

# THE GEOLOGICAL EVIDENCE FOR TRIASSIC TO PLEISTOCENE GLACIATIONS: IMPLICATIONS FOR EUSTASY

PAUL J. MARKWICK AND DAVID B. ROWLEY

*The Paleogeographic Atlas Project, Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, USA*

**ABSTRACT:** Evidence for Mesozoic and early Cenozoic glaciations is ambiguous at best. Most of the purported evidence including faunal changes, glendonites and stable isotope paleothermometry imply cold conditions but do not explicitly require ice-sheets. In the absence of established indicators of glaciation, such as striated pavements, geomorphic features and tillites, only erratic bearing deposits, if interpreted as ice-rafted dropstones, provide direct evidence of large-scale terrestrial ice. It is shown here that such erratics can be equally well explained by non-glacial processes such as organic-rafting. Erratics in the Chalk of southern England and the middle Cretaceous of Australia are representative of the problems of "glacial" indicators in the Mesozoic.

The interpretation of high-frequency, large-magnitude, eustatic sea-level oscillations requires the existence of large ice sheets throughout much of the Mesozoic and Cenozoic. Although a temporal and spatial relationship between erratic-bearing deposits and transgressions is noted, the lack of demonstrable evidence for glaciation suggests that the amplitude of interpreted sea-level changes may have been exaggerated. We suggest that during non-glacial times the magnitude of any glacio-eustatic signal would have been no greater than 10–20 m and generally much less. Such oscillations would have been swamped by intra-basinal effects. We therefore suggest that global correlation of derived "3rd-order" or equivalent eustatic curves is untenable. We further suggest that beach front erosion of forested coastlines during sea-level rises (local or eustatic) may better explain the origin of erratic-bearing deposits than continental ice-sheets and icebergs.

## INTRODUCTION

Since the early nineteenth century, the general perception of Mesozoic and early Cenozoic climates has been of global warmth and ice-free poles (Lyell, 1830; Beaumont, 1836; Frakes, 1979). But recent work has suggested that this perception may be in error and that an ice-free Earth may never have existed (Frakes and Francis, 1988). This suggestion, however, is not new. Mesozoic ice has been proposed since the discovery of erratics in the Cretaceous Chalk of southern England (Mantell, 1833). Indeed, the climatic paradox that such erratics created led to considerable literature on the problem throughout the nineteenth century (Croll, 1875; Godwin-Austin, 1858, 1860; Lyell, 1841, 1872; Martin, 1897; Stebbing, 1897), most of which still has relevance today. It is such erratics that still form the crux of arguments for the existence of Mesozoic-early Cenozoic glaciation (Frakes and Francis, 1988).

Arguments concerning the presence or absence of Mesozoic-early Cenozoic ice-sheets also have major implications for eustasy and thus the potential use of sequence stratigraphy for global correlation. Fluctuations in global sea level (eustasy) require changes in the volume of the ocean basins and/or the volume of sea water. As has been recognized by many workers, repeated, large-amplitude, high-frequency eustatic oscillations, such as those implied by the 3rd-order cycles of Vail et al. (1977) and the "short-term curve" of Haq et al. (1987) can presently only be explained by glacio-eustatic processes (Haq, 1991; Pitman and Golovchenko, 1983; Pitman, 1978; Rowley and Markwick, 1992). This is shown clearly in Table 1 which tabulates the mechanisms and estimated rates by which both ocean basin volume and ocean water volume can change.

Rowley and Markwick (1992) derived a relationship for the volume change required for a specified change in sea level, assuming that the –200-m to +300-m hypsometry (Cogley, 1985) has not changed significantly over time:

$$V_{sw} = 0.5 A \text{ dSL} + A_0 \text{ dSL} \quad (1)$$

where  $V_{sw}$  is the volume of sequestered water, dSL is the change in sea level from the present,  $A_0$  is the initial surface area of the ocean, and  $A$  is the additional area due to dSL. The results are shown in Figure 1, which also gives the ice coverage required

if the water is sequestered as ice. Rowley and Markwick (1992) applied this method to the eustatic 3rd-order curves of Haq et al. (1987) using the first order, or "M," curve as the no-ice tectonic eustatic signal (Fig. 2). Because high stands on the "M" curve represent the flooding of large areas,  $A$  is large and the volume of sequestered water necessary for a specified sea-level change is correspondingly greater than were the same sea-level change to occur during periods of lowstand on the "M" curve. Consequently, for major eustatic changes such as that of the late Turonian (Haq et al., 1987) large ice-sheets are required (Fig. 3). Thus, while evidence of glaciations exists for the late Paleozoic, as well as other definable geologic periods (Fig. 4), the absence of unambiguous evidence for Mesozoic-early Cenozoic ice-sheets is problematic (Haq, 1991). This has led many workers to question the validity of high-frequency eustatic curves, especially of the magnitude of the 3rd-order Haq curves (Christie-Blick et al., 1989; Carter et al., 1991; Rowley and Markwick, 1992). However, other workers have suggested that Mesozoic ice-sheets existed and that the evidence has been either misinterpreted or lost (Frakes and Francis, 1988, 1990; Kemper, 1983, 1987; Brandt, 1986).

In this study we examine the evidence for Mesozoic-early Cenozoic glaciation using published reports dating back to the early nineteenth century. We also consider the literature on rafting mechanisms and provide calculations of carrying capacities of wood to assess its potential as a rafting agent in the geological record. Information on past glaciations is principally taken from the compilation of Hambrey and Harland (1981), which has been entered into a computerized relational database. The integration of this information with a study of glacial sedimentation and our compilations and analysis of the Mesozoic and Cenozoic paleoclimatic record enables us to assess the confidence with which we can consider glacio-eustatic sea-level changes and also to understand the overall history of global climate change. We have also attempted to clarify misconceptions that have become embedded in the geological literature such as the definition of a "glacial interval" and our general perception of global paleoclimate. It is these questions that we address first.

TABLE 1.—MECHANISMS CONTROLLING SHORT AND LONG TERM EUSTATIC SEA LEVEL\*

	Magnitude (m)	Duration (myr)	Rate m/myr
CLIMATE CONTROLS: OCEAN WATER VOLUME			
Glacial	120	$20 \times 10^{-3}$	6000
Present Day sea level equivalents in modern ice masses (not corrected for isostatic effects)			
Antarctica†	74.1	—	—
East Antarctica†	65.5	—	—
Greenland‡	6.6	—	—
Mountain Glaciers§	0.5	—	—
Dessication	10	$3 \times 10^{-3}$	3300
Ocean temperature	10	$1 \times 10^{-3}$	10000
TECTONIC CONTROLS: OCEAN BASIN VOLUME			
Long term ridge volume (maximum)	300	75	4
Long term ridge volume (mean)	200	75	2.7
Long term ridge volume (minimum)	100	75	1.3
Maximum interval ridge volume	45	5	9
Collisional decrease in continental area	70	50	1.4
Extensional increase in continental area	15	70	0.2
Sediment infilling	35	50	0.7
Hot spots	35	70	5

\*based primarily on Table 2 in Rowley and Markwick (1992)

†based on volume of ice given in Drewry (1983)

§based on volume of ice given in Flint (1971)

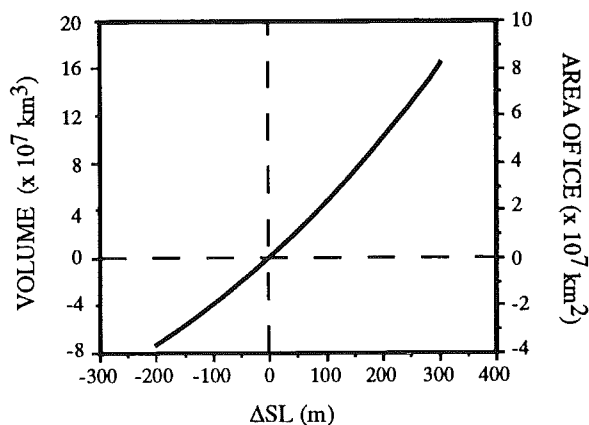


FIG. 1.—The relationship between changes in global sea level (ΔSL), volume of water sequestered and ice area required.

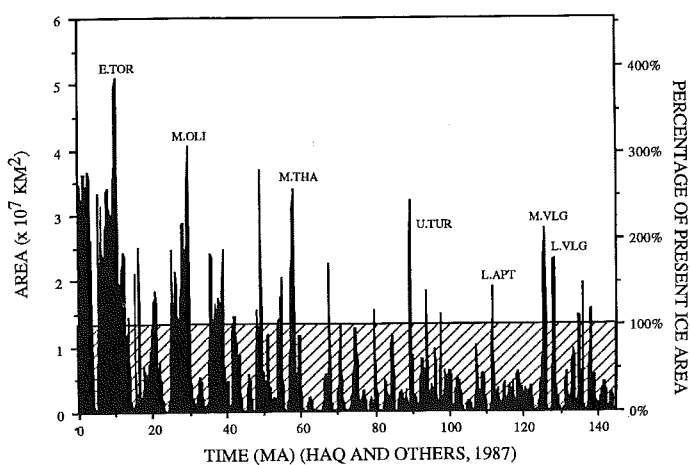


FIG. 2.—The area of ice implied by the 3rd-order eustatic sea-level curve of Haq et al. (1987). After Rowley and Markwick (1992).

## WHAT IS A GLACIAL INTERVAL?

In this study we define a “glacial interval” as “an interval with glaciation” using Gary et al.’s (1972, p. 299) definition of a “glaciation” as the “covering of large land areas by glaciers or ice sheets.” Implicit in this definition is that large volumes of water must be sequestered from the hydrological cycle, which will affect eustasy. As shown in Figure 1, even small changes in global sea level require the development of substantial ice sheets, such as the 6.6-m change associated with the deglaciation of Greenland ( $1.7 \times 10^6 \text{ km}^2$ ) or the 74.1-m change associated with Antarctic ( $12 \times 10^6 \text{ km}^2$ ) deglaciation. An im-

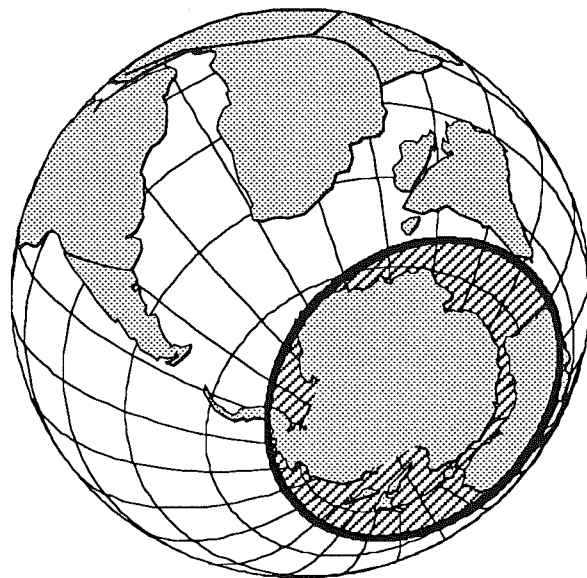


FIG. 3.—The area of ice required to account for the Upper Turonian sea-level fall of Haq et al. (1987). All of Antarctica and Australia would need to be covered. Such ice sheets would not extend into the deep oceans and this residual would have to be placed elsewhere, most probably in the northern hemisphere.

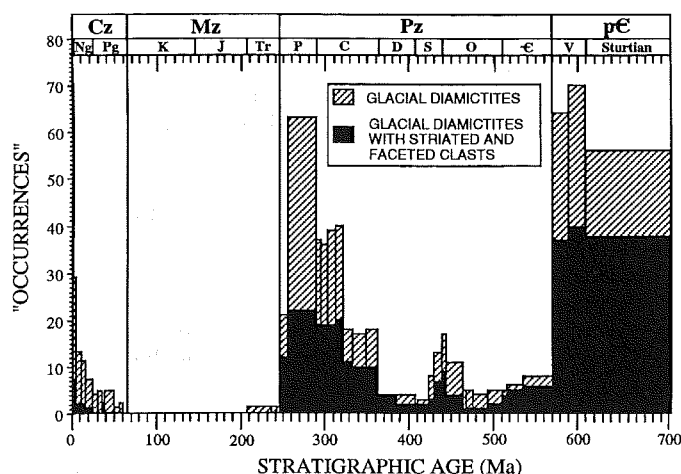


FIG. 4.—Distribution of glaciation in the geologic record as implied by the frequency of glacial diamicrite occurrences. Diagonally shaded bars represent glacial diamicrites, black shaded bars represent glacial diamicrites with striated and faceted clasts. Data are taken ostensibly from Hambrey and Harland (1981).

portant consequence of this definition is that it does not preclude the existence of some ice during "non-glacial" periods, nor does it require global climatic "equability" or high latitude warmth. As noted by North and Crowley (p. 482, 1985) "... an ice free earth does not necessarily imply a particularly warm earth." This must be stressed. Generalizing global climate, such as "warm Cretaceous," is extremely misleading: low latitudes, even during glacial times such as today, were probably always "warm," while high elevations in high latitudes were probably always "cool" or "cold." Similarly, the practice of applying the paleoclimatic interpretations of a single locality to the entire world is at best naive.

#### *Essentials for Creating a Glacier*

The presence of glaciers is dictated by the intersection of the Equilibrium Line Altitude (ELA, the line on a glacier where net accumulation of ice and net ablation—ice loss—are equal) and the Earth's topographic surface (Fig. 5). The exact shape of the ELA is dependent on temperature, available moisture, and solar radiation (Charlesworth, 1957; Seltzer, 1994). Given sufficient elevation, glaciers can occur even in equatorial regions, as they do today in east Africa and Papua New Guinea. However, as the ELA rises, the potential area for accumulation decreases and consequent glacial volumes are small with glacial terminations well above sea level (Fig. 5). Consequently, mountain glaciers, as distinct from ice sheets, comprise only  $\approx 0.6\%$  of the total ice sequestered water today, which is equivalent to about a 0.3-m sea-level change once water loading effects have been considered. During the last glacial maximum when the ELA was  $\approx 900\text{--}1000$  m below its present value irrespective of latitude (Pelto, 1992; Robin, 1988; Seltzer, 1994), mountain glaciers accounted for  $\approx 1.5\%$  of ice sequestered water (Flint, 1971). Thus the presence of mountain glaciers in the geological past can be assumed to have had a negligible effect on eustasy.

For the cryosphere (the portion of the Earth represented by ice) to have a significant effect on eustasy (i.e.,  $>5\text{--}10\text{-m}$  sea-level change), large continental ice-sheets must develop. This

requires that accumulation must be greater than ablation for large areas of the world. For this to occur there must be a significant depression of the ELA and/or the topography must rise. Robin (1988) calculated paleo-ELA's, despite the inherent problems involved (Andrews, 1975; Flint, 1971), and estimated that during the middle Cretaceous (100 Ma) the ELA was at  $\approx 2000$  m at the poles and  $\approx 2200$  m at  $75^\circ$  paleolatitude. Based on a quantitative analysis of the fossil floral data of the North Slope of Alaska, Spicer and Parrish (1990) suggested permanent ice existed at elevations above 1700 m at  $75^\circ\text{N}$  in the Cenomanian. Using these values we can estimate the size of the ice-sheet that would form by assuming the following: Drewry's isostatically reconstructed ice-free topography of Antarctica (Drewry, 1983, see Fig. 6) represents a plausible pre-glacial geography, and the ELA divides a glacier into two equal parts. With an ELA of 2000 m,  $\approx 1.4 \times 10^6 \text{ km}^2$  would be covered with ice, equivalent to a sea-level change from present of only  $\approx 3.7$  m. During the Cretaceous this effect would have been much less due to the higher sea level. Even were the ELA to have been as low as 1500 m, the sea-level effect would have been no more than  $\approx 15.6$  m. The absence of glacial evidence on the continental margin off Dronning Maud Land, which represents part of this pre-glacial elevation, suggests that even such "small" ice-sheets did not exist during this period. The effects of higher ELA's during "warmer" geological periods would have been compounded or perhaps even induced during times when global topography itself (especially in high latitudes) was lower than present. This is a scenario implied for much of the Mesozoic (Fig. 7). However, with  $\approx 97\%$  of Antarctica presently hidden beneath ice any geological reconstructions of that continent's glacial and pre-glacial evolution must remain speculative.

#### PUTATIVE GEOLOGICAL EVIDENCE FOR MESOZOIC AND EARLY CENOZOIC GLACIATIONS

Most of the evidence for past glaciations is sedimentological and includes the presence of tillites (diamicrites formed by glacial processes and usually evidenced by associated striated clasts and other glacial indicators), striated pavements and paleo-geomorphological features such as "U"-shaped valleys. This sedimentological evidence has been reviewed by numerous other workers (Boulton and Deynoux, 1981; Brodzikowski and Loon, 1991; Dowdeswell and Scourse, 1990; Eyles, 1993; Hambrey and Harland, 1981). The more salient features are summarized in Table 2 based on information in Hambrey and Harland (1981). Although such features as striated pavements and striated and faceted clasts have been recognized in other definable "glacial" geological periods (Fig. 1), this is not the case for the Mesozoic and early Cenozoic where the sedimentological evidence is ambiguous at best and restricted to two phenomena: cyclicity, interpreted as due to glacio-eustatic oscillations (this also includes eustatic curves such as the 3rd-order curves of Haq et al., 1987), and pebbly mudstones, interpreted as ice-rafted dropstones. Oxygen isotopic data provides the only other direct method for retrodicting past ice volumes (Matthews, 1984). Other "corroborating" evidence such as glendonites and stable isotope paleo-thermometry imply only the existence of cold conditions and not explicitly the presence of large ice-sheets. Paleontology, the source of most paleoclimatic data, is little help in this case since there are no fossils

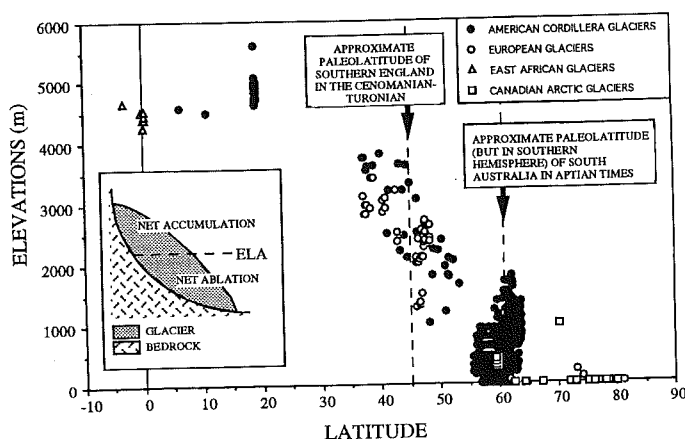


FIG. 5.—The elevation of glacier termini versus latitude. Black filled circles = American Cordillera glaciers; open circles = European glaciers; open triangles = East African glaciers; open squares = Canadian Arctic glaciers. Data are from the following sources: Field (1975); Osmaston (1989a, b). Insert shows the relation of the Equilibrium Line Altitude (ELA) to net ice accumulation and ablation (ice loss).

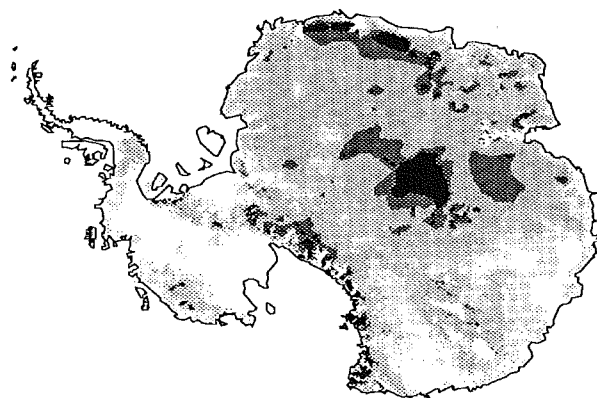


FIG. 6.—The ice-free, isostatically corrected, topography of Antarctica (after Drewry, 1983). The area refers to the amount of land above each elevation, dSL is the sea-level change from present due to an ice-sheet covering that area. No adjustment is made to account for isostatic effects or increases in land area due to sequestering of sea water by ice.

that are direct indicators of ice-sheets. Thus, the use of faunal changes, low diversity, the presence of "cold-climate" assemblages, or the absence of "warm-climate" organisms is purely circumstantial.

Therefore great emphasis is placed on the interpretation of sedimentological and geochemical evidence, and although we do discuss glendonites, the emphasis of this study is to test the validity of the sedimentary evidence for Mesozoic-early Cenozoic glaciation, specifically erratic bearing deposits, and to similarly assess the implications of the isotopic record.

### Rhythmites, Cyclicity, and Eustatic Sea-level Change

Rhythmites (repeated lithological couplets or sequences) are common in the geological record. Although such sequences may be formed by changes in productivity, sedimentation rate, ocean chemistry or dissolution, many have been recognized to represent cyclic shallowing-deepening oscillations. Where such oscillations are demonstrably eustatic, high-amplitude (>5–10 m) and rapid (>100 m/myr), a glacio-eustatic origin is the only explanation (Rowley and Markwick, 1992). Indeed, Björlykke (1985) suggested using sea-level changes in tectonically stable areas to constrain the timing and magnitude of ancient continental glaciations where such changes are globally correlative (eustatic). In most cases this is not clear, but some workers have chosen to use such evidence. Brandt (1986), for example, interpreted glacio-eustatic cycles in the Early Jurassic of Germany based primarily on the contemporary occurrence of glendonites and pebbly mudstones. Kemper (1983), interpreted an Early Cretaceous regression in northern Russia as due to "isostatic uplift of the Arctic as a consequence of melting of a thick Arctic ice sheet," despite the lack of any corroborating evidence of ice. In addition, a regression in northwestern Europe during Plenus Marl time (Cenomanian-Turonian) was interpreted as glacio-eustatic by Jeans et al. (1991), based on isotopic data and the presence of erratics, erratics that in fact also occur before and after the "glaciation." Most important is the Haq 3rd-order curve which, as shown by Rowley and Markwick (1992) and acknowledged by Haq (1991), implies the existence of large ice-sheets since at least the Kimmeridgian that would have to have been larger than the present Antarctic ice sheet on at least 25 occasions (Fig. 2).

### Pebbly Mudstones and Erratics

Erratic bearing deposits, including pebbly mudstones (a rock comprised of dispersed pebbles in a mudstone matrix, Crowell, 1957), present an immediate depositional paradox since they

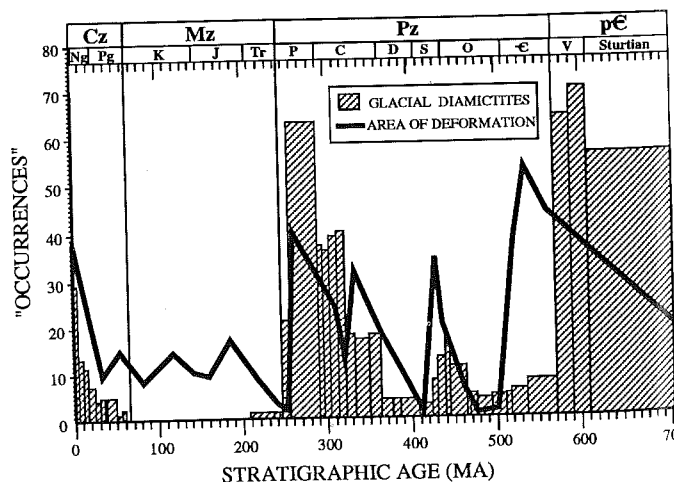


FIG. 7.—The distribution of glacial diamictite occurrences through time which is superimposed the area of deformation as derived by Richter et al. (1992). Shaded bars represent glacial diamictites, thick black line represents the relative area of deformation. Note the correspondence between periods of glaciation and those with large areas of deformation. Deformation is used here as a proxy for mountain building.

TABLE 2.—INDICATORS OF GLACIATION

INDICATOR	DESCRIPTION	COMMENTS
Abraded bed rock surfaces (striated pavements) TERRESTRIAL	presence of striations, grooves, polished pavements, chattermarks, and rouche moutonnée like forms	although striated surfaces could be formed by tectonics, impacts, or mass-flow, generally such features are diagnostic.
Depositional fossil landforms TERRESTRIAL	e.g., drumlins, moraines, eskers, ice-push features, U-shaped valleys	rarely preserved
Chattermark trails on garnets TERRESTRIAL & SUBAQUEOUS	present in glacial deposits not in non-glacial deposits	requires garnets be present and preserved
striated, faceted (soled) and chattermarked clasts TERRESTRIAL & SUBAQUEOUS	striations on pebble surfaces generally in diamictites but also as isolated dropstones in marine settings. Faceting due to subglacier abrasion	can be caused by tectonic causes, for instance in shear zones, impacts, or by abrasion in mass-flow deposits. However generally one of the more diagnostic features associated with glacial sediments.
Stone-rich beds (diamictites) TERRESTRIAL & SUBAQUEOUS	unsorted, large range of grain sizes, may have preferred orientations, irregular thicknesses possible due to filling of hollows etc.	most of these features can be true for mass-flow deposits. Both can also have slump structures.
Dropstones SUBAQUEOUS	best observed in fine laminites where they show disruption of laminae at bottom and draping over top of stones. May be associated with graded laminites (varves). Stones may be striated, soled. Stones must be larger than matrix.	can be dropped from rafts other than ice, including kelp, trees, marine vertebrates and large birds. Certain mass-flow deposits may resemble dropstone-deposits but the disruption of laminites should be diagnostic of rafting.
'Fragile stones' TERRESTRIAL & SUBAQUEOUS	shale fragments mixed with more resistant material. Indicative of rapid deposition and lack of water transport.	mass flow deposits might have same
Variable lithologies TERRESTRIAL & SUBAQUEOUS	clasts are exotic (may be far traveled), and have variable lithologies dependent on size of glacier/ice sheet and bedrock overridden. Minerals often undecomposed suggesting little transport by water and cool conditions resulting in reduced chemical weathering.	dropstones from tree roots or kelp may also show a variety of lithologies depending on source of material; however because of the large amount of chemical weathering associated with organics and soils such material should show more decomposition of unstable minerals (e.g. feldspars)
Stones with wide range of shapes TERRESTRIAL & SUBAQUEOUS	well-rounded to angular, especially sub-angular and sub-rounded	some mass flow deposits may show similar variations as might clasts due to tree rafting etc., depending on source of clasts; however this is quite a good indicator.
Quartz grain textures TERRESTRIAL & SUBAQUEOUS	angular grains, sharp edges and conchoidal fracture	such textures can be subsequently altered
Large areal extent and thickness TERRESTRIAL & SUBAQUEOUS	unsorted deposits over large distances (km's)	mass-flow deposits may be more localized
Finely graded stratification SUBAQUEOUS	laminated clay or siltstones	also found in distal turbidites and some storm deposits
Rock flour TERRESTRIAL & SUBAQUEOUS	clay sized particles ground by the action of the moving glacier.	such particles are indistinguishable under the microscope
Proxy Data (evidence of cooling and cold conditions)	includes fossil data, cold water assemblages, low diversity, etc. glendonites	cold does not explicitly mean glaciation

imply two very different hydrological regimes (the term "erratic" is used throughout this text according to the definition of Gary et al., 1972, p. 238: a "relatively large rock fragment lithologically different from the bedrock on which it lies, either free or as part of the sediment, and that has been transported, sometimes over a considerable distance, from its place of origin). Unfortunately, for most geologists the term also has glacial connotations, which we do not imply; however other terms such as "megaclast" or "lonestone" are less appropriate since they do not convey the exotic nature of the clasts). Although mass-flow may account for some of these deposits (Crowell, 1957), and may be responsible for reworking others, a mass-flow origin is not always demonstrable, and so rafting mechanisms, particularly ice, have often been invoked. In the Mesozoic such deposits have drawn particular attention because of the lack of more direct evidence for glaciation. There are many erratic-bearing marine deposits in the Mesozoic and early Tertiary, a selection of which is presented in Table 3. Two erratic bearing deposits have received particular attention: the Chalk of north-western Europe, and the middle Cretaceous rocks of Australia. It is the erratics of these two units that presently provide the

crux of arguments for Mesozoic glaciation (Frakes and Francis, 1988; Jeans et al., 1991). If such erratics are not demonstrably due to ice-rafting, then such arguments become moot. We thus first discuss the erratic bearing deposits of these two areas, then review erratic emplacement mechanisms so as to better constrain plausible interpretations.

#### *The Erratics of the Chalk and Upper Greensand of Southern England*

Mesozoic erratics have been described since their discovery in the Chalk of southern England in the early nineteenth century (Mantell, 1833). The Chalk, inextricably linked with global warmth and aridity (Bailey, 1924; Chatwin, 1960, p. 54; Gallois, 1965, p. 38; Hancock and Scholle, 1975; Hancock, 1975; Rawson, 1992), seemed immediately to preclude ice rafting (Lyell, 1841). Similar erratics have been found in the underlying greensands (Hawkes, 1943), the Gault Clay (Jukes-Browne and Hill, 1903, p. 196 and p. 346; Dines et al., 1933; White, 1924), the Soest Greensand of northern Germany (Kaefer, 1974; Schmidt and Schreyer, 1973), the Chalk of the

TABLE 3.—SUMMARY OF PRE-PLEISTOCENE ERRATIC BEARING DEPOSITS

Stratigraphic unit with age and general location	Lithology of erratics. Underlying inliers dominant lithology(s)	Size (diameter, cm)	Shape	Association	References
<i>Maruyama Formation</i> Sakhalin (Pliocene)	quartzites, chert, andesites, schists, silicified mudstones, sandstones, basaltic porphyries, siliceous mudstones, clay balls	usually 1–5 up to 1500–2000	usually rounded, occasionally angular		45, 47
<i>Kakert Formation</i> Kamchatka (Miocene)	volcanics, vein rocks, sedimentary rocks	mostly 1–5	rounded to well-rounded	comprise $\approx$ 1–3% of rock; derived from underlying deposits; no striations or faceting known. Interbedded with tuffaceous sediments.	45, 46
<i>Mackenzie Bay Formation</i> Mackenzie Bay area (Miocene)	chert	pebbles		scattered	2
<i>Utkholok Formation</i> Kamchatka (Oligocene)	volcanics (45–50%) and sedimentary (40–45%) rocks, minor metamorphics, vein rocks, intrusive igneous, wood and coal	generally 0.1–1 some 20–30 rare up to 1500	rounded—well-rounded (very largest clasts are sub-rounded)	locally derived, all types present in underlying deposits, wood present. No striations or facets known. These beds are interbedded with coals and tuffaceous sediments	48
<i>Takaradai Formation</i> Sakhalin Island (late Eocene)	siliceous rocks and quartz minor crystalline schists, quartzites, andesites, and shales	usually 1–5 up to 10	well-rounded, rarely angular	interbedded with intermittent coals and tuffaceous deposits	49
<i>Gilsonryggen Formation</i> Svalbard (?Eocene)	quartz, quartzite, chert, dolerite, gray granite, graphic granite, rhyolite porphyry, vein quartz, sandstone	quartz and chert are 1–5, dolerite blocks up to 15–50, porphyry pebbles are up to 2–30	well-rounded; dolerite blocks are angular-sub-rounded	calcite rosettes are found (possibly glendonites?)	41, 42
<i>Sarkofagen Formation</i> Svalbard (Eocene)	95% comprise chert and quartz/quartzite; rarer gneiss, granite, greenschists, sandstones, volcanics	granules and pebbles, some rare cobbles and boulders	generally very well-rounded	restricted to marine parts of sequence. clasts occur in 3 settings: scattered, concentrated on hummocky erosion surfaces, as horizontal concentrations, the lower boundary often been sharp. fragments of fossil wood are known from this formation. calcite rosettes are found (possibly glendonites?)	40, 42
<i>Pukemuri Formation</i> New Zealand (early Eocene)	igneous rocks, greywacke, green sandstone	2–30	mostly rounded, but some are sub-angular	in sandy-silty matrix, large scattered boulders in basal part of formation, clasts generally derived from immediately underlying deposits	38
Sweden (Danian)	black and white cherts	2.3–7.1 cm long	rounded, smoothed	associated with crocodilian remains (gastroliths?)	37
Denmark (Danian)	quartz, schist, gneiss, granite, rhyolite, gabbro, sandstone, shale	up to $7 \times 5.5 \times 3.5$	rounded-sub-angular	found in coral limestones and bryozoan limestone, calcarenites	37, 43
Denmark (Maastrichtian)	quartz, quartzite, sandstone	up to $6.4 \times 4.5 \times 2.0$	rounded-sub-angular	in chalk	43
<i>Bearpaw Shale</i> Montana (Campanian)	black chert	up to 1	rounded, smooth	scattered throughout shale	pers. obs.
<i>Judith River Formation</i> Montana (Campanian)	chert	up to 2	rounded, smooth	occur on reworking surfaces as lags during transgressions, associated with plesiosaur bones, shark teeth, mososaur bones & other vertebrate remains	35
<i>Hue Shale</i> NE Alaska (Campanian)	chert and quartzite	pebbles up to 4		floating in shale, common. organic rich (commonly $>4\%C_{org}$ )	3
West Siberian lowland (lower Paleocene)	—	—	—	pebbly mudstone	45
<i>'Piripauan beds'</i> New Zealand (Campanian)	plutonic, volcanic, quartzite, sedimentary rocks	2–50	sub-angular	No striations	38
<i>Upper Chalk</i> S. England and NE France (Turonian-Maastrichtian)	quartz, quartz schist, quartz phyllite, quartzite, black chert, coal (Lydden Tunnel)	up to 300g, most around 2–8g, coal = $120 \times 120$ and 10–25 thick	mostly well-rounded, some angular	wood impressions and fish found in vicinity; nature of coal remains uncertain	15, 16, 17, 18
<i>Middle Chalk</i> S. England (Turonian)	granite, quartzite, greenstone, siliceous sand, sandstones, dark clay slate	up to 30.5 (Purley, UK)	"water-worn," well rounded	fossil wood found in vicinity of some, many boulders encrusted by serpulids, bryozoans and sponylids	17, 18, 19, 20, 21, 22, 23
<i>Soester Grünsand</i> Germany (Turonian)	gneiss, granite, monzonite, quartzite, greensand, chert	up to 45	rounded	isolated	24

TABLE 3.—SUMMARY OF PRE-PLEISTOCENE ERRATIC BEARING DEPOSITS

Stratigraphic unit with age and general location	Lithology of erratics. Underlining infers dominant lithology(s)	Size (diameter, cm)	Shape	Association	References
<i>Lower Chalk</i> S. England (Cenomanian)	<u>quartzite</u> , cherts, vein-quartz, clay slate, "tourmalinised killas," sphaerulite, greenstone	"pebble," "large blocks," generally as small pebbles	well-rounded	stones mixed with rotten wood (?) at Isleham; at Rochester 107 pebbles closely associated together	17, 19, 20, 21, 25, 26, 27
<i>Osbourne Formation</i> Western Australia (Albian-Cenomanian)	quartz	pebbles		in claystones	56
<i>Upper Greensand</i> S. England (upper Albian)	coarse feldspathic grit, purple shale, gray sandstone, fine conglomerate, black limestone, red sandstone, mica-schist, phosphate nodules, granite, greenstone, mica-hornblende-schist, talcose schist, vein quartz, quartzites, spherulitic rhyolite, labradorite	sizes range from 5–55 up to 35.5 × 30.5 × 15	angular-rounded, generally angular (c. 10% rounded)	some coated in phosphate, many encrusted by bivalves, faint striations on one phosphate nodule (striations then covered by Cretaceous encrusters), faint striations on one mica schist (?); some specimens seem highly weathered others are very fresh (no decomposition)	17, 28, 29, 30
<i>Gault Clay</i> S. England (Albian)	quartzite, milky quartz, black slate, hornstone, sandstone	boulders (25.5 × 15 × 15 and 18 × 18 × 15), mostly pebbles	boulders are angular, but generally pebbles are rounded (some "water-worn"). Flat polished pebble found near Brighton	boulders encrusted by <i>Plicatula</i> and <i>Spondylus</i> . At Folkstone pebbles associated with remains of a plesiosaur (gastroliths?)	25, 31, 32, 33
<i>Manahau Formation</i> New Zealand (Albian)	rhyolite, ignimbrite, tuff, plutonic rocks, chert	2–5	well-rounded, polished, scattered	clasts are exactly the same as those of the immediately underlying conglomerates	38
<i>Carolinefjellet Formation</i> ( <i>Imkjegla Member</i> ) Svalbard (upper Aptian-lower Albian)	<u>chert</u> and <u>quartzite</u>	pebbles	—	driftwood also found in this member	39
<i>Bulldog Shale</i> South Australia & New South Wales (Aptian)	<u>Devonian quartzites</u> , volcanic rocks	boulders, up to 300	well-rounded		57, 58
<i>Marree Formation</i> South Australia (Aptian)	<u>quartzite</u> and rare shale	up to 50			62
<i>Wallumbilla Formation</i> Queensland (Aptian)	<u>quartz</u>	pebbles	well-rounded	associated with wood and vegetal matter	59, 60
<i>Rumbalara Shale</i> Northern Territory, Australia (Aptian)	<u>quartz</u>	boulders	—	silicified wood in this unit	
<i>Rolling Downs Formation</i> Queensland and South Australia (Aptian)	<u>quartzite</u> , feldspar porphyry, granite, schists, gneisses	pebbles, boulders, mostly less than 61 but some up to 167.5 in length	sub-rounded–well-rounded ("water-worn")	associated with numerous fossil trees in South Australia	60, 61, 51
<i>Monash Formation</i> ( <i>Merreti Member</i> ) South Australia and New South Wales (Aptian)	lithic	pebbles and cobbles			54
<i>Monash Formation</i> ( <i>Pyap Member</i> ) South Australia and New South Wales (Aptian)	—	cobbles and pebbles		in clays, slump structures	54
<i>Unit 6 (Mullaman Beds)</i> Northern Territory, Australia (Aptian)	—	pebbles		in claystone interbeds, glauconitic, with carbonaceous material and pyritized wood fragments	52
<i>Cadni-Owie Formation</i> South Australia (Neocomian-Aptian)	<u>quartzite</u> , rhyolite, others	pebbles, cobbles and boulders up to 120	sub-rounded–rounded		57, 62, 63
<i>Leederville Formation</i> Western Australia (Neocomian-Aptian)	quartz	pebbles		in claystones	56
unit not given, probably the <i>Mullaman Beds</i> Northern Territory and Queensland (Neocomian-Aptian)	mostly sedimentary	up to 26, generally granules and small pebbles	rounded–sub-angular	no striae or chattermarks.	53
<i>Blythesdale Sandstone</i> South Australia (Neocomian-Aptian)	<u>quartzite</u> , quartz feldspar porphyries, quartz, slate, schists	up to 182	rounded	some faceted, no striations, wood and leaf impressions, associated fossil wood	50, 51

TABLE 3.—SUMMARY OF PRE-PLEISTOCENE ERRATIC BEARING DEPOSITS

Stratigraphic unit with age and general location	Lithology of erratics. Underlining infers dominant lithology(s)	Size (diameter, cm)	Shape	Association	References
<i>Loongana Sandstone</i> South Australia (Neocomian-Aptian)	<u>granite</u> , schist	>10 (the diameter of the core)		in feldspathic sandstone, some of the granite and schist pebbles may have been in a conglomerate	4
<i>Unit 2 (Mullaman Beds)</i> Northern Territory, Australia (Neocomian)	—	pebbles and cobbles	—	associated with sandstones and conglomerates which have poorly rounded pebbles and boulders. Clasts also concentrated in lenses. Very fossiliferous unit	36, 52
<i>Pebble Shale</i> North Slope, Alaska (Hauterivian-Barremian)	<u>chert</u> , <u>quartzite</u>	pebbles or granules with rare cobbles		floating sand grains and pebbles, pebbles are not concentrated (although there is some increase in number of clasts) in basal part of shale unit as is typical of most transgressive shale units. Unit is organic rich (possible oil source rock for Prudhoe Bay oil-field)	34, 3, 36
<i>Kemik Sandstone (Marsh Creek Member)</i> NE Alaska (Hauterivian-Barremian) below Pebble Shale Unit	—	pebbles	—	common in interbedded black mudstone & dark gray argillaceous siltstone	55
northern Siberia (Middle-Upper Jurassic)	—	pebbles	rounded and slightly flat	in non-bedded silty claystones	44, 45
northern Siberia (Bajocian)	—	cobbles and boulders up to 200 long	—	—	44
<i>Lower Beaufort Shales</i> South Africa (Middle Triassic)	—	up to size of an "orange"	"water-worn" pebbles	often associated with masses of fossil wood "... great masses of silicified wood and that a large number of water-worn stones were lying amongst the wood."	1
<i>Snowdon Formation</i> New Zealand (upper Scythian or early Anisian)	chert, granite, argillite, basalt, andesite, granophyre, gabbro	3–35 diameter	angular-rounded	spaced between 20 cm and 1 m apart, in black siltstone matrix, underlain by a conglomeratic member	38

AUSTRALIAN ERRATICS: the relationship of the erratic bearing horizons is further confounded by the plethora of names used for the beds in which they occur. In this summary the names are those as given by the workers given in the reference column. To clarify, the following units are laterally equivalent: Wallumbilla Formation = Bulldog Shale = Roma Formation = Unit 6 (Mullaman Beds) = Rumbalara Shale = lower part of Maree Formation = Merreti Member of the Monash Formation = lower part of Rolling Downs Formation (Day, 1969; Exon and Senior, 1976). The Cadni-Owie Formation stratigraphically underlies these units and is equivalent to the Pyap Member of the Monash Formation (Thornton, 1974) and may be equivalent to the Leederville Formation of the Perth Basin, unit 2 of the Mullaman Beds and the Blythesdale Sandstone of South Australia (Day, 1969).

## FOR COMPARISON

Carboniferous coals UK & Germany (Pennsylvanian)	<u>quartzite</u> , quartz, granite,	"small" (Germany); up to 11 × 8 × 3.8 (Wales); 2.5–20 (England); pebbles up to 25 (Derbyshire, UK)	rounded ("water-worn"), well-worn	one in-situ in coal layer (Wales), in coal seam (Staffordshire, UK); enveloped in coal (Leicestershire, UK); in underclay (Derbyshire, UK)	5,6,7,8,9
Carboniferous limestones Ireland (Carboniferous)	<u>quartzite</u> , schist, quartzite, vein-quartz, slate	up to 20 diameter	angular	little evidence of decomposition of fragments	10
Carboniferous coals USA (Pennsylvanian)	<u>quartzite</u> , vein-quartz, sandstone conglomerate, granite, quartz porphyry, limestone, talcose slate, grit, phyllite, pegmatites	up to 48 × 38 × 35.5 (73.5 kg) (West Virginia); up to 60, most between 1 and 4 (Upper Pottsville Fm, Alabama)	angular to well-rounded, mostly rounded and polished	some faceted clasts, some from within coal seams; in Upper Pottsville Fm., clasts associated with wood remains, largest log is 700 long and 50 diameter	5, 12, 11, 13, 14
La Salle Limestone II., USA (Pennsylvanian)	vein-quartz, greenstone, granite, schist, quartzite	up to 11	smooth, possible faceting	no striations	11

## REFERENCES

- 1-Broom, 1911; 2-Nentwich and Yole, 1982; 3-Molenaar et al., 1988; 4-Lowry, 1970; 5-Price, 1932; 6-Dix, 1944; 7-Spencer, 1887; 8-Bonney, 1873; 9-Gresley, 1885; 10-Ball, 1888; 11-Savage and Griffin, 1928; 12-Newberry, 1872; 13-Hicks, 1879; 14-Liu and Gastaldo, 1992; 15-Cayeux, 1897; 16-Robbie, 1950; 17-Stebbing, 1897; 18-Godwin-Austin, 1860; 19-Double, 1931; 20-Hawkes, 1951; 21-Dixon, 1850; 22-Dibley, 1910; 23-Dibley, 1918; 24-Schmidt and Schreyer, 1973; 25-Jukes-Browne and Hill, 1903; 26-Godwin-Austin, 1858; 27-Strahan, 1906; 28-Sollas and Jukes-Browne, 1873; 29-Hawkes, 1943; 30-Watts, 1881; 31-Woods, 1895; 32-Seeley, 1877; 33-White, 1924; 34-Molenaar, 1988; 35-Rogers, 1994; 36-Walpole et al., 1968; 37-Troedsson, 1924; 38-Waterhouse and Flood, 1981; 39-Nagy, 1970; 40-Dalland, 1977; 41-Birkenmajer and Narebski, 1963; 42-Birkenmajer et al., 1972; 43-Noe-Nygaard, 1975; 44-Chumakov, 1981; 45-Epshteyn, 1978; 46-Grechin, 1981a; 47-Melankholina, 1981a; 48-Grechin, 1981b; 49-Melankholina, 1981b; 50-Woodard, 1955; 51-Woolnough and David, 1926; 52-Skwarko, 1966; 53-Frakes and Krassay, 1992; 54-Thornton, 1974; 55-Muil, 1987; 56-Playford et al., 1976; 57-Flint et al., 1980; 58-Frakes and Francis, 1988; 59-Moore, 1870; 60-Jack and Etheridge, 1892; 61-Jack, 1931; 62-Carr et al., 1979; 63-Wopfner et al., 1970.



Paris Basin (Cayeux, 1897), the Danian and Maastrichtian limestones of Denmark (Noe-Nygaard, 1975) and Sweden (Troedsson, 1924), and the Mesozoic and Tertiary of Spitsbergen (Birkenmajer et al., 1972; Nagy, 1966, 1970; Woolnough and David, 1926). Most of the erratics found in the Chalk and Upper Greensand reside in museum and private collections and locality, stratigraphic and sedimentological details are generally scarce. Collection biases may have influenced both the spatial distribution of the erratics (Fig. 8; through mining operations, Double, 1931) and also size distributions from initial collection preferences for larger clasts. Throughout this discussion we use the traditional subdivision of the Chalk (Gallois, 1965).

The erratics of the Chalk comprise various lithologies, outlined in Table 3, with granite (Godwin-Austin, 1858) and quartzites the most common types (Hawkes, 1951). With the possible exception of a large coal clast (the largest "erratic" reported from the Chalk— $1.22 \times 1.22 \times 0.25$  m and whose provenance is unclear, Godwin-Austin, 1860), all of the erratics in the Chalk are "water-worn," which is consistent with most of the purported dropstone deposits of the Mesozoic. The largest demonstrable erratic, known as the Purley boulder, was estimated to have been  $\approx 91.4$  cm in diameter (Woolnough and David, 1926), although the boulder's exact size is uncertain since it was broken up by the workers who found it (Godwin-Austin, 1858). Hawkes (1951) suggested a smaller size of  $40.6 \times 22.9 \times 25.4$  cm based on the fragments in the Geological

Survey and Museum. Most of the pebbles in the Chalk are much smaller, and the size range of 0.5–5 cm quoted for most of those in the Wiltshire and Dibley collections is more typical (Hawkes, 1951). To date no faceted or unambiguously striated pebbles have been described.

Although generally found in isolation, associations of pebbles do occur, such as those at Rochester where 150 pebbles were found within a 1- or 2-m radius (Hawkes, 1951). At Purley, Godwin-Austin (1858) found that although the granite boulder had been removed, its original site did not seem "... to have been much disturbed." Lyell (1872) added further that the boulder weighed over 18 kg. Associated with this material Godwin-Austin (1858) found a 9-kg boulder, "... some coarse shingle, and a quantity of loose sea-sand." Betchworth quarry in Surrey, which was heavily used in the mid-nineteenth century, accounts for most of the described erratics in the Chalk (about 70 stones, Double, 1931). One granite cobble was found encrusted with several Cretaceous clams (lower valves of *Spondylus latus*) and serpulids (Double, 1931). Encrusted clasts have also been found in the Catt collection from the Lewes area, Sussex (fauna includes a serpulid (*Diblasus* or *Isis*), a bryozoan (*Diastopora ramosa*?) and lower valve of *Spondylus lineatus*, Godwin-Austin, 1858), in the Upper Greensand of Cambridgeshire and the Gault Clay from Stanbridge, south Bedfordshire. Most of the erratics have been found from either the Lower or Middle Chalk.

The erratics of the Upper Greensand are also dominated by resistant siliceous lithologies. Hawkes (1943) noted that 94% of his samples were siliceous: mainly quartzites, greywackes and sandstones are present, with biotite-granite-gneiss, vein quartz, rhyolites and schists also quite common, with the remainder consisting of hornstone-tuffs, quartz-porphyrates and more basic rocks. Compared with the erratics of the overlying Chalk, those of the Upper Greensand are generally more angular (Sollas and Jukes-Browne, 1873; Bonney, 1872), larger, and more common (Hawkes, 1943). They are usually found isolated (Hawkes, 1943; Bonney, 1872), although Sollas and Jukes-Brown (1873) report six "large stones ... huddled together at Waterbeach." Except for possible wood associated with the pebbles at Isleham (Jukes-Browne and Hill, 1887; Stebbing, 1897), none of the pebbles is directly associated with organic matter. The Upper Greensand does, however, contain balls of vegetal matter (Bonney, 1872) as well as a diverse vertebrate fauna including crocodilians, turtles, fish and dinosaurs (Bonney, 1872; Chatwin, 1961).

#### Depositional environment and provenance.—

The Cambridge Greensand is a condensed deposit that formed on the northern margin of the London Platform and is the lateral equivalent of the Upper Greensand of the Weald. It seems to represent nearshore clastic shelf deposition (Chatwin, 1961), although the exact details are still unclear (Anderton et al., 1979). It is usually less than 1 ft (c. 30.5 cm) thick, with "sandy and chalky marl with abundant phosphate nodules at the base" among which the erratics are generally found (Chatwin, 1961). The unit contains an abundant and diverse fauna including pterodactyls, dinosaurs, crocodilians and sharks, as well ammonites, bivalves, brachiopods and corals.

The Chalk is a fine grained (dominantly 4–10  $\mu\text{m}$ ), exceptionally pure limestone with greater than 96%  $\text{CaCO}_3$  (Han-

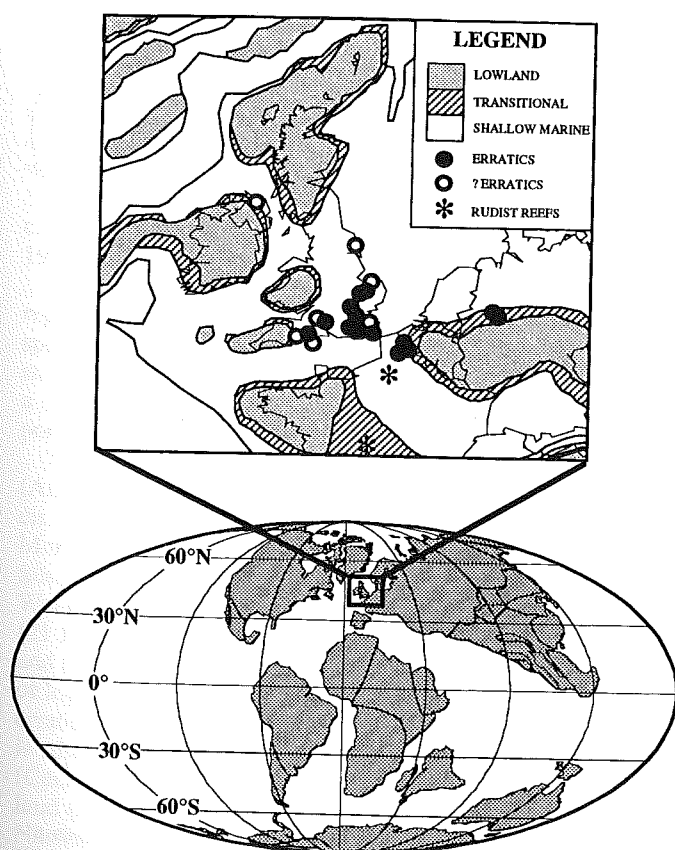


FIG. 8.—Distribution of middle Cretaceous erratics in northwest Europe. See Table 3 for references. Paleogeography after Ziegler (1990). Plate reconstruction is for 92 Ma, Cenomanian (Rowley, unpublished data).

cock, 1975). Although the Lower Chalk contains a large proportion of siliciclastic material, detrital material is generally extremely rare for most of the Chalk. However, it may become locally significant near presumed terrestrial sources: the upper Turonian Tuffeau Jaune de Touraine Formation in the southwestern part of the Anglo-Paris Basin has up to 20% angular quartz grains (Jarvis and Gale, 1984) and the Cenomanian Beer Head Limestone in southeast Devon has up to 50% quartz sand. In Northern Ireland, the White Limestone (Chalk equivalent) onlaps onto older rocks and also contains large amounts of detritus including pebbles of quartz, quartzite and quartz porphyry (Hume, 1897). The Chalk, like the Greensands below, contains an abundant and diverse fauna, although the strongly alkaline conditions seem to have largely precluded the preservation of plant material except within flints (Dixon, 1850). Hancock (1975) outlines the evidence supporting a soft "watery" nature for the Chalk sea floor. The bathymetric relief of the chalk sea bottom was not insignificant, with large carbonate banks, such as those of Normandy where the banks are up to 50 m high and 1.5 km long (Kennedy and Juignet, 1974) and of Portsdown, England (Gale, 1980). Slumps adjacent to these banks are common (Gale, 1980; Mortimore and Pomerol, 1991). Omission surfaces, scouring and hardground development are evidence of erosion and/or non-deposition (Kennedy and Garrison, 1975) and have been used to interpret sea-level changes during Chalk times. Hancock (1989) extensively discussed discrepancies between these changes and the eustatic curve of Haq et al. (1987).

The source of the erratics has been problematic. For those of southern England, much of the material was derived from older deposits (Hawkes, 1943), especially conglomerates such as those of the Triassic (Hume, 1897). Clasts of similar petrology were available in most of the underlying beds, such as the Upper Greensand, Lower Greensand and especially the Wealden; provenance studies of these beds in turn show not only derivation from primary source areas such as Cornubia, Brittany or the London Platform (Allen, 1949, 1960, 1967, 1969, 1972, 1981; Kirkaldy, 1947; Sladen and Batten, 1984; Wells and Gossling, 1947), but also reworking from Liassic rocks (Edmonds et al., 1975, p. 66). It is clear that cobbles and boulders were available on local uplifts such as the London Brabant Platform (Prestwich, 1856). Although source areas, as positive features, have probably been subsequently removed, onlapping directions and detrital compositions suggest possible sources. In the southwestern Paris Basin, detrital quartz concentrations increase to the southwest (Jarvis and Gale, 1984); detrital concentrations in the Lower and Middle Chalk deposits of southern England generally increase westward towards Cornubia (Groves, 1931), concomitant with an increase in coarseness of the chalk. Smith (1961) suggested that the Cornubian Massif was submerged by the time of Middle Chalk deposition. Groves (1931) noted a similar trend for the Upper Greensand, particularly in East Devon, Wiltshire, and Lulworth Cove (the Upper Greensand of the Isle of Wight in Hampshire appears to be sourced from Brittany). Possible contemporary beach deposits have been reported in Devon (Ali, 1976, although Jarvis and Woodroof, 1984, dispute this), southern Belgium (Prestwich, 1888, p. 300) and Northern Ireland (Hancock, 1961; Wilson, 1972).

### The Erratics of South Australia

Although Moore (1870) described well-rounded quartz pebbles in Cretaceous soils or clays from Wallumbilla (interpreted as concretions by Jack and Etheridge, 1892), the first large middle Cretaceous erratics were described by Brown in 1885 from just north of Lake Gairdner ("quartzite water-worn boulders," Brown, 1885). Later, Jaquet (1893) described similar boulders from the opal deposits at White Cliffs, New South Wales (N.S.W.). Additional erratics were discovered during the early geological mapping of South Australia by Brown (1892a, b, 1894, 1895, 1898a, b, 1905), who was the first to suggest a glacial origin for them (a view subsequently expounded by Woolnough and David, 1926). There have since been various explanations for these deposits, with a literature extending to the present day. Erratic bearing deposits and pebbly mudstones are now known from the Great Artesian, Eucla and Perth Basins. Their distribution is summarized in Figure 9.

The erratics are known principally from the southern margins of the Great Artesian Basin in South Australia and northwestern N.S.W. (Fig. 9). It is this area that has the greatest density of clasts, the greatest variety of compositions (though dominated by quartzites and quartz-rich rocks) and the only evidence of faceting and striae (David, 1932; Ward, 1925; Woolnough and David, 1926). The rarity and faintness of the striae suggested

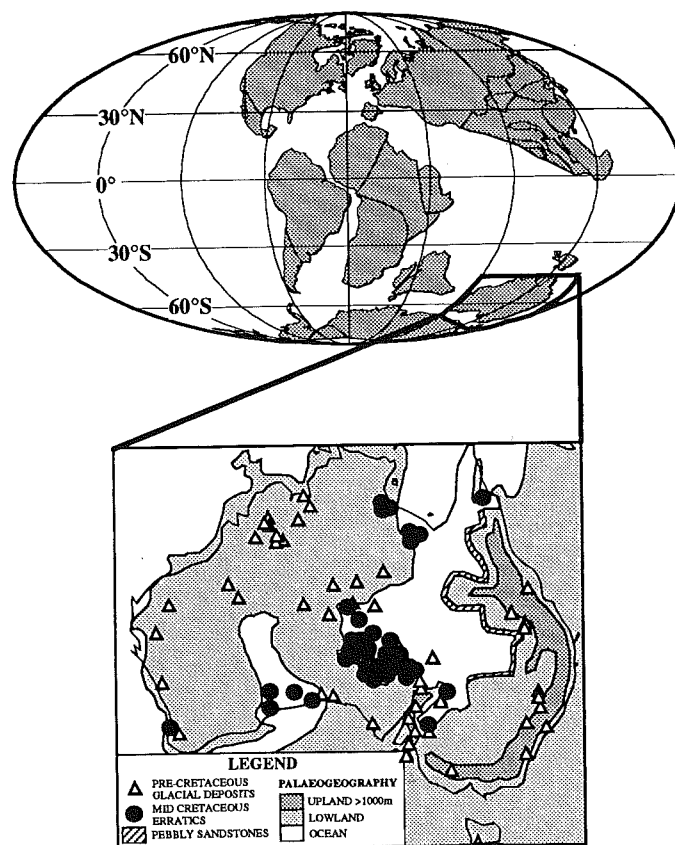


FIG. 9.—Distribution of Australian middle Cretaceous erratics. Open triangles = pre-Cretaceous erratics, diagonally shaded area = pebbly sandstones. See Table 3 for references. Paleogeography after BMR Paleogeographic Group (1990). Plate reconstruction is for 105 Ma, Albian (Rowley, unpublished data).

to Woolnough and David (1926) that the striated clasts had undergone subsequent water-borne transport. Furthermore, confusion of faceting with fracture surfaces is a possibility. The erratics are generally well-rounded ("water-worn" of earlier authors, Brown, 1894; Woolnough and David, 1926). It is also in this area (between White Cliffs and Dalhousie) that we find the largest erratic clasts of the Mesozoic and early Cenozoic (>1 m in diameter, up to 3 m in diameter, Frakes and Francis, 1988; although most reports seem to be less than 1.5 m in diameter). Jack (1931), noting the diminution in size and quantity from south to north, suggested that this might reflect the transport direction. Glendonites have been reported associated with these erratics (Anderson and Jevons, 1905; David and Taylor, 1905; Jaquet, 1893; Raggatt, 1938).

Erratics also occur in the Eucla Basin, where the only erratics so far recognized are granite boulders from the Loongana Sandstone (Lowry, 1970) of probable late Neocomian-early Aptian age (Lowry, 1970; Skwarko, 1969). Scattered quartz pebbles are reported from numerous deposits of this age: from the Wyandra Sandstone Member (Aptian) of the Cadni-Owie Formation in the Eromanga Basin (Exon and Senior, 1976), the claystone of the Neocomian-Aptian Leederville Formation (Playford et al., 1976), the Albian-Cenomanian Osbourne Formation in the Perth Basin (Playford et al., 1976), and Unit 6 (Aptian) of the "Coastal Belt suite" of Skwarko (1966; Walpole et al., 1968) in the Northern Territories, which is probably equivalent to the unit where Frakes and Krassay (1992) described erratics. In addition Skwarko (1966) describes isolated pebbles and boulders from the Neocomian marine sandstones of Unit 2 from the same area. Quartz boulders are found in the Rumbalara Shale (Aptian) south of Alice Springs in the Northern Territory. Pebbly sandstones and conglomeratic layers occur along the eastern margin of the Great Artesian Basin associated with the middle Cretaceous transgression, but no demonstrable "erratics" are reported. In the northern Territory the largest clast recorded is only 26 cm in diameter (Frakes and Krassay, 1992).

Sedimentary features associated with the erratics are rarely reported, since most erratics are known from loose surficial specimens. Frakes and Krassay (1992) noted "penetration structures" in immediately underlying laminae consistent with a dropstone origin for their erratics, and this has also been reported in South Australia (Frakes and Francis, 1988).

The erratics are commonly associated with fossilized wood (Alley, 1988; David, 1932; Flint et al., 1980; Frakes and Francis, 1988, 1990; Frakes and Krassay, 1992; Krieg, 1986; McKirdy et al., 1986; Moore and Pitt, 1985; Pittman, 1901; Süssmilch, 1914; Walkom, 1929; Ward, 1927; Woodard, 1955; Woolnough and David, 1926), with preserved logs up to 6.4 m (21 ft) long and up to 1.1 m (3.5 ft) in diameter (Woolnough and David, 1926). Woolnough and David (1926) found a group of logs near Muloowurtina amidst which were numerous small erratics and a large quartzite boulder over 1 m long. Fossil wood is also reported from the Perth Basin of Western Australia (Cockbain and Playford, 1972; Playford et al., 1976), Queensland (Day and Tweedale, 1960; Jack and Etheridge, 1892) and Northern Australia (Skwarko, 1966). Concentrations of erratics and wood appear to occur in distinct horizons or boulder beds. These coincide with the basal portions of transgressive units such as the base of the Bulldog Shale and in the Cadni-Owie

Formation (Flint et al., 1980). Indeed, the concentration of wood may be diagnostic of transgressive units (Savrda, 1991).

#### *Depositional environment and provenience.—*

During the middle Cretaceous, a series of major marine transgressions inundated much of Australia (BMR, 1990; Frakes and Rich, 1982). The coals and fluvial deposits of the Late Jurassic and earliest Cretaceous were replaced by marine clays, siltstones and sandstones, which grade into fluvial sandstones and conglomerates around the basin peripheries. Although there were highlands in the east and southeast of the continent associated with the initial rifting between Australia and Antarctica in the south (Otway and Gippsland basins) and between the Lord Howe and Norfolk Rises in the east, most of the land at this time was relatively low lying. There may also have been small islands of Paleozoic rocks, such as Mt. Woods, in parts of the southwestern Great Artesian Basin (Jack, 1915). The land masses were forested, especially in the south, with evidence of upland forests dominated by podocarps (Dettman et al., 1992) during the Aptian. In Victoria a diverse biota including theropod dinosaurs, hypsilphodontids, turtles and birds is known from fluvial and lacustrine deposits of the same period, as are abundant plant remains (Douglas and Williams, 1982; Rich et al., 1988; Rich and Rich, 1989). The Aptian shallow seas appear depauperate in comparison with times before and after; Whitehouse noted the absence of phylloceratid, lytoceratid, hoplitid, or pseudoceratitic ammonites, hibolitid belemnites, reef coral faunas, rudistic lamellibranchs, nerineid gastropods, or large foraminifera (David, 1932; Day, 1969; Scheibnerová, 1971).

Many of the erratics seem to be reworked from earlier diamictite deposits (David, 1907; Ludbrook, 1966; Moore and Pitt, 1985; Parkin, 1956; Woodard, 1955; Woolnough and David, 1926). This may explain both the high density of erratics (especially large erratics) in southern Australia and also the fact that only in this area do Mesozoic erratics show any evidence of striations or facets, the faintness reported for the rare striae reflecting reworking. Flint et al. (1980) suggested that the Devonian quartzite boulders at White Cliffs were originally derived from the Amphitheatre Group near Gobar, N.S.W., and were initially transported from there during the Permian glaciation of the area. Indeed, the clasts of the Cretaceous and those of the Permian tillite are lithologically quite similar. This reworking has probably occurred more than once. Flint et al. (1980) further noted that these clasts are not restricted to the Bulldog Shale but also occur in the underlying Mt. Anna Sandstone, Cadni-Owie Formation and the fluvial Algebuckina Sandstone (nomenclature as given in Flint et al., 1980). Slumping is present in the Bulldog Shale (Flint et al., 1980; Wopfner et al., 1970). As with the erratics of the Chalk, it is probable that such material littered shorelines during this period (Flint et al., 1980; Hawke and Bourke, 1984; Wopfner et al., 1970).

#### *Erratic Emplacement Mechanisms*

##### *Non-rafting mechanisms.—*

**Impact.**—Oberbeck et al. (1993) and Rampino (1992, 1994) have recently drawn attention to the purported resemblance between diamictites of glacial and those of impact origin. While some previously described "glacial" diamictites may indeed be impact ejecta, established glaciations with their repeated glacial

cycles, geomorphic landscapes (glacial valleys, nunataks, etc.) and facies transitions, are difficult to reinterpret as impact related, and we find no support for this alternative interpretation. An impact origin for the pebbly mudstones and erratic bearing deposits of the Mesozoic-early Cenozoic is untenable.

**Mass flow.**—Mass flow deposits form in geological settings where gravitational instabilities exist. They are typified by diamictites ("terrigenous sedimentary rocks that contain a wide variety of particle sizes," Flint et al., 1960) and are more or less recognizable depending on the characteristics of the flow regime responsible. Thus the presence of slumps or graded stratification (indicative of plastic and viscous fluid flows respectively) is generally diagnostic, but intermediate flow regimes (fluid enough not to preserve slump structures, but cohesive enough to prevent total separation and differential resettling) can be ambiguous. Such intermediate flow regimes are typified by pebbly mudstones (see Crowell, 1957; Dott, 1963; Middleton and Hampton, 1973; Stanley, 1969), which are the major facies used in the Mesozoic to infer glaciation (Epshteyn, 1978; Frakes and Francis, 1988).

The superficial resemblance between diamictites of glacial and mass flow origin is problematic, especially in the absence of lateral facies constraints or demonstrable glacial striae. This has led some authors to suggest that many "glacial" deposits may in fact be mass flow deposits and should be re-evaluated (Crowell, 1957; Crowell and Winterer, 1953; Dott, 1961) (viz., Squantum "tillite," Massachusetts (Coleman, 1926; Dott, 1961); Ridgeway and Gunnison "tillites," Colorado (Van Houten, 1967); middle Caradocian Cosquer Formation, Brittany, France, (Long, 1991) or the Precambrian Poudingue de Granville of Normandy (Winterer, 1964)). Where such deposits are associated with turbidites and slumped units, as in the Campanian-aged Lago Sofia Conglomerate (Cerro Toro Formation) of Chile, this re-interpretation seems justifiable (Cecioni, 1957; Scott, 1966). However, a study of Antarctic depositional systems shows that the two are not mutually exclusive (Kuvaas and Leitchenkov, 1992; Wright et al., 1983). Indeed, Heezen and Hollister (1964) proposed a link between periods of high turbidite deposition and periods of glaciation. Nonetheless, whereas glaciation may lead to increased physical weathering and sediment supply, resulting in high volumes of sediment on the continental shelf and concomitant instability, the reverse need not be true. Without corroborating evidence, mass flow is no more than evidence of gravitational instability and slope failure and not necessarily of glaciation.

The lack of any direct association between slumping and erratics in either South Australia or the Chalk of southern England would suggest that this is not the principle emplacement mechanism in either case, although it may have been responsible for reworking the clasts once they are deposited. In both cases the clasts must be transported into the depositional basin by another process and this can only be through rafting.

#### *Rafting mechanisms.*—

**Ice.**—Glacio-marine sediments are currently forming in  $\approx 10\%$  of the world's oceans (Drewry, 1986). During the last glaciation, such deposition accounted for far greater volumes of sediment. In the Pleistocene North Atlantic up to 40% of the sediment deposited was transported by ice rafting (Molnia, 1983). A distinction must be made between iceberg rafting (evidence

of calving glaciers) and sea or coastal ice rafting (indicative of at least seasonal freezing).

**Coastal, sea and river ice.**—Coastal, sea and river ice form by in-situ freezing. Although such ice makes no contribution to eustasy, it has been used as evidence of prevailing cold conditions and possible glacial conditions in higher latitudes. It has also been suggested as a rafting agent to explain Cretaceous erratics (Lyell, 1872; Frakes and Francis, 1990).

Observational data suggest that ice growth is a function of the number of successive days with air temperatures below freezing (more realistically taken as  $-1.8^\circ\text{C}$ , the freezing temperature of "average" sea water) (Bilello, 1961; Fig. 10). This initially occurs in shallow or low salinity regions such as coasts or especially river mouths (Markham, 1986), where sediment is most likely to be entrained. Although today perennial sea-ice is essentially limited to the Arctic Ocean and a narrow belt around the Antarctic continent (Gow and Tucker, 1990), seasonal freezing of water bodies does occur elsewhere. Historical records report ice formation in low latitudes during particularly severe cold periods, such as the Baltic (Lindgrén and Neumann, 1982), the Venetian lagoon (Camuffo, 1987), and the Suffolk coast (Lamb, 1985), and in 829AD ice was even reported on the Nile River (Lamb, 1985, p. 427). Such low latitude sea and river ice is generally thin, reflecting the limited time available for growth. Since deposition of the Chalk occurred at about  $45^\circ$  paleolatitude, rafting by sea- or river-ice would imply that seasonal thermal conditions during the middle-late Cretaceous were similar to, or indeed colder than, those of the present. These conditions are incompatible with fossil evidence.

Although we can estimate the carrying capacity of sea or river ice (Fig. 11), observations show that the limiting factor for rafting of debris is in-situ melting, not carrying capacity. Entrainment of coarse material occurs mostly through basal freezing adjacent to the sediment-water interface (Osterkamp and Gosink, 1984). Since this is also the site of early melting (indeed such melting is a prerequisite if the ice is to move away from the shore), most coarse material is lost before significant transport has occurred (Clark and Hanson, 1983; Kempema et

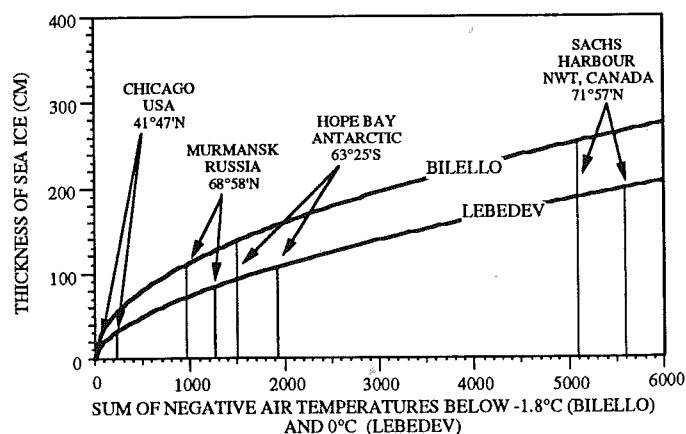


FIG. 10.—The relationship of ice thickness to its effective growing period. The effective growing period is approximately represented by the sum of mean daily temperatures for days with temperatures below either  $0^\circ\text{C}$  as used by Lebedev, or  $-1.8^\circ\text{C}$  used by Bilello, 1961;  $-1.8^\circ\text{C}$  more closely approximates the freezing temperature of sea-water.

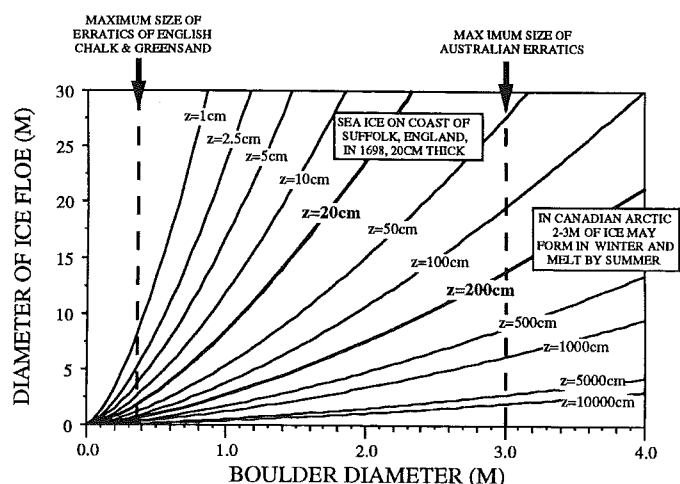


FIG. 11.—The carrying capacities of ice bodies of different thicknesses (cm) and areas (m). The area of ice required to carry boulders of specified sizes is represented as a circle with the diameter given on the y-axis. Note that sea-ice loses most of its entrained material in-situ during initial melting.

al., 1989; Wollenburg et al., 1988). Studies in the Beaufort Sea of Alaska show that in-situ melting accounts for the loss of 90% of entrained sediments before any transport occurs (Drewry, 1986). Similarly, Drake and McCann (1982) found that boulders were also deposited in-situ on Canadian tidal flats during the early stages of breakup and melting. Here, sliding is the dominant mechanism for moving large boulders, a process that is precluded when the water depth is greater than the diameter of the boulder. Quantitatively, only fine material (silt or finer) is transported more than a few 100 meters from the coast, and the sediment content of sea ice is dominated almost exclusively by aeolian derived material within a few kilometers offshore (Drewry, 1986). Wollenburg et al. (1988) noted that the sea ice north of Svalbard comprised 40–60% clay and 30–50% silt with a maximum of only  $\approx 10\%$  fine sand. Sharma (1979) found that sea-ice sediment from the Bering Sea comprised mostly silt (35–80%) and clay (12–60%) with only minor sand (1–8%), while Hoskin and Valenica (1976) noted that ice rafted sediment accumulating on the floor of Yakuta Bay, Alaska, is mainly mud. Thus although the high paleolatitude of South Australia in the Mesozoic is not necessarily incompatible with seasonal freezing (Dettman et al., 1992), the large sizes of the clasts (especially those  $>1\text{m}$ ) precludes rafting by such ice.

**Icebergs.**—The size of transported clasts is not a limiting factor for iceberg rafting, although like sea ice, debris in icebergs is dominated by the finer fraction (e.g., Kane cores, Pacific Ocean: coarse pebble fraction comprised  $<1\%$  of total sediment; silt and clay fraction average 77.2% of all sediment, Molnia, 1983), but the method of entrainment differs. Glacially-derived material enters the ice system either through subglacial erosion or from material falling onto the ice surface (supraglacial). Once entrained, material can be moved throughout the glacier by internal deformation. Observations have shown that Arctic derived icebergs typically contain much greater amounts of debris throughout the iceberg than do those from Antarctica (Anderson et al., 1980), although quantitatively the basal layers are the most important source of rafted material (Dowdeswell and Dowdeswell, 1989). Arctic glaciers are generally small valley

types with adjacent mountains supplying morainic material onto the glacial surface. Such supraglacial debris is generally absent in Antarctica, where the large ice sheets have largely overridden the valley sides. This difference is reflected in the character of glacial debris. Material from basal levels has undergone mechanical breakdown and sorting during transit (Anderson et al., 1980; Domack et al., 1980). It is typically sub-rounded to rounded (Dowdeswell and Dowdeswell, 1989; Gottler and Powell, 1989) and is dominantly fine grained close to the base (Drewry, 1986). Supraglacial material which has not experienced comminution is typically angular and poorly sorted (Dowdeswell and Dowdeswell, 1989; Gottler and Powell, 1989). This distinction can be used in the geological record for distinguishing between alpine type glacial deposits and those formed from ice sheets (Matsch and Ojakangas, 1991). Mesozoic and early Cenozoic erratics (see Table 3) are dominated by smoothed and rounded clasts, such that if they were transported by icebergs the source of that ice would have been large ice-sheets rather than localized mountain (alpine) glaciers.

Ultimately, melting is the limiting factor in the distribution of ice rafted debris (IRD). Calculations of melting rates suggest that on average 1 m of basal ice is lost every 66 days (Drewry, 1986), although rates range between 0.1 and 100 m per year (Drewry and Cooper, 1981). As a consequence, most iceberg rafted material is lost early, as in Spitsbergen where little IRD makes it out of the fjords. Studies in the fjords of the Antarctic Peninsula show that the percentage of sand decreases exponentially with distance from the ice front (in Lapeyriere Bay the amount of sand in surface sediments drops from  $\approx 80\%$  at the ice front to less than 5% 15 km down fjord, Domack et al., 1989). Furthermore, most of the basal material carried by the inland ice sheets in Antarctica is lost by melting close to the grounding line (Drewry and Cooper, 1981) and is not present in the ice shelf or calved icebergs.

Icebergs form by calving from glacial termini. If the entrained material is to be deposited in marine sediments then these termini must be at sea level and the ELA will be at low elevations which, according to the present glacier distribution (Fig. 5), suggests that land regions poleward are more or less fully glaciated. This is unrealistic for the erratics of the Chalk, but is also difficult to accept for those of South Australia because such glaciers would require that all of contemporary Antarctica be glaciated for which there is no demonstrable evidence. But is iceberg rafting really necessary? The answer is unequivocally no, because there are other viable rafting agents available.

**Animals.**—Many organisms, including marine mammals, crocodiles, fish and birds, are known to transport pebbles in their stomachs, either as an aid to digestion or as possible ballast (Emery, 1963; see Table 4). Emery (1963) reported finding stones in the stomachs of 73 of 170 California sealions studied (Emery and Tschudy, 1941; Fleming, 1951). In the fossil record, “gastroliths” have been found associated with marine reptiles, notably the plesiosaurs (Bearpaw Shale, Montana, Darby and Ojakangas, 1980; Pierre Shale, South Dakota, Welles and Bump, 1949; and Gault Clay, England, Seeley, 1877). A study of the Eocene vertebrates of the Messel Shale of Germany noted that almost all adult specimens of the alligatorid genus *Diplocynodon* contained a number of small pebbles (Schaal and Ziegler, 1992). Described gastroliths are invariably rounded and



TABLE 4.—RAFTING MECHANISMS

Mechanism	Sizes	Sorting	Shape	Other
Icebergs	clay to boulders <sup>1</sup>	poor <sup>1</sup>	angular (supraglacial), to rounded (subglacial)	facets, striations may be present <sup>1</sup>
Sea/coastal ice	clay to boulders, <sup>1</sup> dominantly wind blown material (silt & fine sand)	poor to good <sup>1</sup> (beach derived may be very well sorted depending on source)	angular to rounded, <sup>1</sup> depends on source. beach derived material generally rounded <sup>11</sup>	some striations, <sup>11</sup> more proximal to source than icebergs <sup>1,6</sup> (i.e. coastal). Organic matter is rare, <sup>11</sup> Carbonate content low, <sup>11</sup>
River Ice	clay to boulders, dominantly wind blown material	poor to good, depends on source	depends on source, but generally rounded	deposited close to river mouth, associated with other fluvial material, terrigenous input
Mammals	up to 9.4 cm long recorded (sea lion) <sup>9</sup>	depends on source	generally sub-well-rounded, <sup>2</sup> but depends on source	may occur in groups depending on amount of postmortem reworking; occasionally found with remains of organism; very proximal to source <sup>7</sup>
Reptiles	up to 12 cm <sup>2</sup> (Pebbles associated with Cretaceous Elasmosaurs are between 1 and 12.8 cm, mostly between 2 and 8 cm <sup>10</sup> )	depends on source	generally rounded	may occur in groups depending on amount of postmortem reworking; occasionally found with remains of organism <sup>10,12,13</sup>
Fish	up to 10 cm diameter, <sup>2</sup> generally smaller		generally rounded	
Trees	up to at least 400 cm diameter <sup>3</sup>	depends on source	depends on source especially whether they are derived from a soil (river-beach bank) or via tree-root dislocation along joints (may be more angular)	widespread, <sup>2</sup> clasts generally isolated, but aggregations reported <sup>3</sup>
Seaweed	up to 30 cm diameter, depending on size of alga (see discussion)	depends on source	often rounded, <sup>2</sup> but depends on source	generally isolated clasts, but some aggregations reported, <sup>4</sup> evidence of boring and encrusting organisms may be present, <sup>4</sup> the larger seaweeds are restricted to higher latitudes <sup>3</sup>
Birds	up to c. 3 cm diameter, <sup>2</sup> usually <1 cm <sup>2</sup>		rounded	
Flotation	pumice (various), sand and silt, coral		depends on source, can be angular (pumice)	pumice can float long distances, <sup>2</sup> sand requires very quiet water,
NON-RAFTING MECHANISMS				
Aeolian	up to 200 $\mu$ m for long range transport <sup>8</sup>	very well sorted	well rounded, <sup>2</sup> frosting may be apparent	widespread, Chinese sediment found on Hawaii <sup>8</sup>
Mass-Flows	up to kms (olisthostroemic clasts)	depends on source	depends on source	associated graded beds, slumps

1-Gilbert, 1990; 2-Emery, 1963; 3-Emery, 1955; 4-Emery and Tschudy, 1941; 5-Church, 1919; 6-Clark and Hanson, 1983; 7-Emery, 1941; 8-Betzer et al., 1988; 9-Fleming, 1951; 10-Welles and Bump, 1949; 11-Lisitzin, 1958; 12-Darby and Ojakangas, 1980; 13-Nakaya, 1989.

smoothed, although sizes vary depending on the organism responsible. The sealion gastroliths described by Fleming (1951) range up to 9.4 cm long, while gastroliths found in intimate association with Cretaceous plesiosaur remains range up to 12.8 cm (Welles and Bump, 1949; see Table 4). Thus rafting by marine reptiles can explain most of the erratics of the Mesozoic and early Cenozoic, and indeed a group of 107 stones, interpreted as gastroliths, have been found in the Chalk at Rochester (Hawkes, 1951). However, it is difficult to explain the 3-m diameter boulder found in the Bulldog Shale of Australia as a gastrolith, and thus alternative mechanisms must be operating. *Seaweed*.—During his voyage on H.M.S. Beagle, Darwin noted that certain seaweeds could carry pebbles and boulders far into the ocean (Darwin, 1839; 1896, p. 239). Kelp (the common name for any of the members of the brown algae orders Laminariales and Fucales) are commonly up to 50 m in length (Lüning, 1990, p. 151), and can occasionally reach 200 m long (Emery and Tschudy, 1941). The carrying capacity of kelp is a function of its size and the strength of the holdfast (the rootlike structure at the base of the seaweed). Gilbert (1984) noted that of the 109 stones he studied which had attached *Fucus* specimens,  $\approx 60\%$  were in the size range 3- to 6.5-cm diameter, with

the largest 9 cm in diameter and weighing 1.2 kg. It is not uncommon for one pebble to have more than one alga attached and consequently the combined carrying capacity is much greater. Church (1919) reports one case where nine large Laminarians were found with stones weighing over 25.5 kg (56 lbs). Church (1919) further states that *Saccorhiza bulbosa* frequently carries blocks of 50–60 “or even 80 lbs” (23–27, 36 kg). Darwin’s (1896) description of some of the attached stones as so heavy “that when drawn to the surface, they could scarcely be lifted into a boat by one person” is thus not improbable. Once seaweed reaches neutral or positive buoyancy (and even as it sinks) it is at the whim of ocean currents (Gilbert, 1984). Masses of seaweed have been observed far from land: for example, Emery and Tschudy (1941) report floating kelp 400 km from the nearest land; Menard (1953) reported a mass of floating seaweed (*Nereocystis*) 10 m (c.  $\approx 30$  ft) long just east of Gilbert Seamount, or  $\approx 1000$  km from the nearest land (Alaska) and 480 km from the nearest shallow water where it could have grown (Menard, 1953). One plant in this mass held a fine-grained calcareous sandstone cobble which measured 8 x 5 x 4 cm (Menard, 1953).

Material is released either by sinking of the kelp, due to changes in water density or saturation of cells and buoyancy

organs, or by the severance of the holdfast from the stipe (stem) due to organic activity (consumption by invertebrates, fish etc., Emery, 1963). Edgar (1987) noted that the holdfasts of the kelp *Macrocystis pyrifera* observed off Tasmania were rapidly destroyed by the abundant boring isopods, *Phycolimmoria* spp. Upon reaching the sediment surface the organic matter may be destroyed very quickly through biodegradation or consumption by benthic invertebrates (Gilbert, 1984). Consumption by echinoids and gastropods is especially significant, and as a consequence, evidence about the nature of the transporting medium may be lost. Seaweed also transports numerous organisms including echinoderms, sponges and worms, bryozoa, foraminifera, worm tubes, and calcareous red algae (Emery and Tschudy, 1941; Edgar, 1987).

Unfortunately the fossil record of seaweed is extremely poor and although, like marine reptiles, rafting by seaweeds could potentially explain all but the very largest erratics of the Mesozoic and early Cenozoic, direct support for this mechanism is presently absent.

**Trees.**—Tree rafting has often been considered an explanation for erratics in the geologic record (Lyell, 1841), but has generally been dismissed in preference for an ice origin because of purported size restrictions (Bonney, 1872; Double, 1931; Frakes and Francis, 1988; Frakes and Krassay, 1992; Godwin-Austin, 1858; Jeans et al., 1991; Lyell, 1872). However, the carrying capacity of trees depends entirely on their size and bulk density; the larger the tree, the larger the boulder that can be carried. We can place some constraints on the carrying capacity of wood using Archimedes' principle to assess the length of tree necessary (given wood density and trunk diameter) to carry a specified boulder (the density of granite,  $2.7 \text{ g cm}^{-3}$ , is used). The derived equation used in this calculation is:

$$L_t = ((D_b^3/6) * ((\rho_b - \rho_w)/(\rho_w - \rho_t)))/R_t^2 \quad (2)$$

where  $L_t$  is the length of tree required (cm),  $R_t$  is the radius of the tree (cm),  $D_b$  is the diameter of the boulder (cm), and  $\rho_b$ ,  $\rho_w$  and  $\rho_t$  are the densities of the boulder, water and tree respectively ( $\text{g cm}^{-3}$ ). The results for various tree radii are shown in Figure 12. A similar calculation was made by Liu and Gastaldo (1992) to assess the carrying capacity of trees in the Carboniferous Upper Pottsville Formation of Alabama, although they assumed that log-rafts rather than individual logs were required. Curves represent a range of density values that take into account taxonomic differences as well as different densities resulting from dry wood and water saturated wood.

Historical evidence of tree rafting illustrates the large distances and carrying capacities possible. Darwin (1839) described boulders on the Keeling Islands transported by trees. More recently a 3 m (10 ft) long *Nothofagus* log with embedded pebbles was discovered on a beach in SW Tasmania and which was probably derived from South America, some 16,000 km away (Barber et al., 1959). Emery (1955) reported a sighting of a 35-m tree in the Pacific which held a 3- to 4-m boulder; the sighting was 240 km from land and the log well encrusted with boring organisms and barnacles. Although trees ultimately sink through water saturation of their tissues and boring (Emery, 1963), the distances described above show that this process is not necessarily rapid. Indeed, Pratt (1970) proposed that the erratics dredged from the Blake Plateau were rafted in trees from the Guyana Shield (the largest erratic in this case was 15

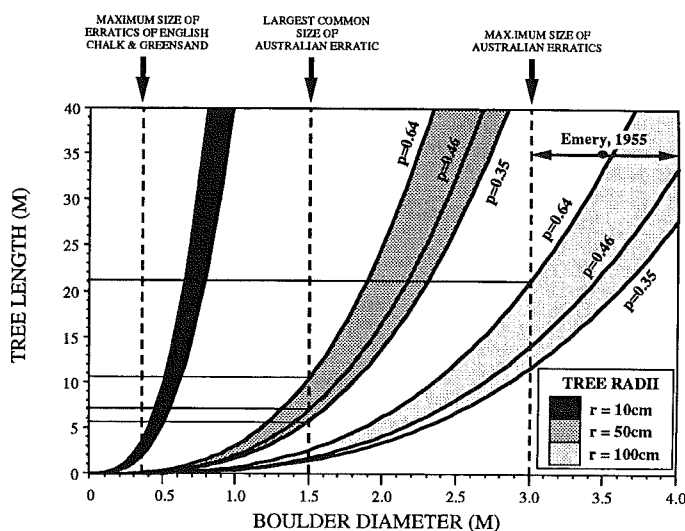


FIG. 12.—Graph showing the tree size required to carry boulders of specified size. The range of tree densities,  $\rho$ , reflects the range of densities in living gymnosperms given moisture contents of 12% (Niklas, 1992). Saturation of the wood during transit will increase the density. The position on the diagram of the 35 m tree with a 3–4 m diameter boulder mentioned by Emery (1955) is indicated by the arrowed line (top right).

x 25 x 20 cm). In addition to isolated boulders or pebbles, sediment can also be caught in the roots of trees and transported (Markwick, personal observation).

From Figure 12 it is clear that all of the erratics listed in Table 3, including the largest clasts of South Australia, could be transported by trees. Since fossil wood is extremely common in Mesozoic and early Cenozoic erratic-bearing and associated deposits, particularly those of Australia (as discussed earlier), it is surprising that it has been so readily dismissed. In part, this dismissal of tree-rafting results from the observation that the preserved wood fragments are incapable of carrying the associated erratics (Frakes and Francis, 1988; Woolnough and David, 1926; Godwin-Austin, 1858). This is untrue, since the preserved "fragments" are undoubtedly smaller than the volumes of contemporary wood available because of taphonomic factors. The rarity of wood and floral material in the Chalk, for instance, despite a good vertebrate and invertebrate record, is almost certainly more a consequence of the alkaline conditions prevailing in a carbonate-rich environment than an indicator of the absence of vegetation on surrounding landmasses. Wood is certainly known from flints preserved in the Chalk (Phillips, 1865; Cayeux, 1897; Dines et al., 1933; Dixon, 1850; Jukes-Browne and Hill, 1887; Lyell, 1841; Stebbing, 1897), which suggests that it was present on adjacent land. Interestingly, wood from the Chalk is commonly water-worn and bored (Mantell, 1833; Dixon, 1850) consistent with rafting in the oceans. *Teredo*-like borings are also common in middle Cretaceous fossil wood from South Australia (David, 1932).

Tree-rafting consequently provides an excellent potential explanation for the erratics of the Mesozoic and early Cenozoic, supplemented with other organic rafters. Consequently, in the absence of any other compelling evidence for ice-rafting, there is no necessity for continental glaciation in the Mesozoic or early Cenozoic to explain such deposits. Thus, we are left with

only two lines of evidence: the 3rd-order curves of Haq et al. (1987) or their equivalents, which we have already shown are problematic, and the geochemical evidence for ice-sheets.

*Geochemical Evidence: Oxygen Isotopes as an Indicator of Sequestered Water Volumes*

It has been known since the 1950's that gradients in the concentration of  $^{18}\text{O}$  observed in the surface waters of the world's oceans are primarily controlled by evaporation, hence the apparent relationship with changes in salinity. The continuous loss of  $^{16}\text{O}$ -rich freshwater to ice regions leads to a relative enrichment of the oceans in  $^{18}\text{O}$  (Epstein and Mayeda, 1953). Since the amount of enrichment is proportional to the volume of water sequestered, the record of  $^{18}\text{O}$  in seawater ( $\delta^{18}\text{O}_w$ ) through time should also provide a record of glacial volume changes, and thus a potential means of testing the validity of proposed glacio-eustatic sea-level curves (Matthews, 1984; Rowley and Markwick, 1992). However, the direct measurement of ancient seawater is not possible. Instead  $\delta^{18}\text{O}_w$  values are determined by analyzing the isotopic composition of carbonate preserved in fossil shells ( $\delta^{18}\text{O}_c$ ). Unfortunately this composition reflects not only  $\delta^{18}\text{O}_w$ , but also the temperature at which the carbonate was precipitated (Epstein et al., 1951, 1953; Urey et al., 1951) such that:

$$T(^{\circ}\text{C}) = 16.9 - 4.38 (\delta^{18}\text{O}_c - \delta^{18}\text{O}_w) + 0.1 (\delta^{18}\text{O}_c - \delta^{18}\text{O}_w)^2 \quad (3)$$

where  $T(^{\circ}\text{C})$  is the temperature and  $\delta^{18}\text{O}_c$  and  $\delta^{18}\text{O}_w$  are respectively the isotopic composition of calcite and sea-water relative to some standard. Thus to calculate  $\delta^{18}\text{O}_w$ ,  $T(^{\circ}\text{C})$  must be specified. Matthews and co-workers attempted this by assuming that surface temperatures in the tropics have remained essentially constant at  $\approx 28^{\circ}\text{C}$  and only analyzing tropical plankton (Matthews and Poore, 1980; Matthews, 1984; Prentice and Matthews, 1988). A consequence of this approach is that for ice-free conditions ( $\delta^{18}\text{O}_w = -1.2\text{‰}$ , the result of melting the present ice sheets, Shackleton and Kennett, 1975) values of  $\delta^{18}\text{O}_c$  for planktonic tropical forms must be  $\leq -3.0\text{‰}$  (relative to PDB). This implies that ice-sheets occupied high latitudes at least back into the Maastrichtian and possibly throughout the Cretaceous (Matthews and Poore, 1980; see Fig. 13). This conclusion differs from that of Miller et al. (1987) in which ice-free conditions are implied prior to the Oligocene using benthic rather than planktonic values of  $\delta^{18}\text{O}_c$  (Fig. 13). This latter method assumes that high-latitude glacial conditions exist when  $T(^{\circ}\text{C})$  for bottom waters is  $\leq 2^{\circ}\text{C}$ , since these temperatures imply that the Antarctic margins were frigid enough for ice-sheet development. This translates to a  $\delta^{18}\text{O}_c$  of  $1.8\text{‰}$  (PDB), the value for which  $T(^{\circ}\text{C})$  is  $\leq 2^{\circ}\text{C}$  given that an ice-free world has an average  $\delta^{18}\text{O}_w = -1.2\text{‰}$ . Since recent sedimentological data from ODP Leg 119 in the Southern Ocean records evidence of ice-rafting back to the Middle Eocene (Ehrmann and Mackensen, 1992), it is clear that the benthic approach is problematic, although the size of the Late Eocene ice-sheet was probably small (Mackensen and Ehrmann, 1992). Indeed the assumption that bottom temperatures of  $>2^{\circ}\text{C}$  mean ice-free conditions neglects the possibility that deep circulation during past times was driven by Warm Saline Bottom Water (WSBW)

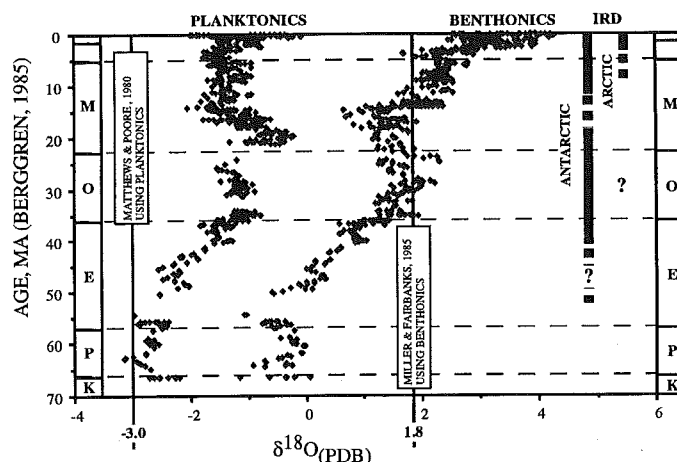


FIG. 13.—The benthonic and planktonic oxygen isotope curves (after Prentice and Matthews, 1988).

derived in low-latitudes (Chamberlin, 1906; Brass et al., 1982). In such a scenario bottom temperatures do not reflect ambient temperatures in high latitudes and thus make no prediction as to possible contemporary ice-sheets. However, this does not necessarily vindicate the tropical planktonic model since as we have already stated there is no unequivocal glacial evidence prior to the about the Middle Eocene.

That the magnitude of the  $\delta^{18}\text{O}_w$  shift should be proportional to the volume of water sequestered led Emiliani and Shackleton (1974) to attempt to constrain the isotopic signature of a specified glacio-eustatic change. Using isotopic compositions representative of subtropical sea-surface water and Antarctic snow, they placed bounds of  $+0.4\text{‰}$  and  $+1.6\text{‰}$ , respectively, on the  $^{18}\text{O}$  shifts resulting from the extraction of a water volume equivalent to a 120 m drawdown of the oceans (equivalent to sequestering  $4.3 \times 10^7 \text{ km}^3$ , the volume of water represented by additional ice at the last glacial maximum, LGM; Emiliani and Shackleton, 1974; a value of  $+1.1\text{‰}$  was used by these authors as being the most representative for the transition between LGM and present). These bounds correspond to isotopic shifts per volume of water sequestered of  $9.30 \times 10^{-9} \text{ ‰/km}^3$  and  $3.72 \times 10^{-8} \text{ ‰/km}^3$ , which were used by Rowley and Markwick (1992) to retrodict the isotopic signal resulting from the sea-level changes shown by the 3rd-order eustatic curve of Haq et al. (1987). If the 3rd-order curves are real then the retrodicted signal should be reflected in the actual isotopic record. However, an analysis of the Paleogene reveals no correspondence in either timing or magnitude between the two (Rowley and Markwick, 1992). Although the differences in magnitudes may be partly explained by non-linear fractionation of oxygen during ice build-up (Mix and Ruddiman, 1984, leading Miller et al., 1987, to suggest a value of  $\approx 1.51 \times 10^{-8} \text{ ‰/km}^3$  during the initial phase of ice-cap development), this does not explain the disparity in the timing of shifts, and Rowley and Markwick (1992) concluded that such disagreement strongly indicates that the 3rd-order eustatic curve of Haq et al. (1987) is invalid.

Comparison between the predicted isotopic curve of Rowley and Markwick (1992) and observed  $\delta^{18}\text{O}$  shifts is unfortunately mainly restricted to the Cenozoic, for which oxygen isotope data are rapidly accumulating (particularly for Oligocene and



younger times through the Ocean Drilling Project, ODP). Reliable data for the Mesozoic remain sparse, in part due to less sampling but also because of problems in determining potential "vital effects" for extinct faunas and increasing diagenetic effects in older rocks. Some data do, however, exist. Barrera et al. (1987) report oxygen isotope data for the Campanian through early Paleocene of Seymour Island, Antarctica, that suggest that shelf waters maintained temperatures between approximately 4.5° to 10.5°C throughout this interval at paleolatitudes between  $\approx 58^\circ\text{S}$  to  $\approx 63^\circ\text{S}$ , which supports interpretations that high latitudes remained ice free. But more significant is the recognition of rapid, high amplitude isotopic shifts in the Cretaceous chalks of Europe that have been interpreted by some workers as reflecting glacio-eustasy (Jeans et al., 1991). Studies by Jeans et al. (1991) and Lamolda et al. (1994) show the greatest isotopic fluctuation occurs in the upper Cenomanian Plenus Marls and lowermost Sussex White Chalk (also known as the Melbourne Rock; Figure 14), a unit of alternating marls and chalks that coincides with the widely recognized Cenomanian-Turonian Boundary Event (CTBE) and the Cenomanian-Turonian Oceanic Anoxic Event (OAE; Schlanger et al., 1987). The nature of these oscillations is therefore of great interest. Superimposed on the overall  $\delta^{18}\text{O}$  shift at this time are fairly systematic isotopic differences between the interbedded marls and chalks which both Jeans et al. (1991) and Lamolda et al. (1994) interpret as deposition of the marls in colder water than the

chalks. Similar differences have been reported from the middle Cenomanian chalks of Kent (Ditchfield and Marshall, 1989; mean marl-chalk  $\delta^{18}\text{O}$  variations of  $\approx 0.4\text{‰}$ ). If the overall shift does reflect the development of high-latitude ice-sheets, as Jeans et al. (1991) suggest, then these short-order fluctuations may be interpreted as glacial-interglacial oscillations. Figure 14 shows the  $\delta^{18}\text{O}$  data of Lamolda et al. (1994) and estimates of the implied volumes of sequestered water and sea level changes, assuming that the changes in  $\delta^{18}\text{O}$  are entirely due to ice volume changes. In order to obtain these we assumed that the ice-free conditions are represented by the data at  $-4\text{‰}$  and that all deviations are produced by ice formation. We used a linear shift of  $3.72 \times 10^{-8}\text{‰}/\text{km}^3$  of sequestered water, equivalent to that suggested by Emiliani and Shackleton (1974) for the Last Glacial Maximum; an average Cenomanian and Turonian elevation of sea level relative to today of 250 m; modern hypsometry from Cogley (1983); a corrected least squares linear regression of elevation and area of  $A_{-200-200\text{m}} = 106045 \cdot E$ , and  $30393700 \text{ km}^2$  for the area between +200 m and +299 m. Even employing a large fractionation effect per volume, the Lamolda et al. (1994) data interpreted in this way would imply rather extreme sea level fluctuations of almost 200 m on quite short time scales. We use stratigraphic thickness following Lamolda et al. (1994) rather than time, but the entire interval portrayed may represent no more than  $\approx 1$  my. Thus the implied fluctuations would be of the same order as those during the Pleistocene. It is worth noting that almost all of the data are more negative than  $-2.7\text{‰}$ , and even the lightest samples have values  $-2.0\text{‰}$ . Assuming an ice-free value of  $\delta^{18}\text{O}_w = -1.2\text{‰}$  and no "vital effects," these values imply sea-surface temperatures of  $>20\text{--}23^\circ\text{C}$ . If significant ice is inferred then the implied sea surface temperatures must increase ( $>25\text{--}28^\circ\text{C}$ ). Irrespectively, these implied sea surface temperatures are rather warm for ice-raftering to be considered a viable mechanism for the erratics of the Chalk.

Despite this apparent support for Cretaceous glaciation during Plenus Marl time, there are a number of problems to which we must draw attention. Haq et al. (1987) inferred an average sea-level change of only 25 m for the interval corresponding to the Plenus Marl, far less than that implied by the isotopic fluctuations. The effects of diagenetic alteration, recognized in the Plenus Marl (Jeans et al., 1991), are uncertain, but compensation for more negative diagenetic values may easily diminish the magnitudes of the oscillations and thus any glacial volumes. The relationship between marl deposition, interpreted by Jeans et al. (1991) as representing regressions, and positive  $\delta^{18}\text{O}$  shifts, that together seem to support a glacial origin, may be of local rather than global origin; indeed the opposite relation was found by de Boer (1982) in the Aptian-Albian marls and chalks near Moria, Italy. The erratics that Jeans et al. (1991) use to corroborate possible Plenus Marl glaciation also occur above and below this unit when there are no isotopic shifts that would seem to require large-magnitude changes in either temperature or sequestered water volumes. Lastly, we re-emphasize that shifts of 2 to 3 ‰ are very large indeed and would require Pleistocene or larger volumes of water to be sequestered as ice, for which we have no other record.

Nonetheless, such rapid, high amplitude fluctuations in the  $^{18}\text{O}$  record during purportedly non-glacial times are problematic. Although their magnitudes may in part reflect difficulties

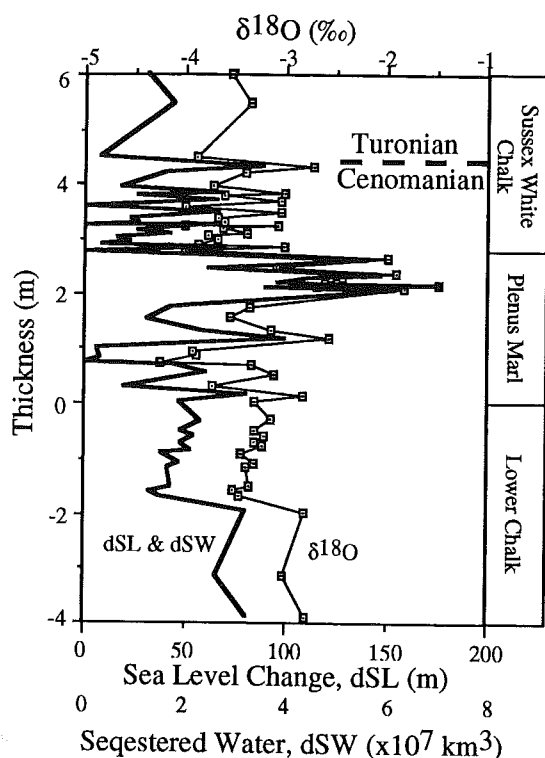


FIG. 14.—The oxygen isotope curve for the Plenus Marl of southern England (after Lamolda et al., 1994) with the sea-level change and volume of sequestered water implied by these values. Stratigraphy is that given in Lamolda et al. (1994; in the traditional stratigraphic nomenclature of Gallois, 1965, the Sussex White Chalk would correspond to the Middle Chalk, and the Plenus Marl would form the uppermost part of the Lower Chalk).

in isolating the various components of the isotope signal, the coincidence of such sudden perturbations with an OAE suggests to us a possible causal link for both. During purportedly non-glacial periods such as the Cretaceous various workers have suggested that deep-water formation will occur in low latitude epeiric seas rather than at high latitudes as at present (Chamberlain, 1906; Brass et al., 1982). Railsback (1990) has modeled the effect of WSBW formation on the oxygen isotope signal of the world's oceans and finds that preferential storage of  $^{18}\text{O}$  in WSBW could result in a depletion in  $^{18}\text{O}$  in contemporary surface waters of  $\approx 0.5 - 1.5\%$ , similar in magnitude though opposite in sign to that due to the presence of large ice-sheets. Overturning of this salinity stratified system would lead to mixing of  $^{18}\text{O}$ -rich WSBW with surface waters and an observed positive shift in  $\delta^{18}\text{O}$ , as seen in the Plenius Marl. Since formation of WSBW is a function of the area of epicontinental seas between  $\approx 10 - 40^\circ \text{N}$  and  $\text{S}$  (Brass et al., 1982), times of high eustatic sea level would be conducive to enhanced WSBW formation. Arthur et al. (1987) suggested this might result in increased rates of deep-water upwelling and thus increased productivity and development of organic rich facies. Intermittant overturning of the salinity stratified water column may have resulted from this increased vertical circulation (Southam et al., 1982) or from global cooling due to decreased atmospheric  $\text{CO}_2$  concentrations following the burial of large volumes of organic carbon (Wilde and Berry, 1982; Arthur et al., 1988). The rates of WSBW production and oceanic overturn may have been extremely rapid (Brass et al., 1982) and may readily explain the  $\delta^{18}\text{O}$  oscillations shown in Figure 14.

From this discussion it should be clear that although oxygen isotopes provide a potential method of examining glacial history, the uncertainties associated with isolating the  $\delta^{18}\text{O}_w$  signal from other factors remains a problem. We strongly suggest that the  $^{18}\text{O}$  signal cannot be interpreted in isolation but must be corroborated with other geological evidence. No where is this better illustrated than in the disparity in ages estimated for the onset of Tertiary glaciation based on isotope data.

#### *Mineralogical Evidence: Glendonites*

The mineralogical evidence centers around the interpretation of mineral pseudomorphs collectively known as glendonites. Their significance depends on the precursor mineral proposed for the pseudomorph. There have been numerous candidates, including gypsum,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (Jaquet, 1893; Pautot and Fontes, 1979); glauberite,  $\text{Na}_2\text{SO}_4 \cdot \text{CaCO}_3$  (David and Taylor, 1905); thenardite,  $\text{Na}_2\text{SO}_4$  (Kemper and Schmitz, 1975, 1981); and most recently ikaite,  $\text{CaCO}_3 \cdot 6\text{H}_2\text{O}$  (Shaikh and Shearman, 1987; Shearman and Smith, 1985).

The coincidence of glendonites with glacial erratics in the Permian of Australia (where Dana first described such pseudomorphs in the 1840's) implies a link with glacial or at least cold conditions (Brown, 1925; Carr et al., 1989; David and Taylor, 1905; Raggatt, 1938). More recently Kaplan (1977) recognized that glendonites were mainly restricted to high latitudes and often associated with pebbly mudstones, which also suggests a circumstantial link to cold climates. This view has been further expounded by Kemper (1987; Kemper and Schmitz, 1981) and more recently by Frakes and Francis (1990). The suggestion that the precursor might be the mineral ikaite, which is only

stable at near  $0^\circ\text{C}$  conditions (Pauly, 1963), has consequently received considerable support from these quarters. However, glendonites are also known from low paleo-latitudes, and in particular from the Upper Triassic red bed basins of the eastern United States (Van Houten, 1965). Thus, although an ikaite origin may be appropriate for most glendonite occurrences based on available evidence, it is not likely for all, and a multiple origin for the pseudomorphs seems possible (David and Taylor, 1905). In the case of the Triassic of the eastern United States, the evaporite mineral glauberite seems more suitable; this mineral occurs today in such basins as the Gulf of Kara Bugaz (Kolosov et al., 1974; Sonnenfeld, 1984; Sonnenfeld and Perthuisot, 1989), Death Valley and the Great Salt Lake where it appears to form as a winter precipitate (Warren, 1989).

Low  $^{13}\text{C}$  values observed in ikaite, as well as glendonites from the Tertiary of Oregon (Boggs, 1972), imply a bacterial origin for the carbon (Suess et al., 1982), an origin which David proposed for glendonites in 1905 (David and Taylor, 1905). This is consistent with recent experiments on the stability of ikaite by Bischoff et al. (1993), which showed that the formation of significant amounts of ikaite in Ca-dominated cold seawater requires large amounts of dissolved orthophosphate and  $\text{HCO}_3^-$ . Both ions are provided by the decomposition of organic matter. We therefore suggest that the distribution of high latitude glendonites during the Mesozoic and early Cenozoic may be as much due to the distribution of organic-rich rocks as to cold conditions. The significance of the association of such organic-rich rocks with transgressive sequences and periods of high sea level has already been discussed.

#### THE PRESERVATION OF TERRESTRIAL GLACIATIONS

Terrestrial glacial deposits have been long claimed to have a poor preservational potential (Croll, 1875; Bjørlykke, 1985; Frakes and Francis, 1990). They are dominantly erosive and deposited material lies largely above local base level where it is subject to reworking and transport, consequently assuming the inherent characteristics (sorting, shape and size) of the new sedimentological regime, often to the total exclusion of any glacial signature (Croll, 1875). The argument that this preservational bias explains the absence of glacial evidence through the Mesozoic and early Cenozoic (Frakes and Francis, 1988, 1990) is, however, invalid. Bjørlykke (1985) noted that pre-Quaternary glacial deposits are often found in marginal marine or continental rift basins, and suggested that the latter especially would provide favorable environments for preserving glacial sediments. In the Mesozoic and early Cenozoic high latitude rift basins are preserved, such as in Spitsbergen in the Triassic and Jurassic, and more pertinently in southeastern Australia in the middle-late Cretaceous, but they do not contain recognizable glaciogenic sediments. What is more, any purported preservational hiatus as an explanation for the lack of glacial deposits through this 200-my period must also seriously compromise our trust in other areas of the Mesozoic and early Cenozoic record. Such a hiatus seems unlikely, as these periods are more than well represented in the geological record (Ronov, 1982). In addition, although the details of known glacial "events" are not always clear, especially the further back in time we go, they are nonetheless demonstrable and their effects are entirely consistent with observations of contemporary cli-

mate elsewhere on the globe. This would not be true for any purported large-scale glaciation during the Mesozoic-early Cenozoic.

#### THE ORIGIN OF MESOZOIC—EARLY CENOZOIC ERRATICS: A DISCUSSION

There is no reason for assigning a common origin for all erratic bearing deposits. Some are clearly due to mass flow (Crowell, 1957; Crowell and Winterer, 1953), such as the Campanian aged Lago Sofia Conglomerate (Scott, 1966), but for most erratics this is not demonstrable and rafting by agents unknown is more appropriate.

Icebergs are the most obvious rafting agents, but their requirement for sea level terminating glaciers is difficult to reconcile with the established climatic interpretation of the geological record during the Mesozoic and early Cenozoic, especially in the low paleolatitudes of Cretaceous northwest Europe. The faunal (Donn, 1987; Habicht, 1979; Markwick, 1992; Romer, 1961) and floral data (Dettman et al., 1992; Francis, 1988; Horrell, 1991; Spicer, 1987, 1989; Spicer and Corfield, 1992; Truswell, 1991) clearly imply warmth in latitudes that should, by analogy with the present, have been cooler if an ice-sheet existed. Even if established paleoclimatic interpretations are incorrect, sea-level terminating glaciers in the middle Cretaceous of South Australia implicitly mean a fully glaciated Antarctica with, one would expect, development of terrestrial glacial and glacio-marine sedimentation around its margins. Yet there is no evidence of such sedimentation (Macellari, 1988; Pirrie, 1989). Instead, we know from paleobotanical data that forests covered the coasts of Antarctica from at least the Devonian and persisted well into the Tertiary (Truswell, 1991). Sea-ice rafting, although not incompatible with high latitude paleoclimates per se, even in the Cretaceous (Dettman et al., 1992; Frakes et al., 1992; Frakes and Krassay, 1992; Spicer and Parrish, 1990) cannot account for the size of the clasts preserved, since such material is lost rapidly through in-situ melting before any large-scale transport occurs. Despite this, recent workers have continued to suggest an ice origin for the erratics of the Mesozoic and early Cenozoic (Epshteyn, 1978; Frakes and Francis, 1988, 1990; Frakes and Krassay, 1992; Jeans et al., 1991; Kemper, 1987). As argued in this paper, however, there are alternative explanations.

Organic rafting is a much maligned agent. Frakes and Francis (1988) dismissed it for the erratics of the Bulldog Shale because of the large size of some of the boulders (up to 3m). This was also the rationale used by Godwin-Austin (1858) and Lyell (1872) for dismissing organic rafting as an explanation of the much smaller erratics of the English Chalk. This reasoning, as we have shown, is invalid. Trees, for instance, are quite capable of transporting large boulders and indeed could transport all of the presently described erratics. The limiting factor is simply the size of the tree (Fig. 12). The close association of erratics and fossil wood in so many erratic-bearing deposits is therefore provocative, such as in the Triassic Lower Beaufort shales of South Africa where Broom (1911) reports of "... great masses of silicified wood and that a large number of water-worn stones were lying amongst the wood." Petrified wood is also occasionally found in the pebble-bearing Aptian Innkjegla Member of the Carolinefjellet Formation of Spitsbergen (Nagy, 1970). The presence of encrusting organisms such as serpulids on

many of the erratics of northwestern Europe (Double, 1931; Godwin-Austin, 1858; Sollas and Jukes-Browne, 1873; Kaever, 1974) may also be consistent with rafting by an organic rather than ice rafter. Such organic activity could have occurred after deposition, but this may have been precluded in the Chalk where the "soupy" nature of the substrate (Hancock, 1975) may have resulted in the clasts being enveloped by the sediment; none of the erratics in the Chalk appear to be associated with hardgrounds, with the possible exception of the pebbles in the Totternhoe Stone, Isleham. The Purley locality, in which large cobbles, pebbles and beach sand are found together (Godwin-Austin, 1858), is also significant in this respect, since the association implies the material was gently lowered to the bottom as a group rather than being dispersed during sinking from the sea-surface. In this case, a sinking tree settling to the bottom to rest on the soupy surface seems appropriate. The logs would have been subsequently destroyed by the high alkalinity and organic activity.

What is more, Kaplan's (1977) recognition of the prevalence of pebbly mudstones in high latitudes may reflect not only the potential distribution of ice, but also the location of the largest forests and lowest rates of decay. In times without a definable tropical rainforest, such as the Mesozoic and early Cenozoic (Ziegler et al., 1987, 1993), mid-high latitudes become the most productive with presumably the largest trees. The Cretaceous coals of the North Slope of Alaska represent about one third of the recoverable coals of North America (Sable and Stricker, 1987) and were produced at latitudes above 70°N (Spicer and Parrish, 1990). In the Late Paleocene—Early Eocene fossil forest of Strathcona Fjord, Ellesmere Island (≈78°N paleolatitude), there are tree trunks up to at least 1 m and root stocks up to 5 m in diameter and which may have been up to 40–50 m high (Francis, 1988).

There is evidence, however, that other rafting mechanisms may have been responsible. In the Chalk, the small sizes of the clasts mean that they could all have been potentially transported as gastroliths by marine reptiles. The group of 107 small pebbles found together at Rochester (Hawkes, 1951) and the occurrence of a plesiosaur in the same quarry as erratics at Houghton (Dixon, 1850) are suggestive of this agent. Unfortunately, no bones have been found in direct association with erratics in either the Chalk or the Upper Greensand, although they do co-occur in the Gault Clay (Seeley, 1877). Plesiosaurs are also known from the middle Cretaceous of the Great Artesian Basin of Australia (Jack and Etheridge, 1892; Molnar, 1982) and the Campanian-Maastrichtian of Banks Island (Jutard and Plauchut, 1973), regions from which erratics are known. The presence of plesiosaurs in high-latitudes may thus explain the occurrence of chert and quartzite pebbles found floating in both the upper part of the Hue Shale (Campanian, pebbles are <4-cm diameter, Molenaar et al., 1988) and the Pebble Shale unit of northern Alaska (Lower Cretaceous, Molenaar et al., 1988). Troedsson (1924) reported on 4 gastroliths (the largest being c. 7.1 cm long) found with crocodilian remains from the Danian limestones of Malmö, Sweden (see also Deslongchamps' suggestion that the smoothly rounded stones found in the oolitic strata of Normandy were deposited by crocodiles, Godwin-Austin, 1858).

Alternatively, even though kelp is not known from the Chalk, the size range of the erratics is within that explicable by modern

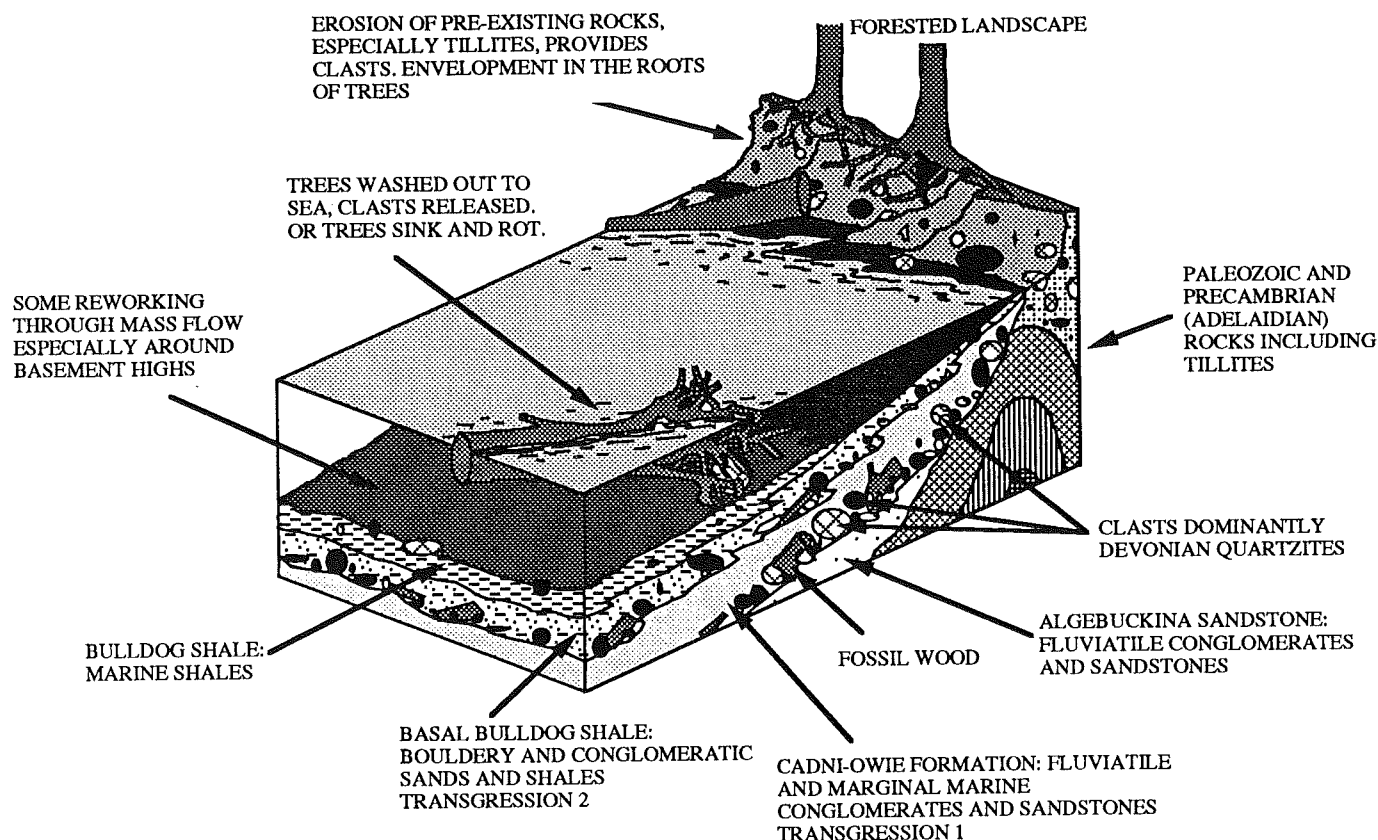


FIG. 15.—A reconstruction of the possible scenario for formation of erratic-bearing beds in South Australia during the middle Cretaceous.

seaweed rafting. Kelp forests today are highly nutrient dependent and commonly occur in mid-latitude upwelling zones (Lüning, 1990). In the Chalk seas bathymetric highs appear to have been the sites of dynamic upwelling. Phosphate nodules and coatings are not uncommon. These areas of high productivity may have been the sites of extensive kelp forests, with large numbers of marine reptiles and fish attracted into the area to feed. Erratics carried by such rafters might then be expected to be concentrated around such highs. Lyell (1841) originally suggested kelp or wood for rafting the erratics of the Chalk. Unfortunately, the preservational potential of kelp is so poor that its significance in the past is difficult to assess.

A further matter of interest is the association between erratic-bearing deposits (Table 3) and marine transgressions. This is clearly seen in Australia where the Neocomian, Aptian and Albian are all times of regionally significant marine inundations (Frakes and Rich, 1982). In South Australia, boulders and cobbles are first concentrated in the initial transgressive phase of the Cadni-Owie Formation (Alley, 1988) and are most abundant in the basal part of the Bulldog Shale marking the major phase of the Aptian transgression (Flint et al., 1980; see Fig. 15). Indeed, the concentration of rafted material along revinement surfaces during such transgressions may account for many erratic bearing deposits. Large amounts of organic rich material are also buried during these transgressions. In the Cretaceous this is particularly true during the Barremian-Aptian-Albian, the Cenomanian-Turonian and to a lesser extent the Coniacian-Santonian (Jenkyne, 1980). These three periods correspond with

Kemper's cold intervals, which were defined on the basis of glendonite occurrences (Kemper, 1987), and also include the erratics of the Chalk and South Australia. Positive  $\delta^{18}\text{O}$  excursions during at least one of these periods (Cenomanian-Turonian) has been interpreted as further evidence for glaciation during this time (Jeans et al., 1991), but as we have shown such shifts can also be explained by oceanic overturning and mixing of surface waters with  $^{18}\text{O}$ -rich WSBW, irrespective of any other effects, such as diagenesis, that might be responsible.

Thus a possible scenario develops with marine transgressions resulting in the erosion of forested land masses, especially in high latitudes, supplying the erratics, complete with organic rafts, to the marine record (Fig. 15). In the highly productive epicontinental seas we may envisage plesiosaurs scouping up such clasts to use as gastroliths while large forests of seaweed occupy the nutrient-rich shallows, occasionally to be ripped up by storms. The expansion of epicontinental seas enlarges the area of the photic zone and enhances productivity as well as WSBW formation. This in turn intensifies deepwater upwelling and consequently increases productivity of the surface waters, while also in part destabilizing the salinity stratified ocean. Cooling due to the burial of large volumes of organic matter further weakens the system such that intermittent rapid overturning occurs, which appears in the  $\delta^{18}\text{O}$  isotope record as sudden positive excursions. As for the glendonites, the deposition of organic-rich rocks in the cool bottom waters of high paleo-latitudes would have provided the ideal environment for ikaite formation.

### The Causes of Glaciation

If the Mesozoic and early Cenozoic were indeed largely ice free, a possibility recognized as early as 1836 by Beaumont (1836) and further discussed by Croll (1875), possible causes must be considered. Although a full discussion of this question is beyond the scope of the present paper, we do draw attention to the following: although there are numerous feedbacks that affect global climate, the ultimate driving force for climate change on geologic timescales ( $>10^6$  years) is tectonics (as expressed in changing land-sea distributions and the history of mountain building). The climatic effects of changing land-sea distributions were noted by Lyell, following the ideas of Baron von Humboldt: "... whenever a greater extent of high land is collected in the polar regions, the cold will augment; and the same result will be produced when there shall be more sea between or near the tropics; while, on the contrary, so often as the above conditions are reversed, the heat will be greater" (Lyell, 1830, p. 115). As stressed at the beginning of this paper, glacier formation requires that land at high latitudes must be of sufficient elevation to intersect the ELA. The coincidence of periods of glaciations and those of mountain building (using area of deformation as a proxy for mountains) is shown in Figure 7. The significance of land-sea distribution and orography are supported by recent computer modeling results (Barron, 1981; Barron et al., 1984; Kutzbach et al., 1989; Ruddiman and Kutzbach, 1989; Ruddiman et al., 1989). Thus the high global sea levels and low topography of the Mesozoic may have precluded the development of large-scale glaciations.

### CONCLUSIONS

If we are to accept the applicability, and magnitudes, of high-frequency eustatic changes as implied by the 3rd-order Haq sea-level curves, or their equivalents, then we must also accept their implications: that either an unknown eustatic mechanism existed in the past or there must have been a continuous history of waxing and waning of Antarctic-sized ice sheets since at least the late Jurassic (Rowley and Markwick, 1992; Fig. 2). We have shown here that the purported evidence for such ice sheets is ambiguous at best: that the erratic-bearing deposits can be better explained by organic rafting during times of marine inundation than by icebergs; that other cited evidence, such as glendonites, imply only cold conditions with no explicit need for large terrestrial ice sheets. That cold periods may have occurred during so-called "hot-house" periods (Cretaceous) is not at issue. Global climate is not uniform and we stress again that even during non-glacial periods in the Earth history it seems likely that mountain glaciers capped the highest mountain peaks, especially in high latitudes. But such small glaciers would have had little impact upon eustasy.

Despite the fact that over 97% of Antarctica is presently hidden beneath ice, our ability to recognize glaciations during other intervals in the past, and also to document the transition into the present "ice-house world" during the Tertiary, suggests that the lack of evidence for glaciations in the Mesozoic and early Cenozoic is because there were no glaciations in the first place. Since the geological evidence around the margins of Antarctica shows no indication of adjacent ice masses, we must conclude that any ice sheets existed far inland. The farther inland they must be placed, the smaller their potential volume

and consequently the smaller their impact on eustasy. Therefore, during non-glacial periods it seems unlikely that any rapid changes in eustatic sea level could have had magnitudes any greater than 10–20 m. On this scale, differentiation between eustatic changes and intrabasinal relative sea-level effects appears questionable. Global correlation using 3rd-order curves must therefore be viewed with caution.

### ACKNOWLEDGMENTS

We would like to first thank Jim Pindell for the opportunity of presenting this material. This manuscript was greatly improved through the comments of Fred Ziegler, Jack Sepkoski and especially Laura Jackson and Richard Lupia. Thanks are due to Karl Niklas for helpful information on wood densities, and Rory Mortimore for his thoughts on erratics in the English Chalk. We also gratefully acknowledge the supporters of the Paleogeographic Atlas Project: Amoco, Exxon, Mobil, Total, Shell, BHP, Agip, and Union Texas. Funding for Paul Markwick was through a teaching assistantship at the University of Chicago.

### REFERENCES

- ALI, M. T., 1976, The significance of a mid-Cretaceous cobble conglomerate, Beer District, south Devon: *The Geological Magazine*, v. 113, p. 151–158.
- ALLEN, P., 1949, Wealden petrology: The top Ashdown Pebble Bed and the top Ashdown Sandstone: *Quarterly Journal of the Geological Society of London*, v. 104, p. 257–321.
- ALLEN, P., 1960, Strand-line pebbles in the mid-Hastings Beds and the geology of the London Uplands. General features. Jurassic pebbles: *Proceedings of the Geological Association*, v. 71, p. 156–168.
- ALLEN, P., 1967, Origin of the Hastings facies in north-western Europe: *Proceedings of the Geological Association*, v. 78, p. 27–105.
- ALLEN, P., 1969, Lower Cretaceous source lands and the North Atlantic: *Nature*, v. 222, p. 657–658.
- ALLEN, P., 1972, Wealden detrital tourmaline: implications for northwestern Europe: *Journal of the Geological Society, London*, v. 128, p. 273–294.
- ALLEN, P., 1981, Pursuit of Wealden models: *Journal of the Geological Society, London*, v. 138, p. 375–405.
- ALLEY, N. F., 1988, Age and correlation of palynofloras from the type Cadnawie Formation, southwestern Eromanga Basin: *Memoir of the Association of Australasian Palaeontologists*, v. 5, p. 187–194.
- ANDERSON, C., AND JEVONS, H. S., 1905, Opal pseudomorphs from White Cliffs, New South Wales: *Records of the Australian Museum*, v. 6, p. 30–37.
- ANDERSON, J. B., DOMACK, E. W., AND KURTZ, D. D., 1980, Observations of sediment-laden icebergs in Antarctic waters: Implications to glacial erosion and transport: *Journal of Glaciology*, v. 25, p. 387–396.
- ANDERTON, R., BRIDGES, P. H., LEEDER, M. R., AND SELLWOOD, B. W., 1979, A dynamic stratigraphy of the British Isles: *London, George Allen and Unwin*, 301 p.
- ANDREWS, J. T., 1975, *Glacial systems. An approach to glaciers and their environments*: North Scituate, Duxbury Press, 191 p.
- ARTHUR, M. A., SCHLANGER, S. O., AND JENKINS, H. C., 1987, The Cenomanian-Turonian Oceanic Anoxic Event, II. Palaeoceanographic controls on organic-matter production and preservation, in Brooks, J., and Fleet, A. J., eds., *Marine Petroleum Source Rocks*, Geological Society Special Publication 26: Oxford, Blackwell Scientific Publications, p. 401–420.
- ARTHUR, M. A., DEAN, W. E., AND PRATT, L. M., 1988, Geochemical and climatic effects of increased marine organic carbon burial at the Cenomanian/Turonian boundary: *Nature*, v. 335, p. 714–717.
- BAILEY, E. B., 1924, The desert shores of the Chalk seas: *The Geological Magazine*, v. 59, p. 102–116.
- BALL, V., 1888, On the probable mode of transport of the fragments of granite and other rocks which are found imbedded in the Carboniferous Limestone of the neighbourhood of Dublin: *Quarterly Journal of the Geological Society of London*, v. 44, p. 371–375.



- BARBER, H. N., DADSWELL, H. E., AND INGLE, H. D., 1959, Transport of drift-wood from South America to Tasmania and Macquarie Island: *Nature*, v. 184, p. 203-204.
- BARRERA, E., HUBER, B. T., SAVIN, S. M., AND WEBB, P.-N., 1987, Antarctic marine temperatures: Late Campanian through Early Paleocene: *Paleoceanography*, v. 2, p. 21-47.
- BARRON, E. J., 1981, Paleogeography as a climatic forcing factor: *Geologische Rundschau*, v. 70, p. 737-747.
- BARRON, E. J., THOMPSON, S. L., AND HAY, W. W., 1984, Continental distribution as a forcing factor for global-scale temperature: *Nature*, v. 310, p. 574-575.
- BEAUMONT, M. E. DE, 1836, On the temperature of the Earth's surface during the Tertiary Period: *The Edinburgh New Philosophical Journal*, v. 21, p. 206-209.
- BETZER, P. R., CARDER, K. L., DUCE, R. A., MERRILL, J. T., TINDALE, N. W., UEMATSU, M., COSTELLO, D. K., YOUNG, R. W., FEELY, R. A., BRELAND, J. A., BERNSTEIN, R. E., AND GRECO, A. M., 1988, Long-range transport of giant mineral aerosol particles: *Nature*, v. 336 p. 568-571.
- BILELLO, M. A., 1961, Formation, growth, and decay of sea-ice in the Canadian Arctic Archipelago: *Arctic*, v. 14, p. 3-24.
- BIRKENMAJER, K., FEDOROWSKI, J., AND SMULIKOWSKI, W., 1972, Igneous and fossiliferous sedimentary drift pebbles in marine Tertiary of Torell Land, Spitsbergen: *Norsk Polarinstitutt Årbok*, v. 1970, p. 146-165.
- BIRKENMAJER, K., SOLIARI JR., E., AND KAWASHITA, K., 1989, Geochronology of Tertiary glaciations on King George Island, West Antarctica: *Bulletin of the Polish Academy of Sciences Earth Sciences*, v. 37, p. 27-48.
- BIRKENMAJER, K. AND NAREBSKI, W., 1963, Dolerite drift blocks in marine Tertiary of Sørkapp Land and some remarks on the geology of the eastern part of this area: *Norsk Polarinstitutt Årbok*, v. 1962, p. 68-79.
- BISCHOFF, J. L., FITZPATRICK, J. A., AND ROSENBAUER, R. J., 1993, The solubility and stabilization of ikaite ( $\text{CaCO}_3 \cdot 6\text{H}_2\text{O}$ ) from 0° to 25°C: environmental and paleoclimatic implication for thiolite tufa: *The Journal of Geology*, v. 101, p. 21-33.
- BJØRLYKKE, K., 1985, Glaciations, preservation of their sedimentary record and sea level changes—a discussion based on the Late Precambrian and Lower Palaeozoic sequence in Norway: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 51, p. 197-207.
- BMR PALAEOGEOGRAPHIC GROUP, 1990, Australia: evolution of a continent: Canberra, Bureau of Mineral Resources, 97 p.
- BOGGS, S., JR., 1972, Petrography and geochemistry of rhombic, calcite pseudomorphs from mid-Tertiary mudstones of the Pacific Northwest, U.S.A.: *Sedimentology*, v. 19, p. 219-235.
- BONNEY, REV. T. G., 1872, On the Upper Greensand or Chloritic Marl of Cambridgeshire: *Proceedings of the Geological Association*, v. 3, p. 1-20.
- BONNEY, REV. T. G., 1873, On the occurrence of a quartzite boulder in a coal-seam in South Staffordshire: *The Geological Magazine*, v. 109, p. 289-291.
- BOULTON, G. S. AND DEYNOUX, M., 1981, Sedimentation in glacial environments and the identification of tills and tillites in ancient sedimentary sequences: *Precambrian Research*, v. 15, p. 397-422.
- BRANDT, K., 1986, Glacioeustatic cycles in the Early Jurassic: *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, v. 1986, p. 257-274.
- BRASS, G. W., SOUTHAM, J. R., AND PETERSON, W. H., 1982, Warm saline bottom water in the ancient ocean: *Nature*, v. 296, p. 620-623.
- BRODZIKOWSKI, K., AND VAN LOON, A. J., 1991, Glacigenic sediments: Amsterdam, Elsevier, *Developments in Sedimentology* 49, 674 p.
- BROOM, R., 1911, On the occurrence of water-worn pebbles in the Lower Beaufort Shales: *Transactions of the Geological Society of South Africa*, v. 14, p. 84-86.
- BROWN, H. Y. L., 1885, Report on the geological character of country passed over from Port Augusta to Eucla: Adelaide, C.E. Bristow, 7 p.
- BROWN, H. Y. L., 1892a, Further geological examination of Leigh's Creek and Hergott districts: Adelaide, C.E. Bristow, 2 p.
- BROWN, H. Y. L., 1892b, Report on country in neighborhood of Lake Eyre: Adelaide, C.E. Bristow, 5 p.
- BROWN, H. Y. L., 1894, From Strangeways to Mount Paisley: Annual Report of the Government Geologist, v. p. 10.
- BROWN, H. Y. L., 1895, Report on Northern Territory explorations: Adelaide, C.E. Bristow, 32 p.
- BROWN, H. Y. L., 1898a, Government Geologists report on explorations in western part of South Australia: Adelaide, C.E. Bristow, 6 p.
- BROWN, H. Y. L., 1898b, Report on the explorations in the western part of South Australia: Parliamentary Paper, v. 56, p. 5.
- BROWN, H. Y. L., 1905, Report on the geological explorations in the west and north west of South Australia: South Australia Government Paper, Adelaide, C.E. Bristow, 1-12 p.
- BROWN, I. A., 1925, Notes on the occurrence of glendonites and glacial erratics in Upper Marine beds at Ulladulla, N.S.W.: *The Proceedings of the Linnean Society of New South Wales*, v. 50, p. 25-31.
- CAMUFFO, D., 1987, Freezing of the Venetian Lagoon since the 9th century A.D. in comparison to the climate of western Europe and England: *Climatic Change*, v. 10, p. 43-66.
- CARR, P. F., JONES, B. G., AND MIDDLETON, R. G., 1989, Precursor and formation of glendonites in the Sydney Basin: *Australian Mineralogist*, v. 4, p. 3-12.
- CARR, S. G., OLIVIER, J. G., CONOR, C. H. H., AND SCOTT, D. C., 1979, Andamooka opal fields. The geology of the precious stones field and the results of the subsidised mining program: Department of Mines and Energy Geological Survey of South Australia Report of Investigation, v. 51, p. 1-68.
- CARTER, R. M., ABBOTT, S. T., FULTHORPE, C. S., HAYWICK, D. W., AND HENDERSON, R. A., 1991, Application of global sea-level and sequence-stratigraphic models in southern hemisphere Neogene strata from New Zealand: Special Publication of the International Association of Sedimentologists, v. 12, p. 41-65.
- CAYEUX, L., 1897, II. Craie du Bassin de Paris, in Cayeux, L., Contribution à l'étude micrographique des terrains sédimentaires: Thèses présentées à la faculté des sciences de l'Université de Lille, Lille, Le Bigot Frères, p. 207-573.
- CECIONI, G. O., 1957, Cretaceous flysch and molasse in Departamento Ultima Esperanza, Magallanes Province, Chile: *The American Association of Petroleum Geologists Bulletin*, v. 41, p. 538-564.
- CHAMBERLIN, T. C., 1906, On a possible reversal of deep-sea circulation and its influence on geological climates: *The Journal of Geology*, v. 14, p. 363-373.
- CHARLESWORTH, J. K., 1957, The Quaternary Era with special reference to its glaciation: London, Edward Arnold Ltd., 1700 p.
- CHATWIN, C. P., 1960, British Regional Geology. The Hampshire Basin and adjoining areas (3 ed.): London, Her Majesty's Stationary Office, 99 p.
- CHATWIN, C. P., 1961, British Regional Geology. East Anglia and adjoining areas (4 ed.): London, Her Majesty's Stationary Office, 100 p.
- CHRISTIE-BLICK, N., MOUNTAIN, G. S., AND MILLER, K. G., 1989, Seismic stratigraphic record of sea-level change, in *Sea Level Change: National Academy of Sciences, Studies in Geophysics*, Washington, D.C., p. 116-140.
- CHUMAKOV, N. M., 1981, C7. Scattered stones in Mesozoic deposits of North Siberia, U.S.S.R., in Hambrey, M. J., and Harland, W. B., eds., *Earth's Pre-Pleistocene Glacial Record*: Cambridge, Cambridge University Press, p. 264.
- CHURCH, A. H., 1919, Weighing moorings: *The Journal of Botany*, v. 57, p. 35-37.
- CLARK, D. L. AND HANSON, A., 1983, Central Arctic Ocean sediment texture: a key to ice transport mechanisms, in Molnia, B. F., ed., *Glacial-Marine Sedimentation*: New York, Plenum Press, p. 301-330.
- COCKBAIN, A. E. AND PLAYFORD, P. E., 1972, Stratigraphic nomenclature of Cretaceous rocks in the Perth Basin: Geological Survey of Western Australia Annual Report for the Year 1971, p. 26-31.
- COGLEY, J. G., 1985, Hypsometry of the continents: *Zeitschrift für Geomorphologie supplement*, v. 53, p. 1-48.
- COLEMAN, A. P., 1926, Ice ages recent and ancient: New York, The Macmillan Company, 296 p.
- CROLL, J., 1875, Climate and time in their geological relations: a theory of secular changes of the Earth's climate: New York, D. Appleton and Company, 577 p.
- CROWELL, J. C., 1957, Origin of pebbly mudstones: *Bulletin of the Geological Society of America*, v. 68, p. 993-1010.
- CROWELL, J. C., 1982, Continental glaciation through geologic time, in *Climate in Earth History*: Washington, D.C., National Academy Press, p. 77-82.
- CROWELL, J. C. AND WINTERER, E. L., 1953, Pebbly mudstones and tillites: *Geological Society of America Bulletin*, v. 64, p. 1502.
- DALLAND, A., 1977, Erratic clasts in the Lower Tertiary of Svalbard—evidence of transport by winter ice: *Norsk Polarinstitutt Årbok*, v. 1976, p. 151-165.
- DARBY, D. G. AND OJAKANGAS, R. W., 1980, Gastroliths from an Upper Cretaceous plesiosaur: *Journal of Paleontology*, v. 54, p. 548-556.
- DARWIN, C., 1839, Journal of researches into the geology and natural history of the various countries visited by H.M.S. Beagle: London, Henry Colburn, p. 496.
- DARWIN, C., 1896, Journal of researches into the natural history and geology of the countries visited during the voyage of H.M.S. Beagle round the world

- under the command of Capt. Fitz Roy, R.N.: New York, D. Appleton and Company, 519 p.
- DAVID, T. W. E., 1907, Conditions of climate at different geological epochs, with special reference to glacial epochs: Congrès Géologique International Compte Rendu, 10th Session, Mexico 1906, p. 437-482.
- DAVID, T. W. E., 1932, Explanatory notes to accompany a new geological map of the Commonwealth of Australia: London, Edward Arnold and Company, 177 p.
- DAVID, T. W. E. AND TAYLOR, T. G., 1905, Occurrence of the pseudomorph glendonite in New South Wales: Records of the Geological Survey of New South Wales, v. 8, p. 161-172.
- DAY, R. W., 1969, The Lower Cretaceous of the Great Artesian Basin, in Campbell, K. S. W., ed., Stratigraphy and Palaeontology. Essays in Honour of Dorothy Hill: Canberra, Australia, Australian National University Press, p. 140-173.
- DAY, R. W. AND TWEEDALE, G. W., 1960, Geology of Queensland. Cretaceous. The Great Artesian Basin. The south-eastern margin: Journal of the Geological Society of Australia, v. 7, p. 310-315.
- DE BOAR, P. L., 1982, Some remarks about the stable isotope composition of cyclic pelagic sediments from the Cretaceous in the Apennines (Italy), in Schlanger, S. O. and Cita, M. B., eds., Nature and Origin of Cretaceous Carbon-rich Facies: London, Academic Press, p. 129-143.
- DETTMAN, M. E., MOLNAR, R. E., DOUGLAS, J. G., BURGER, D., FIELDING, C., CLIFFORD, H. T., FRANCIS, J., JELL, P., RICH, T., WADE, M., RICH, P. V., PLEDGE, N., KEMP, A., AND ROZEFELDS, A., 1992, Australian Cretaceous terrestrial faunas and floras: biostratigraphic and biogeographic implications: Cretaceous Research, v. 13, p. 207-262.
- DIBLEY, G. E., 1910, Excursion to Merstham and Betchworth: Proceedings of the Geological Association, v. 21, p. 483-486.
- DIBLEY, G. E., 1918, Additional notes on the Chalk of the Medway Valley, Gravesend, west Kent, north-east Surrey, and Grays (Essex): Proceedings of the Geological Association, v. 29, p. 68-105.
- DINES, H. G., EDMUNDS, F. H., DEWEY, H., STUBBLEFIELD, C. J., AND CHATWIN, C. P., 1933, The geology of the country around Reigate and Dorking: Memoirs of the Geological Survey England and Wales, v. 286, 204 p.
- DITCHFIELD, P. AND MARSHALL, J. D., 1989, Isotopic variation in rhythmically bedded chalks: paleotemperature variation in the Upper Cretaceous: Geology, v. 17, p. 842-845.
- DIX, E., 1944, On two rounded boulders from an anthracite seam, South Wales: The Geological Magazine, v. 81, p. 127-128.
- DIXON, F., 1850, The geology and fossils of the Tertiary and Cretaceous Formations of Sussex: London, Longman, Brown, Green, and Longman, 423 p.
- DOMACK, E. W., ANDERSON, J. B., AND KURTZ, D. D., 1980, Clast shape as an indicator of transport and depositional mechanisms in glacial marine sediments: George V Continental Shelf, Antarctica: Journal of Sedimentary Petrology, v. 50, p. 813-820.
- DOMACK, E. W., BURKLEY, L. A., AND WILLIAMS, C. R., 1989, Character of modern glacial marine sediments: Antarctic Peninsula and South Shetland Islands: Antarctic Journal of the United States, v. 24, p. 113-115.
- DONN, W. L., 1987, 20: Terrestrial climate change from the Triassic to Recent, in Rampino, M. R., Sanders, J. E., Newman, W. S., and Königsson, L. K., eds., Climate, History, Periodicity, and Predictability: New York, Van Nostrand Reinhold Company, p. 343-352.
- DOTT, R. H., JR., 1961, Squantum "Tillite", Massachusetts—evidence of glaciation or subaqueous mass movements: Geological Society of America Bulletin, v. 72, p. 1289-1306.
- DOTT, R. H., JR., 1963, Dynamics of subaqueous gravity depositional processes: The American Association of Petroleum Geologists Bulletin, v. 47, p. 194-128.
- DOUBLE, I. S., 1931, Some Boulders from the Chalk of Betchworth, Surrey: The Geological Magazine, v. 68, p. 65-71.
- DOUGLAS, J. G. AND WILLIAMS, G. E., 1982, Southern Polar Forests: the Early Cretaceous floras of Victoria and their palaeoclimatic significance: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 39, p. 171-185.
- DOWDESWELL, J. A. AND DOWDESWELL, E. K., 1989, Debris in icebergs and rates of glaci-marine sedimentation: observations from Spitsbergen and a simple model: The Journal of Geology, v. 97, p. 221-231.
- DOWDESWELL, J. A. AND SCOURSE, J. D., eds., 1990, Glacimarine environments: processes and sediments: London, Geological Society Special Publication, v. 53, p. 423.
- DRAKE, J. J. AND MCCANN, S. B., 1982, The movement of isolated boulders on tidal flats by ice floes: Canadian Journal of Earth Science, v. 19, p. 748-754.
- DREWRY, D. J., ed., 1983, Antarctica: glaciological and geophysical folio: Cambridge, Scott Polar Research Institute, 10 p.
- DREWRY, D., 1986, Glacial geologic processes: London, Edward Arnold, 276 p.
- DREWRY, D. J. AND COOPER, A. P. R., 1981, Processes and models of Antarctic glaciomarine sedimentation: Annals of Glaciology, v. 2, p. 117-122.
- EDGAR, G. J., 1987, Dispersal of faunal and floral propagules associated with drifting *Macrocystis pyrifera* plants: Marine Biology, v. 95, p. 599-610.
- EDMONDS, E. A., MCKEOWN, M. C., AND WILLIAMS, M., 1975, British Regional Geology. South-West England (4 ed.): London, Her Majesty's Stationary Office, 136 p.
- EHRMANN, W. U. AND MACKENSEN, A., 1992, Sedimentological evidence for the formation of an East Antarctic ice sheet in Eocene/Oligocene time: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 93, p. 85-112.
- EMERY, K. O., 1955, Transportation of rocks by driftwood: Journal of Sedimentary Petrology, v. 25, p. 51-57.
- EMERY, K. O., 1963, Organic transportation of marine sediments, in Hill, M. H., ed., The Sea: New York, Interscience, p. 776-790.
- EMERY, K. O. AND TSCHUDY, R. H., 1941, Transportation of rock by kelp: Bulletin of the Geological Society of America, v. 52, p. 855-862.
- EMILIANI, C. AND SHACKLETON, N. J., 1974, The Brunhes epoch: isotopic paleotemperatures and geochronology: Science, v. 183, p. 511-514.
- EPSHTEYN, O. G., 1978, Mesozoic—Cenozoic climates of northern Asia and glacial-marine deposits: International Geology Review, v. 20, p. 49-58.
- EPSTEIN, S., BUCHSBAUM, R., LOWENSTAM, H. A., AND UREY, H. C., 1951, Carbonate-water isotopic temperature scale: Bulletin of the Geological Society of America, v. 62, p. 417-426.
- EPSTEIN, S., BUCHSBAUM, R., LOWENSTAM, H. A., AND UREY, H. C., 1953, Revised carbonate-water isotopic temperature scale: Bulletin of the Geological Society of America, v. 64, p. 1315-1326.
- EPSTEIN, S. AND MAYEDA, T., 1953, Variation of  $^{18}\text{O}$  content of waters from natural sources: Geochimica et Cosmochimica Acta, v. 4, p. 213-224.
- EXON, N. F. AND SENIOR, B. R., 1976, The Cretaceous of the Eromanga and Surat Basins: Bureau of Mineral Research Journal of Australian Geology and Geophysics, v. 1, p. 33-50.
- EYLES, N., 1993, Earth's glacial record and its tectonic setting: Earth-Science Reviews, v. 35, p. 1-248.
- FIELD, W. O., ed., 1975, Mountain glaciers of the northern hemisphere: Hanover, American Geographical Society, v. 1, 698 p., and v. 2, 931 p.
- FLEMING, C. A., 1951, Sea Lions as geological agents: Journal of Sedimentary Petrology, v. 21, p. 22-25.
- FLINT, R. B., AMBROSE, G. J., AND CAMPBELL, K. S. W., 1980, Fossiliferous Lower Devonian boulders in Cretaceous sediments of the Great Australian Basin: Transactions of the Royal Society of South Australia, v. 104, p. 57-65.
- FLINT, R. F., 1961, Geological evidence of cold climate, in Nairn, A. E. M., ed., Descriptive palaeoclimatology: New York, Interscience Publishers Inc., p. 140-155.
- FLINT, R. F., 1971, Glacial and Quaternary geology: New York, John Wiley and Sons, Inc., 892 p.
- FLINT, R. F., SANDERS, J. E., AND RODGERS, J., 1960, Diamictite, a substitute term for symmictite: Bulletin of the Geological Society of America, v. 71, p. 1809-1810.
- FRAKES, L., 1979, Climates throughout geologic time: Amsterdam, Elsevier Scientific Publishing Company, 310 p.
- FRAKES, L., AND RICH, P., 1982, Paleoclimatic setting and paleogeographic links of Australia in the Phanerozoic, in Rich, P. V. and Thompson, E. M., eds., The fossil vertebrates of Australia: Clayton, Monash University Offset Printing Unit, p. 28-52.
- FRAKES, L. A. AND FRANCIS, J. E., 1988, A guide to Phanerozoic cold polar climates from high-latitude ice-rafting in the Cretaceous: Nature, v. 333, p. 547-549.
- FRAKES, L. A. AND FRANCIS, J. E., 1990, Cretaceous palaeoclimates, in Ginsburg, R. N. and Beaudoin, B., eds., Cretaceous resources, events and rhythms: Netherlands, Kluwer Academic Publishers, p. 273-287.
- FRAKES, L. A. AND KRASSAY, A. A., 1992, Discovery of probable ice-rafting in the late Mesozoic of the Northern Territory and Queensland: Australian Journal of Earth Science, v. 39, p. 115-119.
- FRANCIS, J. E., 1988, A 50-Million-year-old fossil forest from Strathcona Fiord, Ellesmere Island, Arctic Canada: evidence for a warm polar climate: Arctic, v. 41, p. 314-318.
- GALE, A. S., 1980, Penecontemporaneous folding, sedimentation and erosion in Campanian Chalk near Portsmouth, England: Sedimentology, v. 27, p. 137-151.

- GALLOIS, R. W., 1965, British regional geology. The wealden district (4 ed.): London: Her Majesty's Stationary Office, 101 p.
- GARY, M., MCAFEE JR., R., AND WOLF, C. L., eds., 1972, Glossary of Geology: Washington, D.C., American Geological Institute, p. 805.
- GILBERT, R., 1984, The movement of gravel by the alga *Fucus vesiculosus* (L.) on an Arctic intertidal flat: *Journal of Sedimentary Petrology*, v. 54, p. 463–468.
- GILBERT, R., 1990, Rafting in glacial marine environments, in Dowdeswell, J. A. and Scourse, J. D., eds., *Glacial Marine Environments: Processes and Sediments*: London, Geological Society Special Publication 53, p. 105–120.
- GODWIN-AUSTIN, R., 1858, On a boulder of granite found in the "White Chalk" near Croydon; and on the extraneous rocks from that formation: *Quarterly Journal of the Geological Society (London)*, v. 14, p. 252–266.
- GODWIN-AUSTIN, R., 1860, On the occurrence of a mass of coal in the Chalk of Kent: *Quarterly Journal of the Geological Society of London*, v. 16, p. 326–327.
- GOTTLER, P. F., AND POWELL, R. D., 1989, Processes and deposits of iceberg rafting, Glacier Bay, Alaska: Abstracts with Program 1989. North Central Section GSA 23rd Annual Meeting, v. 21, p. 12.
- GOW, A. J. AND TUCKER, W. B., 1990, Sea ice in the polar regions, in Smith Jr., W. O., *Polar oceanography: Part A. Physical Science*: San Diego, Academic Press, Inc., p. 47–122.
- GRECHIN, V. I., 1981a, C2 Miocene ice-marine deposits of the Kakert Formation of western Kamchatka, U.S.S.R., in Hambrey, M. J. and Harland, W. B., eds., *Earth's Pre-Pleistocene Glacial Record*: Cambridge, Cambridge University Press, p. 250–253.
- GRECHIN, V. I., 1981b, C5 Oligocene ice-marine deposits of the Utkholok Formation of western Kamchatka, U.S.S.R., in Hambrey, M. J. and Harland, W. B., eds., *Earth's Pre-Pleistocene Glacial Record*: Cambridge, Cambridge University Press, p. 258–260.
- GRESLEY, W. S., 1885, On the occurrence of quartzite boulders in a coal-seam in Leicestershire: *The Geological Magazine*, Dec. III, v. 2, p. 553–555.
- GROVES, A. W., 1931, The unroofing of the Dartmoor Granite and the distribution of its detritus in the sediments of southern England: *Quarterly Journal of the Geological Society of London*, v. 87, p. 63–96.
- HABICHT, J. K. A., 1979, Paleoclimate, paleomagnetism, and continental drift: Tulsa, The American Association of Petroleum Geologists Studies in Geology 9, 31 p.
- HAMBREY, M. J. AND HARLAND, W. B., eds., 1981, *Earth's pre-Pleistocene Glacial Record*: Cambridge, Cambridge University Press, p. 1004.
- HANCOCK, J. M., 1961, The Cretaceous System in Northern Ireland: *Quarterly Journal of the Geological Society of London*, v. 117, p. 11–36.
- HANCOCK, J. M., 1975, The petrology of the Chalk: *Proceedings of the Geological Association*, v. 86, p. 499–535.
- HANCOCK, J. M., 1989, Sea-level changes in the British region during the Late Cretaceous: *Proceedings of the Geological Association*, v. 100, p. 565–594.
- HANCOCK, J. M. AND SCHOLLE, P. A., 1975, Chalk of the North Sea, in Woodland, A. W., ed., *Petroleum and the Continental Shelf of North-West Europe*: New York, John Wiley and Sons, p. 413–427.
- HAQ, B. U., 1991, Sequence stratigraphy, sea-level change, and significance for the deep sea: Special Publication of the International Association of Sedimentology, v. 12 p. 3–39.
- HAQ, B. U., HARDENBOL, J., AND VAIL, P. R., 1987, Chronology of fluctuating sea level since the Triassic: *Science*, v. 235, p. 1156–1167.
- HAWKE, J. M. AND BOURKE, D. J., 1984, 2. Stratigraphy, in Hawke, J. W. and Cramsie, J. N., eds., *Contributions to the Geology of the Great Artesian Basin in New South Wales*: p. 23–124.
- HAWKES, L., 1943, The erratics of the Cambridge Greensand—their nature provenance and mode of transport: *Quarterly Journal of the Geological Society of London*, v. 99, p. 93–104.
- HAWKES, L., 1951, The erratics of the English Chalk: *Proceedings of the Geological Association*, v. 62, p. 257–268.
- HEEZEN, B. C., AND HOLLISTER, C., 1964, Turbidity currents and glaciation, in Nairn, A. E. M., ed., *Problems in Palaeoclimatology*: London, Interscience Publishers, p. 99–109.
- HICKS, L. E., 1879, Boulders in coal: *The American Journal of Science and Arts*, v. 117, p. 68–69.
- HORRELL, M. A., 1991, Phytogeography and paleoclimatic interpretation of the Maestrichtian: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 86, p. 87–138.
- HOSKIN, C. M., AND VALENCIA, S. M., 1976, Sediment transported by ice-rafting in southcentral Alaska, in Hood, D. W. and Burrell, D. C., eds., *Assessment of the Arctic marine environment: selected topics*: Fairbanks, Institute of Marine Science, University of Alaska, p. 173–185.
- HUME, W. F. 1897, The Cretaceous strata of County Antrim: *Quarterly Journal of the Geological Society of London*, v. 53, p. 540–606.
- JACK, R. L., 1915, The geology and prospects of the region to the south of the Musgrave Ranges, and the geology of the western portion of the Great Artesian Basin: *Bulletin of the Geological Survey of South Australia*, v. 5, p. 1–53.
- JACK, R. L., 1931, Report on the geology of the region to the north and north-west of Tarcoola: *Bulletin of the Geological Survey of South Australia*, v. 15, p. 1–31.
- JACK, R. L., AND ETHERIDGE, R., 1892, The geology and palaeontology of Queensland and New Guinea, with sixty-eight plates and a geological map of Queensland Brisbane: James Charles Beal, 768 p.
- JAQUET, J. B., 1893, Report on White Cliffs opal-field: *Annual Report of the Department of Mines and Agriculture*, v. 1892, p. 140–142.
- JARVIS, I. AND GALE, A. S., 1984, The Late Cretaceous transgression in the SW Anglo-Paris Basin: stratigraphy of the Craie de Villedieu Formation: *Cretaceous Research*, v. 5, p. 195–224.
- JARVIS, I. AND WOODROOF, P. B., 1984, Stratigraphy of the Cenomanian and basal Turonian (Upper Cretaceous) between Branscombe and Seaton, SE Devon, England: *Proceedings of the Geological Association*, v. 95, p. 193–215.
- JEANS, C. V., LONG, D., HALL, M. A., BLAND, D. J., AND CORNFORD, C., 1991, The geochemistry of the Plenus Marls at Dover, England: evidence of fluctuating oceanographic conditions and of glacial control during the development of the Cenomanian-Turonian  $\delta^{13}\text{C}$  anomaly: *Geological Magazine*, v. 128, p. 603–632.
- JENKYN, H. C., 1980, Cretaceous anoxic events: from continents to oceans: *Journal of the Geological Society, London*, v. 137, p. 171–188.
- JUKES-BROWNE, A. J. AND HILL, W., 1887, On the lower part of the Upper Cretaceous series in west Suffolk and Norfolk: v. 43, p. 544–598.
- JUKES-BROWNE, A. J. AND HILL, W., 1903, The Cretaceous rocks of Britain. Vol. II.—The Lower Chalk of England: London, Wyman and Sons, *Memoirs of the Geological Survey of the United Kingdom*, 568 p.
- JUTARD, G., AND PLAUCHUT, B. P., 1973, Cretaceous and Tertiary stratigraphy northern Banks Island, in Aitken, J. D. and Glass, D. J., eds., *GAC-CSPG Proceedings of the Symposium on the Geology of the Canadian Arctic: Saskatchewan, GAC-CSPG*, p. 203–219.
- KAEVER, M., 1974, Agglutinated foraminifera and other epizoans from an erratic boulder in the Turonian of south-eastern Münsterland (Westphalia, Germany): *Neues Jahrbuch fuer Geologie und Paläontologie Abhandlungen*, v. 146, p. 179–194.
- KAPLAN, M. Y., 1977, Calcite pseudomorphs in sedimentary rocks and their paleogeographic significance: *Doklady Akademii Nauk SSSR*, v. 237, p. 167–169.
- KEMPEMA, E. W., REIMNITZ, E., AND BARNES, P. W., 1989, Sea ice sediment entrainment and rafting in the Arctic: *Journal of Sedimentary Petrology*, v. 59, p. 308–317.
- KEMPER, E., 1983, Über kalt- und warmzeiten der Unterkreide: *Zitteliana*, v. 10, p. 359–369.
- KEMPER, E., 1987, Das Klima der Kreide-Zeit: *Geologisches Jahrbuch*, v. A96, p. 5–185.
- KEMPER, E. AND SCHMITZ, H. H., 1975, Stellate nodules from the Upper Deer Bay Formation (Valanginian) of arctic Canada: *Geological Survey of Canada Paper*, v. 75-1C p. 109–119.
- KEMPER, E. AND SCHMITZ, H. H., 1981, Glendonite—Indikatoren des polar-marinen Ablagerungsmilieus: *Geologische Rundschau*, v. 70, p. 759–773.
- KENNEDY, W. J. AND GARRISON, R. E., 1975, Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of southern England: *Sedimentology*, v. 22, p. 311–386.
- KENNEDY, W. J. AND JUIGNET, P., 1974, Carbonate banks and slump beds in the Upper Cretaceous (Upper Turonian-Santonian) of Haute Normandie, France: *Sedimentology*, v. 21, p. 1–42.
- KIRKALDY, J. F., 1947, The provenance of the pebbles in the Lower Cretaceous rocks: *Proceedings of the Geological Association*, v. 58, p. 223–241.
- KOLOSOV, A. S., PUSTYL'NIKOV, A. M., AND FEDIN, V. P., 1974, Precipitation of glauconite and conditions of deposition of glauconite-bearing sediments in the Kara Bogaz Gol: *Doklady Akademii Nauk SSSR*, v. 219, p. 184–186.
- KRIEG, G. W., 1986, Stratigraphy and tectonics of the Dalhousie Anticline, southwest Eromanga Basin: *Geological Society of Australia Special Publication*, v. 12, p. 175–182.
- KUTZBACH, J. E., GUETTER, P. J., RUDDIMAN, W. F., AND PRELL, W. L., 1989, Sensitivity of climate to Late Cenozoic uplift in southern Asia and the American west: numerical experiments: *Journal of Geophysical Research*, v. 94, p. 18393–18407.



- KUVAAS, B. AND LEITCHENKOV, G., 1992, Glaciomarine turbidite and current controlled deposits in Prydz Bay, Antarctica: *Marine Geology*, v. 108, p. 365-381.
- LAMB, H. H., 1985, *Climate history and the future Vol. 2.*: Princeton, Princeton University Press, 835 p.
- LAMOLDA, M. A., GOROSTIDI, A., AND PAUL, C. R. C., 1994, Quantitative estimates of calcareous nannofossil changes across the Plenus Marls (latest Cenomanian), Dover, England: implications for the generation of the Cenomanian-Turonian boundary event: *Cretaceous Research*, v. 15, p. 143-164.
- LINDGRÉN, S., AND NEUMANN, J., 1982, Crossings of ice-bound sea surfaces in history: *Climatic Change*, v. 4, p. 71-97.
- LISITZIN, A. P., 1958, Types of Marine sediments connected with the activity of ice: *Proceedings of the Academy of Sciences of the USSR. Geological Sciences Sections*, v. 118, p. 45-47.
- LIU, Y. AND GASTALDO, R. A., 1992, Characteristics and provenance of log-transported gravels in a Carboniferous channel deposit: *Journal of Sedimentary Petrology*, v. 62, p. 1072-1083.
- LONG, D. G. F., 1991, A non-glacial origin for the Ordovician (Middle Caradocian) Cosquer Formation, Vercors, Crozon Peninsula, Brittany, France: *Geological Journal*, v. 26, p. 279-293.
- LOWRY, D. C., 1970, Geology of the western Australian part of the Eucla Basin: *Geological Survey of Western Australia Bulletin*, v. 122, p. 1-201.
- LUDBROOK, N. H., 1966, Cretaceous Biostratigraphy of the Great Artesian Basin in South Australia: *Geological Survey of South Australia Bulletin*, v. 40, p. 1-223.
- LÜNING, K., 1990, *Seaweeds their environment, biogeography, and ecophysiology*: New York, John Wiley and Sons, Inc., 527 p.
- LYELL, C., 1830, *Principles of geology, being an attempt to explain the former changes of the Earth's surface, by reference to causes now in operation* (1 ed.): London, John Murray, 511 p.
- LYELL, C., 1841, *Elements of geology* (2 ed.): London, John Murray, 437 p.
- LYELL, C., 1872, *Principles of geology or the modern changes of the Earth and its inhabitants considered as illustrative of geology* (11 ed.): New York, D. Appleton, 671 p.
- MACCELLARI, C. E., 1988, Stratigraphy, sedimentology, and paleoecology of Upper Cretaceous/Paleocene shelf-deltaic sediments of Seymour Island: *Geological Society of America Memoir*, v. 169, p. 25-53.
- MACKENSEN, A. AND EHRLMANN, W. U., 1992, Middle Eocene through early Oligocene climate history and paleoceanography in the Southern Ocean: stable oxygen and carbon isotopes from ODP sites on Maud Rise and Kerguelen Plateau: *Marine Geology*, v. 108, p. 1-27.
- MANTILL, G., 1833, *The geology of the south-east of England*: London, Longman, Rees, Ormew, Brown, Green, and Longman, 415 p.
- MARKHAM, W. E., 1986, The ice cover, in Martini, I. P., ed., *Canadian Inland Seas*: Amsterdam, Elsevier, p. 101-116.
- MARKWICK, P. J., 1992, Fossil crocodilian distributions, Upper Cretaceous to Present: implications for paleoclimate, in Lidgard, S. and Crane, P. R., eds., *Fifth North American Paleontological Convention: Chicago, Abstracts and Program*, The Paleontological Society, p. 198.
- MARTIN, E. A., 1897, Foreign boulders in the Chalk: *The Geological Magazine*, v. 4, p. 169-170.
- MATSCH, C. L. AND OJAKANGAS, R. W., 1991, Comparisons in depositional style of "polar" and "temperate" glacial ice; Late Paleozoic Whiteout Conglomerate (West Antarctica) and late Proterozoic Mineral Fork Formation (Utah), in Anderson, J. B. and Ashley, G. M., eds., *Glacial Marine Sedimentation: Paleoclimatic Significance*: Boulder, Geological Society of America, p. 191-206.
- MATTHEWS, R. K., 1984, Oxygen isotope record of ice-volume history: 100 million years of glacio-eustatic sea-level fluctuation, in Schlee, J. S., ed., *Interregional Unconformities and Hydrocarbon Accumulation*: Tulsa, American Association of Petroleum Geologists, p. 97-107.
- MATTHEWS, R. K. AND POORE, R. Z., 1980, Tertiary  $\delta^{18}\text{O}$  record and glacio-eustatic sea-level fluctuations: *Geology*, v. 8, p. 501-504.
- MCKIRDY, D. M., EMMETT, J. K., MOONEY, B. A., COX, R. E., AND WATSON, B. L., 1986, Organic geochemical facies of the Cretaceous Bulldog Shale, western Eromanga Basin, South Australia: *Geological Society of Australia Special Publication*, v. 12, p. 287-304.
- MELANKHOLINA, E. N., 1981a, C3. Scattered stones in the Neogene Maruyama Formation of Sakhalin Island, U.S.S.R., in Hambrey, M. J. and Harland, W. B., eds., *Earth's Pre-Pleistocene Glacial Record*: Cambridge, Cambridge University Press, p. 254-255.
- MELANKHOLINA, E. N., 1981b, C6. Scattered stones in the Palaeogene Takaradai Formation of Sakhalin Island, U.S.S.R., in Hambrey, M. J. and Harland, eds., *Earth's Pre-Pleistocene Glacial Record*: Cambridge, Cambridge University Press, p. 261-263.
- MENARD, H. W., 1953, Pleistocene and recent sediment from the floor of the northeastern Pacific Ocean: *Bulletin of the Geological Society of America*, v. 64, p. 1279-1294.
- MIDDLETON, G. V. AND HAMPTON, M. A., 1973, Sediment gravity flows: mechanics of flow and deposition, in Middleton, G. V. and Bouma, A. H., eds., *Turbidites and Deep-water Sedimentation*: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 1-38.
- MILLER, K. G., FAIRBANKS, R. G., AND MOUNTAIN, G. S., 1987, Tertiary oxygen isotope synthesis, sea level history, and continental margin erosion: *Paleoceanography*, v. 2, p. 1-19.
- MIX, A. C. AND RUDDIMAN, R. G., 1984, Oxygen isotope analyses and Pleistocene ice volumes: *Quaternary Research*, v. 21, p. 1-20.
- MOLENAAR, C. M., 1988, 25. Depositional history and seismic stratigraphy of Lower Cretaceous rocks in the National Petroleum Reserve in Alaska and adjacent areas, in Gryc, G., ed., *Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982*: Washington, United States Government Printing Office, p. 593-621.
- MOLENAAR, C. M., BIRD, K. J., AND KIRK, A. R., 1988, Cretaceous and Tertiary stratigraphy of northeastern Alaska, in Tailleux, I., and Weimer, P., eds., *Alaskan North Slope Geology: Bakersfield, California and Anchorage, Alaska*: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists and The Alaska Geological Society, p. 513-528.
- MOLNAR, R., 1982, Australian Mesozoic reptiles, in Rich, P. V. and Thompson, E. M., eds., *The fossil vertebrates of Australia*: Clayton, Victoria, Monash University Offset Printing Unit, p. 169-225.
- MOLNIA, B. F., 1983, Distal glacial-marine sedimentation: abundance, composition, and distribution of North Atlantic Ocean Pleistocene ice-rafted sediment, in Molnia, B. F., *Glacial-Marine Sedimentation*: New York, Plenum Press, p. 593-626.
- MOORE, C., 1870, Australian Mesozoic geology and palaeontology: *Quarterly Journal of the Geological Society of London*, v. 26, p. 226-260.
- MOORE, P. S. AND PITT, G. M., 1985, Cretaceous subsurface stratigraphy of the southwestern Eromanga Basin: a review: *Special Publication*, South Australia Department of Mines and Energy, v. 5, p. 269-286.
- MORTIMORE, R. N. AND POMEROL, B., 1991, Upper Cretaceous tectonic disruptions in a placid Chalk sequence in the Anglo-Paris Basin: *Journal of the Geological Society, London*, v. 148, p. 391-404.
- MULL, C. G., 1987, Kemik sandstone, Arctic National Wildlife Refuge, northeastern Alaska, in Tailleux, I. and Weimer, P., eds., *Alaskan North Slope Geology: Bakersfield, California and Anchorage, Alaska*: Los Angeles, Pacific section, Society of Economic Paleontologists and Mineralogists and The Alaskan Geological Society, p. 405-431.
- NAGY, J., 1966, Preliminary report on the geology of Eastern Torell Land, Vestspitsbergen: *Norsk Polarinstitutt Årbok*, v. 1964, p. 69-72.
- NAGY, J., 1970, Ammonite faunas and stratigraphy of Lower Cretaceous (Albian) rocks in southern Spitsbergen: *Norsk Polarinstitutt Skrifter*, v. 152, p. 1-58.
- NAKAYA, H., 1989, Upper Cretaceous elasmosaurid (Reptilia, Plesiosauroidea) from Hobetsu, Hokkaido, northern Japan: *Transactions and Proceedings of the Palaeontological Society of Japan, New Series*, v. 154, p. 96-116.
- NENTWICH, F. W. AND YOLE, R. W., 1982, Sedimentary petrology and stratigraphic analysis of the subsurface Reindeer Formation (early Tertiary) Mackenzie Delta-Beaufort Sea area, Canada, in Embry, A. F. and Balkwill, H. R., eds., *Arctic Geology and Geophysics*: Calgary, Canadian Society of Petroleum Geologists, p. 55-81.
- NEWBERRY, J. S., 1872, *Geological Survey of Ohio: American Naturalist*, v. 6, p. 289-292.
- NIKLAS, K. J., 1992, *Plant Biomechanics. An engineering approach to plant form and function*: Chicago: The University of Chicago Press, 607 p.
- NOE-NYGAARD, A., 1975, Erratics of the Danish Maastrichtian and Danian marine limestones: *Bulletin of the Geological Society of Denmark*, v. 24, p. 75-81.
- NORTH, G. R. AND CROWLEY, T. J., 1985, Application of a seasonal climate model to Cenozoic glaciation: *Journal of the Geological Society, London*, v. 142, p. 475-482.
- OVERBECK, V. R., MARSHALL, J. R., AND AGGARWAL, H., 1993, Impacts, tilites, and the breakup of Gondwanaland: *The Journal of Geology*, v. 101, p. 1-19.
- OSMASTON, H., 1989a, Glaciers, glaciations and equilibrium line altitudes on Kilimanjaro, in Mahaney, W. C., *Quaternary and environmental research on East African Mountains*: Rotterdam, A.A. Balkema, p. 7-30.

- OSMASTON, H., 1989b, Glaciers, glaciations and equilibrium line altitudes on the Ruwenzori, in Mahaney, W. C., ed., Quaternary and Environmental Research on East African Mountains: Rotterdam, A.A. Balkema, p. 31-104.
- OSTERKAMP, T. E. AND GOSINK, J. P., 1984, Observations and analyses of sediment-laden sea ice, in Barnes, P. W., Schell, D. M., and Reimnitz, E., eds., The Alaskan Beaufort Sea: Ecosystems and Environments: Orlando, Academic Press, Inc., p. 73-93.
- PARKIN, L. W., 1956, Notes on the younger glacial remnants of northern South Australia: Transactions of the Royal Society of South Australia, v. 79, p. 148-151.
- PAULY, H., 1963, "Ikaite", a new mineral from Greenland: Arctic, v. 16, p. 263-264.
- PAUTOT, G. AND FONTES, J. CH., 1979, Gypsum-calcite rosettes in sediments from the Congo deep-sea fan: Oceanologica Acta, v. 2, p. 13-18.
- PELTO, M. S., 1992, Equilibrium line altitude variations with latitude, today and during the Late Wisconsin: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 95, p. 41-46.
- PHILLIPS, I., 1865, Oxford Fossils: The Geological Magazine, v. 2, p. 292-293.
- PIRRIE, D., 1989, Shallow marine sedimentation within an active margin basin, James Ross Island, Antarctica: Sedimentary Geology, v. 63, p. 61-82.
- PITMAN III, W. C. AND GOLOVCHENKO, X., 1983, The effect of sea-level change on the shelfedge and slope of passive margins in Stanley, D. J. and Moore, G. T., eds., The Shelfbreak: Critical Interface on Continental Margins: Tulsa, Society of Economic Paleontologists and Mineralogists Special Publication 33, p. 41-58.
- PITMAN III, W. C., 1978, Relationship between eustasy and stratigraphic sequences of passive margins: Geological Society of America Bulletin, v. 89, p. 1389-1403.
- PITTMAN, E. F., 1901, The mineral resources of New South Wales Geological Survey of New South Wales: Sydney, William Applegate Gullick, 487 p.
- PLAYFORD, P. E., COCKBAIN, A. E., AND LOW, G. H., 1976, Geology of the Perth Basin Western Australia: Geological Survey of Western Australia Bulletin, v. 124, p. 1-200.
- PRATT, R. M., 1970, Granitic rocks from the Blake Plateau: Geological Society of America Bulletin, v. 81, p. 3117-3122.
- PRENTICE, M. L. AND MATTHEWS, R. K., 1988, Cenozoic ice-volume history: development of a composite oxygen isotope record: Geology, v. 16, p. 963-966.
- PRESTWICH, J., 1856, On the boring through the Chalk at Kentish Town, London: Proceedings of the Geological Association, v. 12, p. 6-14.
- PRESTWICH, J., 1888, Geology: Chemical, Physical, and Stratigraphical: Oxford, Clarendon Press, 606 p.
- PRICE, P. H., 1932, Erratic boulders in Sewell Coal of West Virginia: The Journal of Geology, v. 40, p. 62-73.
- RAGGATT, H. G., 1938, On the occurrence of glendonites in New South Wales, with notes on their mode of origin: Royal Society of New South Wales, Journal and Proceedings, v. 71, p. 336-349.
- RAILSBACK, L. B., 1990, Influence of changing deep ocean circulation on the Phanerozoic oxygen isotopic record: Geochimica et Cosmochimica Acta, v. 54, p. 1501-1509.
- RAMPINO, M. R., 1992, Ancient "glacial" deposits are ejecta of large impacts: the ice age paradox explained: EOS, Transactions, American Geophysical Union, v. 73, p. 99.
- RAMPINO, M. R., 1994, Tillites, diamictites, and ballistic ejecta of large impacts: The Journal of Geology, v. 102, p. 439-456.
- RAWSON, P. F., 1992, The Cretaceous, in Duff, P. MCL. D. and Smith, A. J., eds., Geology of England and Wales: London, The Geological Society, p. 355-388.
- RICH, P. V., RICH, T. H., WAGSTAFF, B. E., MASON, J. M., DOUTHITT, C. B., GREGORY, R. T., AND FELTON, E. A., 1988, Evidence for low temperatures and biologic diversity in Cretaceous high latitudes of Australia: Science, v. 242, p. 1403-1406.
- RICH, T. H. V. AND RICH, P. V., 1989, Polar dinosaurs and biotas of the Early Cretaceous of Southeastern Australia: National Geographic Research, v. 5, p. 15-53.
- RICHTER, F. M., ROWLEY, D. B., AND DEPAOLO, D. J., 1992, Sr isotope evolution of seawater: the role of tectonics: Earth and Planetary Science Letters, v. 109, p. 963-966.
- ROBBIE, J. A., 1950, The Chalk Rock at Winterborne Abbas, Dorset: The Geological Magazine, v. 87, p. 209-213.
- ROBIN, G. DE Q., 1988, The Antarctic ice sheet, its history and response to sea level and climatic changes over the past 100 million years: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 67, p. 31-50.
- ROGERS, R. R., 1994, Marine facies of the Judith River Formation (Campanian) in the type area, north-central Montana, 1993 Montana Geological Society Guidebook: Billings, Montana Geological Society.
- ROMER, A. S., 1961, Palaeozoological Evidence of Climate. (1) Vertebrates, in Nairn, A. E. M., ed., Descriptive Palaeoclimatology: New York, Interscience Publishers Inc., p. 183-206.
- RONOV, A. B., 1982, The Earth's sedimentary shell (quantitative patterns of its structure, compositions, and evolution): International Geology Review, v. 24, p. 1313-1363.
- ROWLEY, D. B. AND MARKWICK, P. J., 1992, Haq et al. Eustatic sea level curve: implications for sequestered water volumes: Journal of Geology, v. 100, p. 703-715.
- RUDDIMAN, W. F. AND KUTZBACH, J. E., 1989, Forcing of Late Cenozoic northern hemisphere climate by plateau uplift in southern Asia and the American West: Journal of Geophysical Research, v. 94, p. 18409-18427.
- RUDDIMAN, W. F., PRELL, W. L., AND RAYMO, M. E., 1989, Late Cenozoic uplift in southern Asia and the American West: rationale for general circulation modeling experiments: Journal of Geophysical Research, v. 94, p. 19379-19391.
- SABLE, E. G. AND STRICKER, G. D., 1987, Coal in the National Petroleum Reserve in Alaska (NPRA): framework geology and resources, in Tailleux, I. and Weimer, P., eds., Alaskan North Slope Geology: Bakersfield, The Pacific Section, Society of Economic Paleontologists and Mineralogists and The Alaska Geological Society, p. 195-215.
- SAVAGE, T. E. AND GRIFFIN, J. G., 1928, Significance of crystalline boulders in Pennsylvanian Limestone in Illinois: Bulletin of the Geological Society of America, v. 39, p. 421-428.
- SAVRDA, C. E., 1991, *Teredolites*, wood substrates, and sea-level dynamics: Geology, v. 19, p. 905-908.
- SCHAAL, S. AND ZIEGLER, W., 1992, Messel. An insight into the history of life and of the Earth: Translated by Shaffer-Fehre, M. Oxford, Clarendon Press, 322 p.
- SCHIEBNEROVÁ, V., 1971, Palaeoecology and palaeogeography of Cretaceous deposits of the Great Artesian Basin (Australia): Records of the Geological Survey of New South Wales, v. 13, p. 1-48.
- SCHMIDT, K., AND SCHREYER, E. D., 1973, Erratische Gerölle im Turon (Soester Grünsand) des südöstlichen Münsterlandes (Westfalen): Neues Jahrbuch fuer Geologie und Paläontologie Monatshefte, v. 1973, p. 297-312.
- SCLANGER, S. O., ARTHUR, M. A., JENKINS, H. C., AND SCHOLLE, P. A., 1987, The Cenomanian-Turonian Oceanic Anoxic Event, I. Stratigraphy and distribution of organic carbon-rich beds and the marine  $\delta^{13}\text{C}$  excursion, in Brooks, J. and Fleet, A. J., eds., Marine Petroleum Source Rocks: Oxford, Blackwell Scientific Publications, Geological Society Special Publication 26, p. 371-399.
- SCOTT, K. M., 1966, Sedimentology and dispersal pattern of a Cretaceous flysch sequence, Patagonian Andes, southern Chile: The American Association of Petroleum Geologists Bulletin, v. 50, p. 72-107.
- SEELEY, H. G., 1877, On *Mauisaurus gardneri* (Seeley), an Elasmosaurian from the base of the Gault at Folkestone: Quarterly Journal of the Geological Society of London, v. 33, p. 541-547.
- SELTZER, G. O., 1994, Climatic interpretation of alpine snowline variations on millennial time scales: Quaternary Research, v. 41, p. 154-159.
- SHACKLETON, N. J. AND KENNETT, J. P., 1975, Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analysis in DSDP sites 277, 279, and 281, in Kennett, J. P., Houtz, R. E., et al., eds., Initial Reports of the Deep Sea Drilling Project, v. 29: Washington D. C., United States Printing Office, p. 743-755.
- SHAIKH, A. M. AND SHEARMAN, D. J., 1987, On ikaite and the morphology of its pseudomorphs, in Rodríguez-Clemente, R. and Tardy, Y., eds., Geochemistry and Mineral Formation in the Earth Surface: Madrid, Consejo superior de investigaciones científicas, p. 791-803.
- SHARMA, G. D., 1979, The Alaskan Shelf. Hydrographic, Sedimentary, and Geochemical Environment: New York, Springer-Verlag, 498 p.
- SHEARMAN, D. J. AND SMITH, A. J., 1985, Ikaite, the parent mineral of jarrowite-type pseudomorphs: Proceedings of the Geological Association, v. 96, p. 305-314.
- SKWARKO, S. K., 1966, Cretaceous stratigraphy and palaeontology of the Northern Territory: Australian Bureau of Mineral Resources, Geology and Geophysics Bulletin, v. 73, p. 1-47.
- SKWARKO, S. K., 1969, A correlation chart for the Cretaceous system in Australia: BMR Bulletin Palaeontological Papers, v. 1969, p. 55-63.
- SLADEN, C. P. AND BATTEN, D. J., 1984, Source-area environments of Late Jurassic and Early Cretaceous sediments in southeast England: Proceedings of the Geological Association, v. 95, p. 149-163.

- SMITH, W. E., 1961, The detrital mineralogy of the Cretaceous rocks of South-East Devon, with particular reference to the Cenomanian: *Proceedings of the Geological Association*, v. 72, p. 303-332.
- SOLLAS, W. J. AND JUKES-BROWNE, A. J., 1873, On the included rock-fragments of the Cambridge Upper Greensand: *Proceedings of the Geological Association*, v. 29, p. 11-16.
- SONNENFELD, P., 1984, *Brines and evaporites* Orlando: Academic Press, Inc., 613 p.
- SONNENFELD, P. AND PERTHUISOT, J.-P., 1989, *Brine and evaporites*: Washington, D.C., American Geophysical Union, *Short Course in Geology* 3, 126 p.
- SOUTHAM, J. R., PETERSON, W. H., AND BRASS, G. W., 1982, Dynamics of anoxia: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 40, p. 183-198.
- SPENCER, J., 1887, On boulders found in seams of coal: *Quarterly Journal of the Geological Society of London*, v. 43, p. 734-735.
- SPICER, R. A., 1987, The significance of the Cretaceous flora of northern Alaska for the reconstruction of the climate of the Cretaceous: *Geologisches Jahrbuch*, v. A96, p. 265-291.
- SPICER, R. A., 1989, 3—Reconstructing high-latitude Cretaceous vegetation and climate: Arctic and Antarctic compared, in Taylor, T. N. and Taylor, E. L., ed., *Antarctic Paleobiology. Its role in the Reconstruction of Gondwana*: New York, Springer-Verlag, p. 27-36.
- SPICER, R. A. AND CORFIELD, R. M., 1992, A review of terrestrial and marine climates in the Cretaceous with implications for modelling the 'Greenhouse Earth': *Geological Magazine*, v. 129, p. 169-180.
- SPICER, R. A. AND PARRISH, J. T., 1990, Late Cretaceous—early Tertiary palaeoclimates of northern high latitudes: a quantitative view: *Journal of the Geological Society, London*, v. 147, p. 329-341.
- STANLEY, D. J., 1969, Sedimentation in slope and base-of-slope environments, in Stanley, D. J., ed., *The new concepts of continental margin sedimentation application to the geological record*: Washington, D.C., American Geological Institute, p. 1-25.
- STEBBING, W. P. D., 1897, On two boulders of granite from the Middle Chalk of Betchworth, Surrey: *Quarterly Journal of the Geological Society of London*, v. 53, p. 213-220.
- STRAHAN, A., 1906, *Proceedings of the Geological Society: The Quarterly Journal of the Geological Society of London*, v. 62 p. cxxxiii.
- Suess, E., BALZER, W., HESSE, K.-F., MÜLLER, P. J., UNGERER, C. A., AND WEFER, G., 1982, Calcium carbonate hexahydrate from organic-rich sediments of the Antarctic Shelf: precursors of glendonites: *Science*, v. 216, p. 1128-1131.
- SÜSSMILCH, C. A., 1914, *An introduction to the geology of New South Wales*: Sydney, Angus and Robertson Ltd., 269 p.
- THORNTON, R. C. N., 1974, Hydrocarbon potential of western Murray Basin and infrabasins: Department of Mines Geological Survey of South Australia Report of Investigations, v. 41, p. 1-43.
- TROEDSSON, G. T., 1924, On crocodilian remains from the Danian of Sweden: *Lunds Universitets Årsskrift Ny Följd*, v. 20, p. 1-75.
- TRUSWELL, E. M., 1991, Antarctica: a history of terrestrial vegetation, in Tingey, R. J., ed., *The Geology of Antarctica*: Oxford, Clarendon Press, p. 499-537.
- UREY, H. C., LOWENSTAM, H. A., EPSTEIN, S., AND MCKINNEY, C. R., 1951, Measurement of paleotemperatures and temperatures of the Upper Cretaceous of England, Denmark, and the southeastern United States: *Bulletin of the Geological Society of America*, v. 62, p. 399-416.
- VAIL, P. R., MITCHUM JR, R. M., AND THOMPSON III, S., 1977, Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes of sea level: Tulsa, Association of Petroleum Geologists Memoir 26, p. 83-97.
- VAN HOUTEN, F. B., 1965, Crystal casts in Upper Triassic Lockatong and Brunswick Formations: *Sedimentology*, v. 4, p. 301-313.
- VAN HOUTEN, F. B., 1967, Appraisal of Ridgway and Gunnison "Tillites" southwestern Colorado: *Geological Society of America Bulletin*, v. 68, p. 383-388.
- WALKOM, A. B., 1929, Note on a fossil wood from central Australia: *Proceedings of the Linnean Society of New South Wales*, v. 54, p. 147-149.
- WALPOLE, B. P., DUNN, P. R., RANDAL, M. A., SKWARKO, S. K., AND HAYS, J., 1968, Geology of the Katherine-Darwin region, Northern Territory: Australian Bureau of Mineral Resources, Geology and Geophysics Bulletin, v. 82, p. 1-170.
- WARD, L. K., 1925, Notes on the geological structure of central Australia: *Transactions and Proceedings of the Royal Society of South Australia*, v. 49, p. 61-84.
- WARD, L. K., 1927, A new edition of the geological map of South Australia. Appendix to The Annual Report of the Director of Mines and Government Geologist for 1927.
- WARREN, J. K., 1989, Evaporite sedimentology: importance in hydrocarbon accumulation London: Prentice-Hall International (UK) Limited, 285 p.
- WATERHOUSE, J. B. AND FLOOD, P. G., 1981, D1. Poorly sorted conglomerates, breccias and diamictites in Late Palaeozoic, Mesozoic and Tertiary sediments of New Zealand, in Hambrey, M. J. and Harland, W. B., eds., *Earth's Pre-Pleistocene Glacial Record*: Cambridge, Cambridge University Press, p. 438-446.
- WATTS, W. W., 1881, Pebble from the Cambridge Greensand: *The Geological Magazine*, v. 8, p. 95.
- WELLES, S. P. AND BUMP, J. D., 1949, *Alzadasaurus pambertoni*, a new elasmosaur from the Upper Cretaceous of South Dakota: *Journal of Paleontology*, v. 23, p. 521-535.
- WELLS, A. K. AND GOSSLING, F., 1947, A study of the Pebble Beds in the Lower Greensand in East Surrey and West Kent: *Proceedings of the Geological Association*, v. 58, p. 194-222.
- WHITE, H. J. O., 1924, The geology of the country near Brighton and Worthing: *Memoirs of the Geological Survey England and Wales*, v. 318 and 333, p. 1-114.
- WILDE, P., AND BERRY, W. B. N., 1982, Progressive ventilation of the oceans—potential for return to anoxic conditions in the post-Paleozoic, in Schlanger, S. O. and Cita, M. B., eds., *Nature and origin of Cretaceous carbon-rich facies*: London, Academic Press, p. 209-224.
- WILSON, H. E., 1972, *Regional Geology of Northern Ireland* Belfast: Her Majesty's Stationary Office, 115 p.
- WINTERER, E. L., 1964, Late Precambrian pebbly mudstone in Normandy, France: Tillite or tilloid?, in Nairn, A. E. M., ed., *Problems in Palaeoclimatology*: London, Interscience Publishers, p. 159-178.
- WOLLENBURG, I., PEIRMAN, S., AND LANGE, M., 1988, Sediment in Eurasian Arctic sea ice: *Eos*, v. 69, p. 1263.
- WOODARD, G. D., 1955, The stratigraphic succession in the vicinity of Mt. Babbage Station, South Australia: *Transactions of the Royal Society of South Australia*, v. 78, p. 8-17.
- WOODS, H., 1895, Boulders in a coprolite bed at Stanbridge: *The Geological Magazine*, v. 2, p. 377-378.
- WOOLNOUGH, W. G. AND DAVID, T. W. E., 1926, Cretaceous glaciation in Central Australia: *Quarterly Journal of the Geological Society of London*, v. 82, p. 332-351.
- WOPFNER, H., FREYTAG, I. B., AND HEATH, G. R., 1970, Basal Jurassic-Cretaceous rocks of western Great Artesian Basin, South Australia: stratigraphy and environment: *The American Association of Petroleum Geologists Bulletin*, v. 54, p. 383-416.
- WRIGHT, R., ANDERSON, J. B., AND FISCO, P. P., 1983, Distribution and association of sediment gravity flow deposits and glacial/glacial-marine sediments around the continental margin of Antarctica, in Molnia, B. F., ed., *Glacial-marine Sedimentation*: New York, Plenum Press, p. 265-300.
- ZIEGLER, A. M., PARRISH, J. M., JIPING, Y., GYLLENHAAL, E. D., ROWLEY, D. B., PARRISH, J. T., SHANGYOU, N., AND BEKKER, A., 1993, Early Mesozoic phytogeography and climate: *Philosophical Transactions of the Royal Society, series B*, v. 341, p. 297-305.
- ZIEGLER, A. M., RAYMOND, A. L., GIERLOWSKI, T. C., HORRELL, M. A., ROWLEY, D. B., AND LOTTES, A. L., 1987, Coal, climate and terrestrial productivity: the Present and Early Cretaceous compared, in Scott, A. C., ed., *Coal and coal-bearing Strata: Recent Advances*: London, Geological Society, p. 25-49.
- ZIEGLER, P. A., 1990, Geological atlas of western and central Europe 1990: The Hague, Shell International Petroleum Maatschappij B. V., 239 p.