deep sea unconformities. See figure 1 for identification of interval and unconformity age notations.

8. Seismic expression of North Atlantic unconformities

Seismic sections from the eastern Atlantic continental margin off West Africa (figures 5 and 6), and the western Atlantic Blake Continental slope (figures 8 and 9), illustrate how unconformities can be recognized in the deep sea by analysing patterns of onlap, downlap, and truncation. Chronostratigraphic charts, figures 7 and 10, show the distribution of the depositional sequences and hiatal breaks in terms of geologic time, as well as summarizing the seismic well ties and projections.

Seismic sections (figures 5, 6, 8 and 9) are used to show the seismic stratigraphic interpretation methods of identifying deep sea unconformities and developing a stratigraphic framework. This report does not represent an in-depth geologic study of the respective margins. Data for dating the unconformities are very inadequate, as discussed earlier, but the unconformities that could be tied or projected to well control are indicated. No wells are located

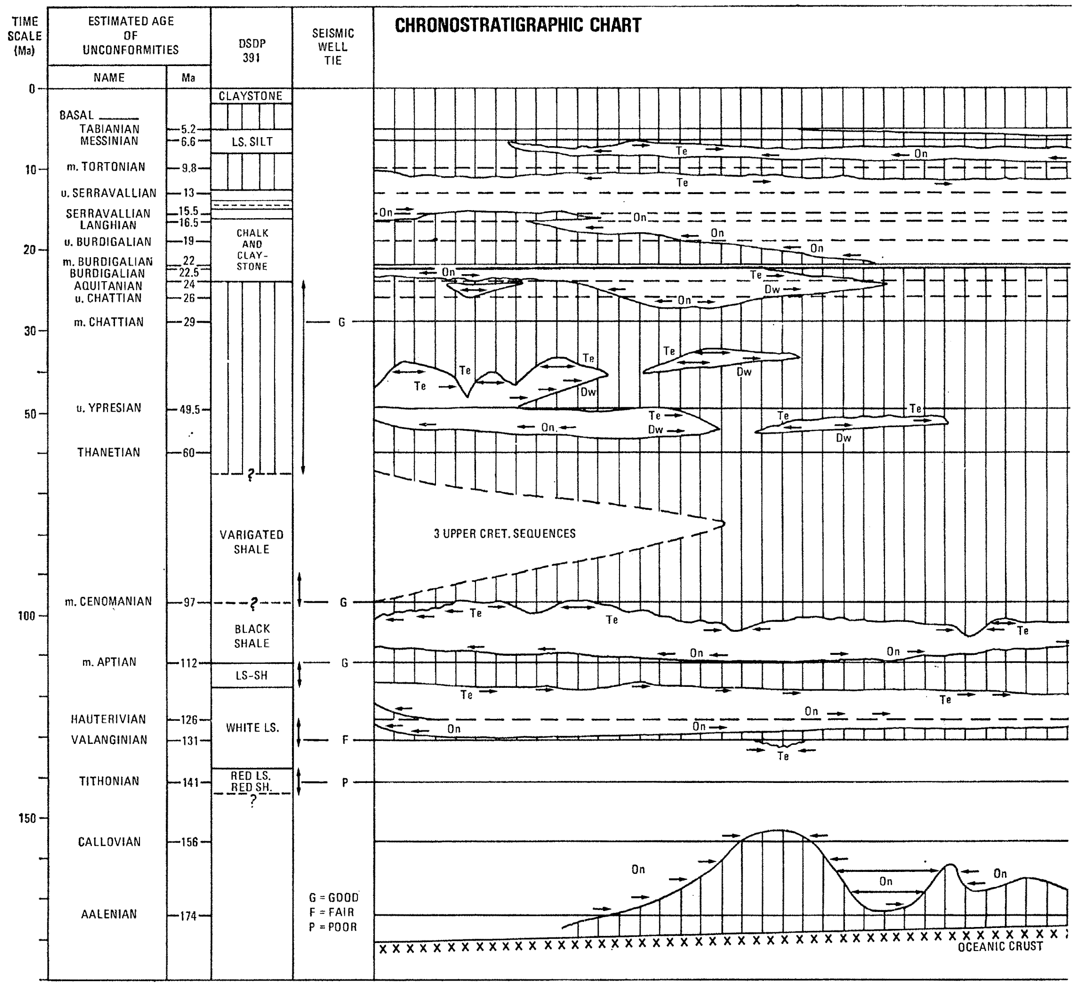

Figure 10. Chronostratigraphic chart constructed from seismic sections shown on figures 8 and 9.

directly on either of these lines. Therefore, at best, the surfaces are correlated to the wells on the basis of additional seismic data, which in some cases was of poor quality or had correlation problems.

For more accurate results a regional seismic grid tied directly to all available well control is necessary. Therefore the interpretations shown on these sections are subject to revision as the existing data are more thoroughly analysed and new data becomes available.

The interpretations were made on large scale seismic sections. Unfortunately, much of the detail of this interpretation is lost when the sections are reduced to page size for publication.

Many of the unconformities defined on the global sea level chart (figure 1) have been tentatively identified on the seismic sections from both areas. Within seismic resolution the seismic sections tend to support the contention that the major unconformities occur at the same time. Good examples are the basal Valanginian, basal middle Aptian, basal middle Chattian and basal Burdigalian (see figures 5–10). The minor unconformities are recognized where rates of deposition are high and the seismic data quality is good.

Submarine erosion evidenced by significant truncation was identifiable on most of the major unconformities (table 2). One minor Jurassic unconformity also showed evidence of

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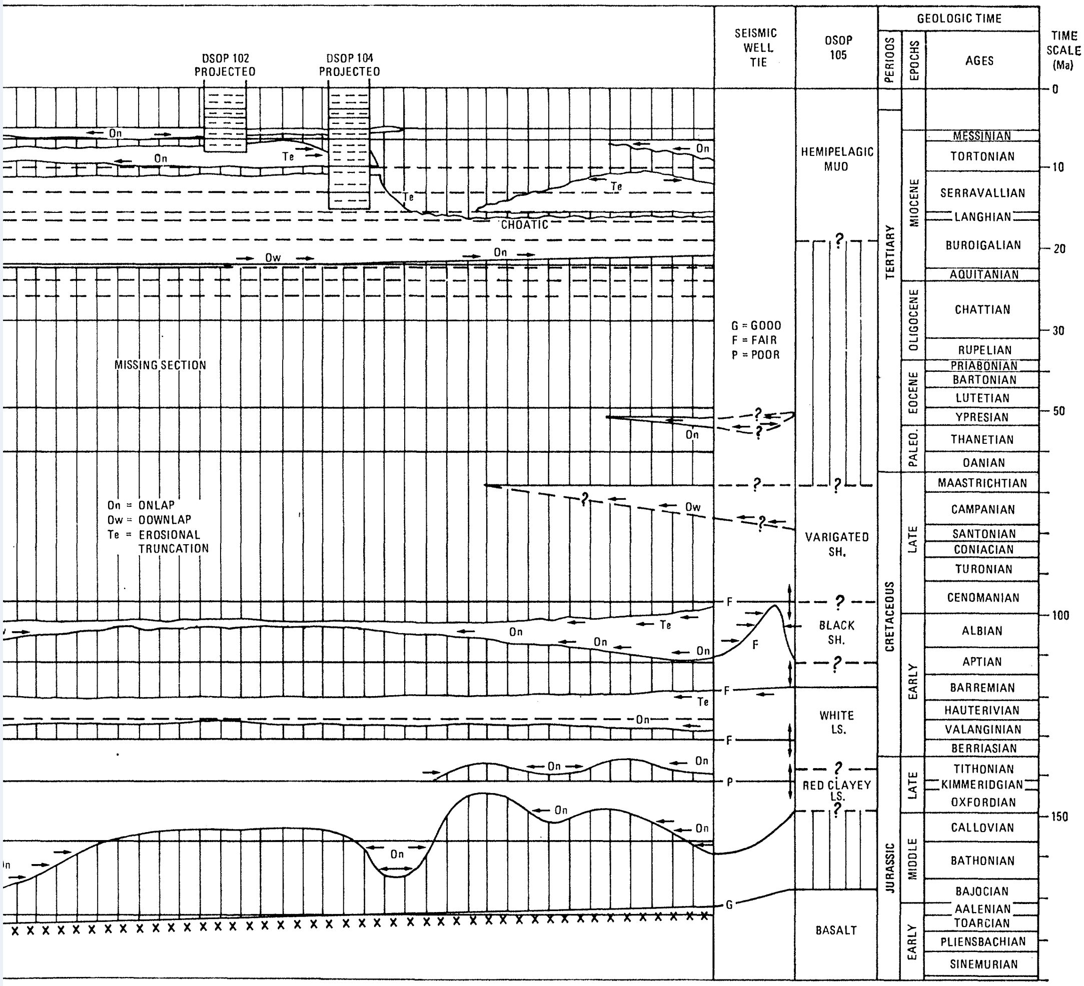

truncation in the thick Jurassic section off West Africa. Since all these erosional unconformities are separated by periods of deposition, major erosional activity must be periodic. Although confirming well data are not completely adequate, the periods of greatest erosion appear to be associated with the greatest relative falls of sea level.

Truncation along updip surfaces of contourite deposits appears to be due to sedimentary scour and bypass associated with deposition of the contourites over fairly long periods of time. Pronounced erosion may later modify the contourite depositional patterns.

Marine onlap suggestive of deep marine fans (figure 3) is present above many of the major unconformities. Examples are the Valanginian (K1·1), upper Chattian (TO2), Burdigalian (TM1·3), upper Tortonian (TM3·1), and Messinian (TM3·2). Offlap, as shown in figure 3, and/or draping suggestive of highstand deposits are present during the late Jurassic and Neocomian of the Blake Continental Margin, but not West Africa. They are also present in the latest Cretaceous, Paleocene – early Eocene of West Africa, and in the middle Miocene of both sections. The contourites of the Blake Outer Ridge also appear to be associated with the middle to late Miocene high to intermediate sea level stands.

Slump features are not especially prevalent. Two significant slumps are interpreted on the continental slope of the West African section; one of middle Miocene (TM2) and the other of

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Aptian–Neocomian (K1·2) age (figure 5). The chaotic seismic facies pattern near the east side of the Blake Continental Margin section is interpreted to result from an eastward slump of the Blake Outer Ridge near the end of middle Miocene time. Other evidence for this slump is the large number of tensional faults of Miocene (TM1+TM2) age shown in figures 8 and 9.

Table 2. Unconformities showing evidence of erosional truncation

unconformity	Blake continental margin	West Africa
basal Messinian – 6.6	×	×
basal middle Tortonian – 9.8	×	—
basal middle Burdigalian – 22.0	—	×
basal middle Chattian – 29	×	×
basal uppermost Ypresian – 49.5	×	×
basal Thanetian – 60	—	×
basal middle Cenomanian – 97	×	—
basal mid Aptian – 112	×	×
basal Valanginian – 131	×	—
basal Tithonian – 141	—	×
basal Callovian – 156	—	×

Many interesting stratigraphic and structural features are shown in these two seismic sections and their accompanying chronostratigraphic charts, but are not discussed in detail. A large-scale presentation of the entire Blake Margin seismic sections and a more detailed discussion is included in Shipley *et al.* (1978) and Buffler *et al.* (1978). As stated earlier, the sections (figures 8 and 9) are shown to encourage deep sea seismic stratigraphic interpretation rather than to solve specific geolocial problems.

9. Application of unconformity concepts for interpreting deep-sea seismic data

Recognition and correlation of unconformities is only the first step in a seven-step procedure for interpreting geologic age, depositional environment and facies in the deep sea. The resulting interpretations provide information for the development of a chronostratigraphic framework, the geological history, and the optimum location for drilling D.S.D.P. holes in sedimentary sections.

The recommended interpretation procedure consists of the following seven steps:

(1) identification and regional correlation of unconformities;
(2) estimation of geologic age from well control and charts of global changes in sea level;
(3) determination of regional distribution of genetic depositional intervals and hiatal gaps;
(4) definition of seismic facies;
(5) comparison of seismic facies to relative changes of sea level;
(6) interpretation of depositional environment and lithofacies;
(7) construction of chronostratigraphic sections and seismic facies maps.

This approach is discussed in more detail in Vail *et al.* (1977*a*, part 7).

In order to make the best seismic stratigraphic interpretation, it is important to obtain the best quality seismic data and highest resolution that are practical. Seismic sections must be clearly presented with only a small vertical exaggeration to avoid miscorrelation. The scale should be large enough to mark individual reflexions. Best results are obtained if detailed grids are tied with regional shelf–slope–basin profiles utilizing multichannel data, where necessary, and all available well control.

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Discussion

D. H. Matthews, F.R.S. (*Department of Geodesy and Geophysics, Madingley Road, Cambridge*). Can I have heard Dr Vail right? He said that seismic reflexions, correlated across a record, correspond to chrono-stratigraphic boundaries (bedding planes) and may be traced through changes of facies? I have been responsible for teaching several generations of undergraduate geologists that reflexions are solely due to changes in accoustic impedance, the product of velocity and density, and can *not* simply be interpreted as a geological section.

P. R. Vail. I would agree with Dr Matthews that seismic reflexions are generated by impedance contrasts. Our research in seismic stratigraphy, however, indicates that these impedance contrasts are produced at stratal (bedding) surfaces or unconformities. Since stratal surfaces are depositional surfaces, they are essentially time-synchronous. Reflexion continuity will cross facies changes in the same manner as stratal surfaces. Reflexion character and waveform will change, however, as the reflexion coefficients and bed spacing change with the facies. Unconformity reflexions are not usually time-synchronous, but they are time boundaries, since all the rocks above an unconformity are younger than those below it. We conclude that a seismic section portrays the chronostratigraphy, but the resolution, of course, is limited by the seismic system and the geology. A more detailed discussion of this subject is presented in Vail *et al.* (1977, part 5).

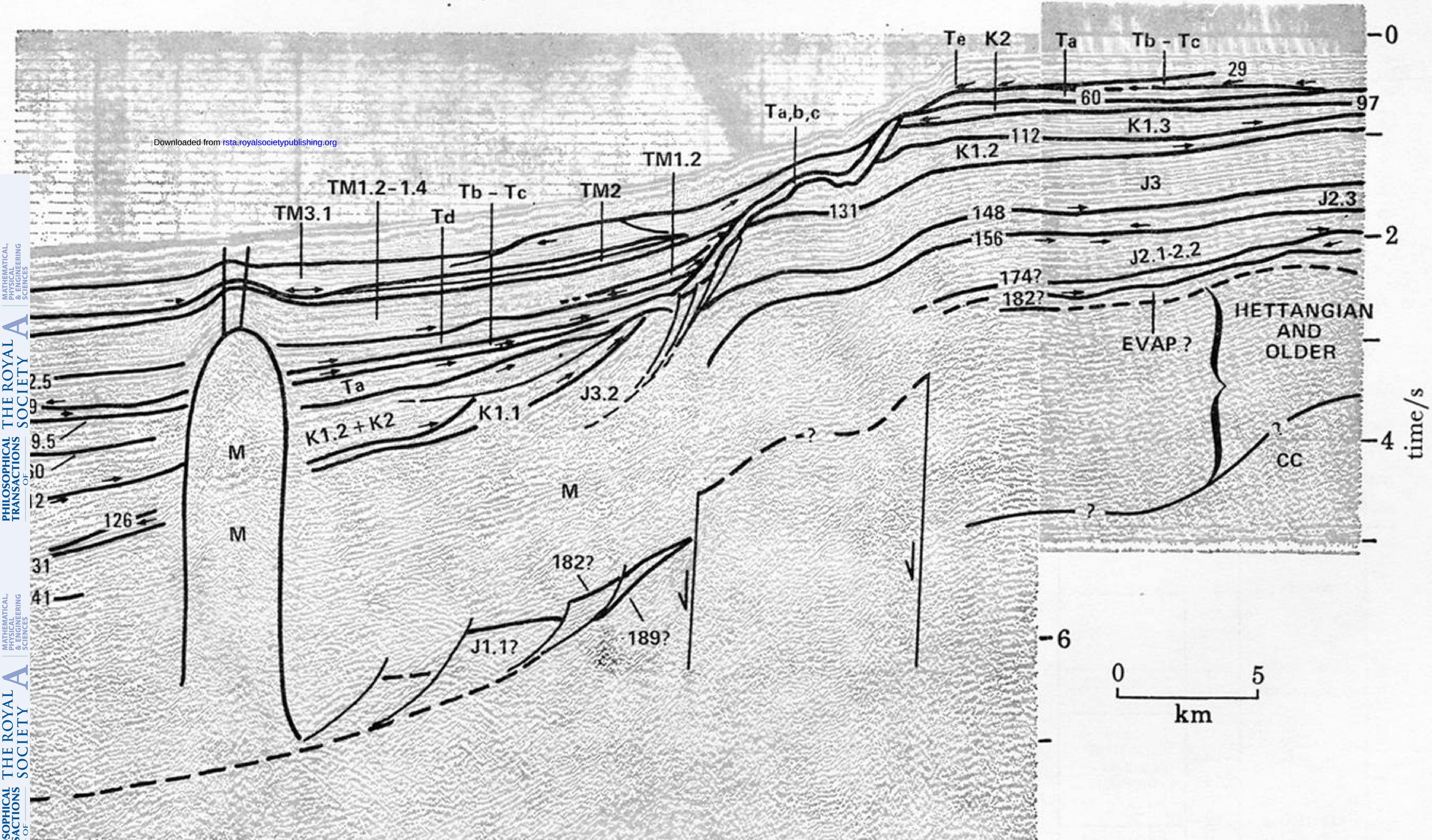

FIGURE 5. Eastern Atlantic African continental shelf and slope 24-fold c.d.p. seismic section showing deep sea unconformities. See figure 1 for identification of interval and unconformity age notations.

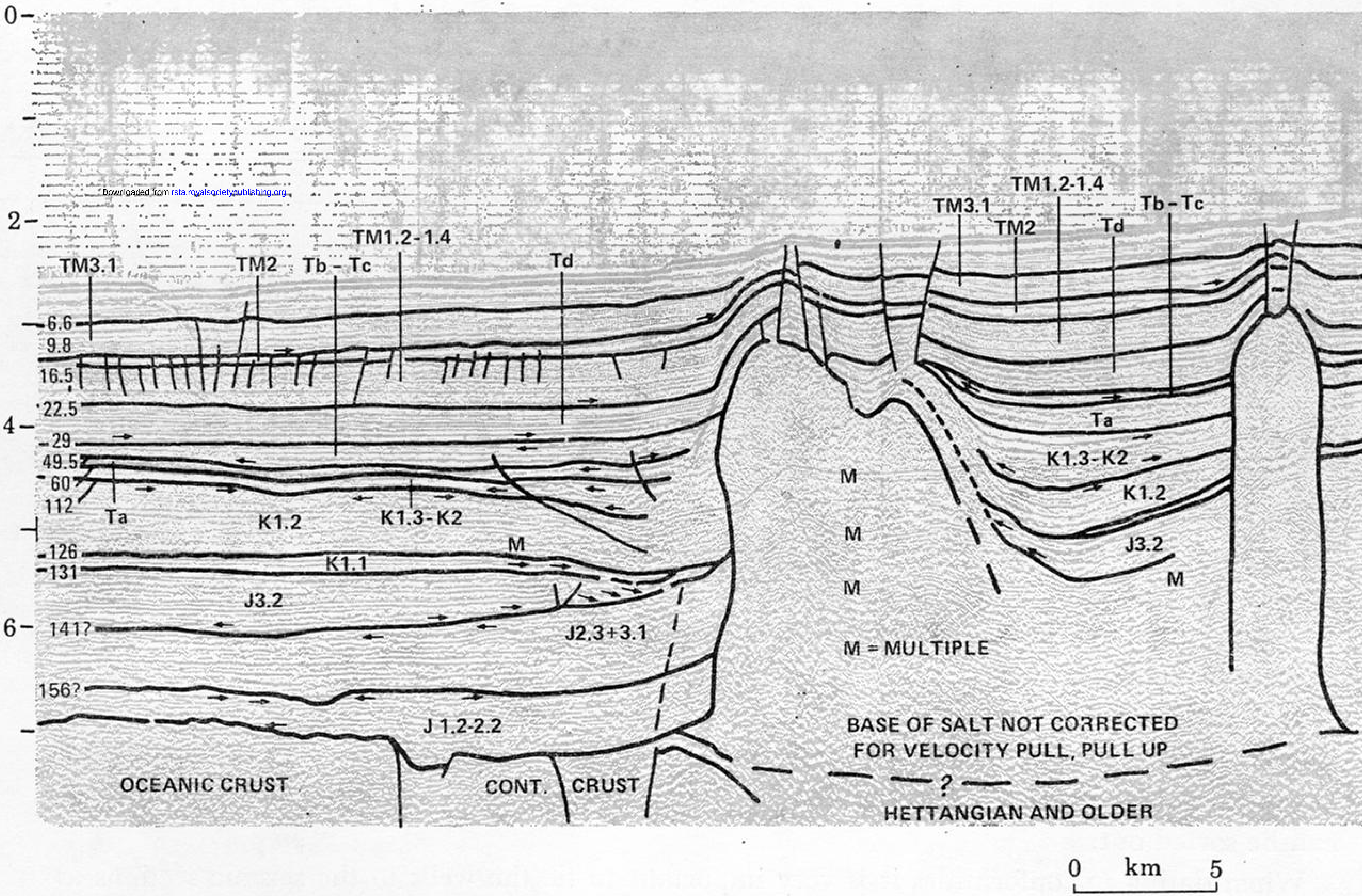

FIGURE 6. Eastern Atlantic African continental rise 24-fold c.d.p. seismic section showing deep sea unconformities. See figure 1 for identification of interval and unconformity age notations.

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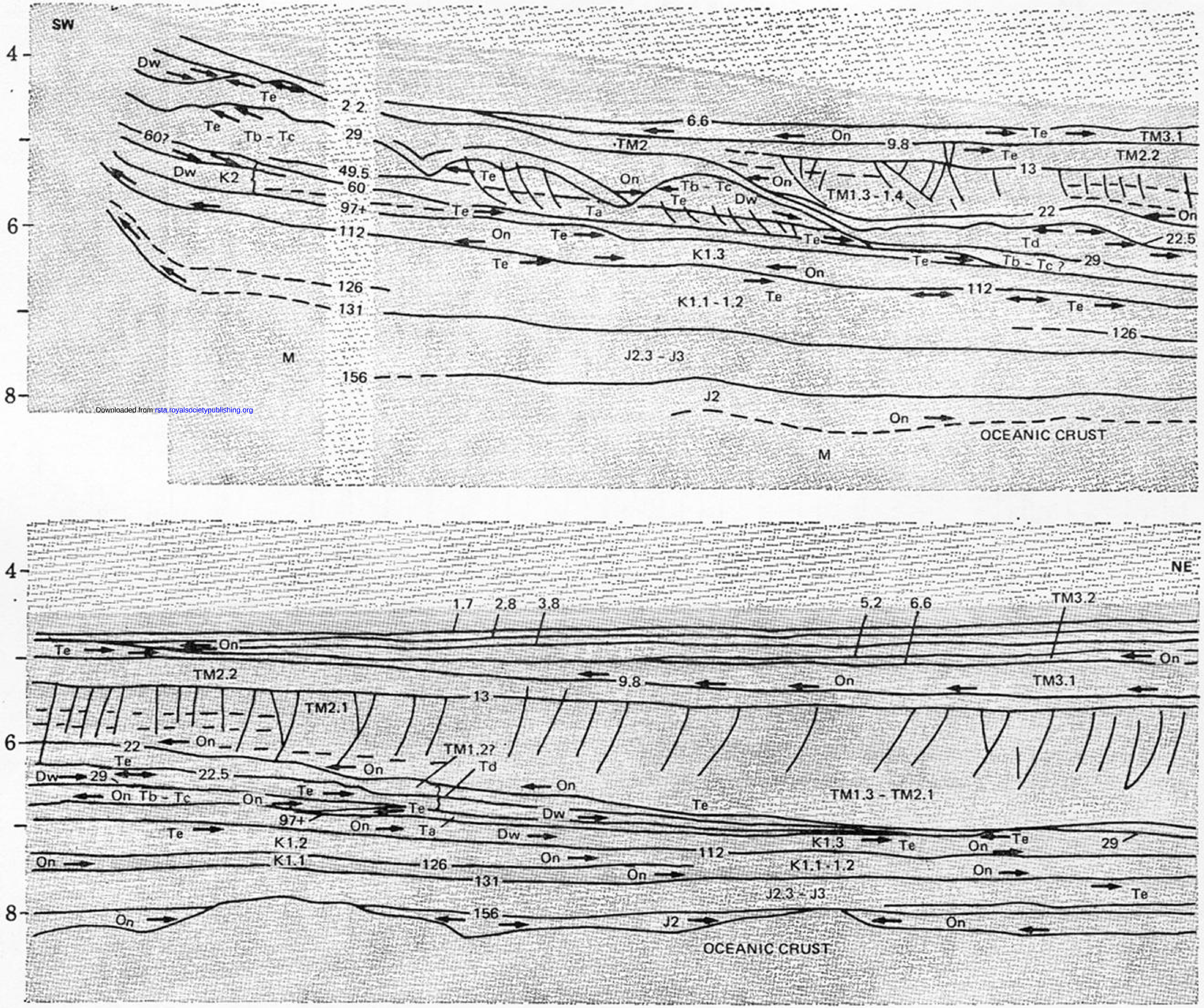

FIGURE 8. Western Atlantic Blake 12-fold c.d.p. seismic section showing deep sea unconformities. See figure 1 for identification of interval and unconformity age notations.

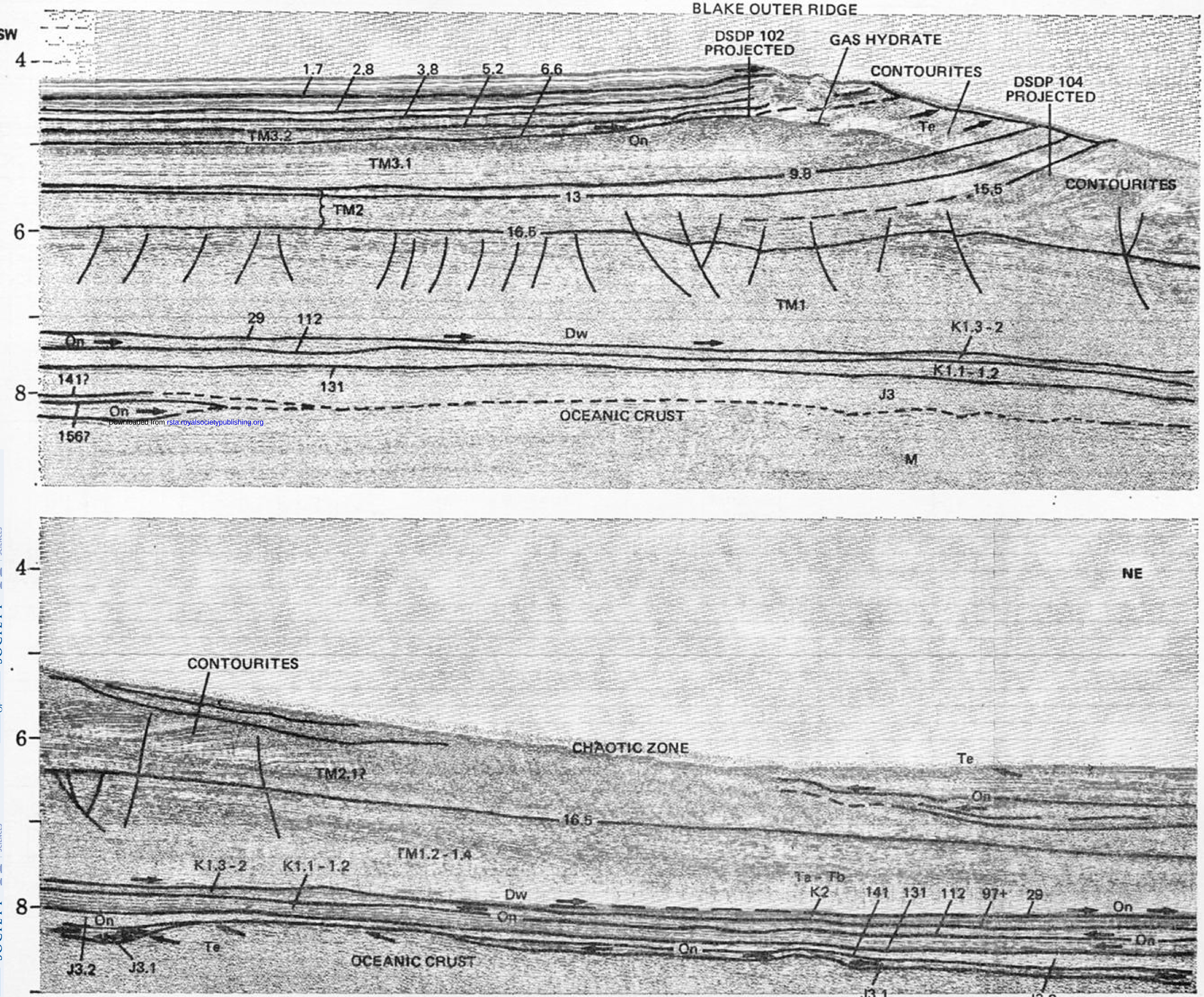

FIGURE 9. Western Atlantic Blake outer ridge 12-fold c.d.p. seismic section showing deep sea unconformities. See figure 1 for identification of interval and unconformity age notations.