ANTARCTIC ICE AND SANGAMON SEA LEVEL[1]

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ABSTRACT

Lake sediments and inactive solifluxion flows in central Antarctica indicate that summer temperatures were 7°C to 10°C higher than they are today sometime during the Pleistocene. A temperature rise of this amount would have little effect on the East Antarctic Ice Sheet, which has probably existed since the late Pliocene, but all ice shelves would be destroyed, because they consist of "cold" ice and cannot exist where the mean temperature of the warmest month is much above freezing point. The portion of the West Antarctic Ice Sheet that is grounded below sea level and is in dynamic equilibrium with the Ross and Filchner ice shelves would disintegrate, raising sea level by about 4 m to 6 m. That this has happened at least once during the Pleistocene is suggested by a well-marked sea level stand of about 6 m, dated by uranium and thorium isotopes at about 120,000 years ago, probably at the end of the Sangamon Interglacial. The present West Antarctic Ice Sheet has re-formed since then.

RÉSUMÉ

Les sédiments lacustres et des écoulements inactifs de solifluction dans l'Antarctique central montrent que les températures d'été durant le Pléistocène étaient de 7 à 10°C plus élevées que maintenant. Une hausse de température de cet import aurait peu affecté la couche de glace de l'Antarctique oriental, qui a probablement existé depuis le Pliocène le plus récent, mais tous les champs de glace flottants auraient été détruits, car ils consistent en glace « froide » et ne peuvent exister quand la température moyenne du mois le plus chaud est de beaucoup supérieure au point de solidification. La portion de la couche de glace de l'Antarctique occidental qui descend sous le niveau de la mer et est en équilibre dynamique avec les masses de glace flottantes de Ross et de Filchner se seraient désintégrées, relevant le niveau de la mer de 4 à 6 m environ. Que ceci se soit produit au moins une fois au cours du Pléistocène est suggéré par un niveau de la mer bien marqué d'environ 5 m, daté par des isotopes d'uranium et de thorium à 120 000 ans, probablement à la fin de l'Interglaciaire Sangamon. La présente couverture de glace de l'Antarctique occidental s'est reformée depuis lors.

INTRODUCTION

Absolute sea level is the former level that the sea would have reached on a tectonically stable coast, and relative sea level is the level that the sea actually reached on the land. As Flint (1966, p. 674) points out, no independent datum is available from which absolute changes in sea level can be deduced from relative sea level because no distinction is possible between eustatic variations and crustal movement. Thus the alleged stability of a coast cannot be proved. Nevertheless, former stands of the sea of the same age and at similar heights in different parts of the world that are believed to be stable would suggest that the coasts probably are, in fact, stable.

The relative contributions of glacial and non-glacial eustasy to higher Pleistocene absolute sea levels are a matter of controversy; some investigators (e.g. Fairbridge, 1961, fig. 9, 10) believe that during most of the Pleistocene, glacio-eustatic changes were superimposed on a eustatic fall from other causes, so that interglacial absolute sea levels were progressively lower, whereas Donn and others (1962) and Russell (1964 b) contend that absolute sea levels have been dependent on glacio-eustasy, at least since Illinoian time.

During the last interglacial, the sea remained at the same high level on allegedly stable coasts for a considerable time. In theory, a prolonged constant sea level on a

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stable coast could result from a balance between opposing glacial and non-glacial eustatic changes; this is unlikely except for short intervals, and the simplest explanation is that constant sea level on a stable coast reflects constancy of the earth's land ice cover. In effect, this means stability of ice sheets; today, if all other glaciers melted, sea level would rise only about 70 cm, ignoring thermal expansion. The volumes of the Antarctic Ice Sheet, the Greenland Ice Sheet, and all other glaciers are approximately in the ratio 100:10:1 (Thiel, 1962, p. 175).

The problem is to account for a prolonged glacially-controlled absolute sea level higher than today's. Present sea level was attained essentially as the result of the melting of the North American and Eurasian Pleistocene ice sheets, caused by rising temperatures, and although some workers disagree (see below), it has probably changed little during the last 5000 years, despite temperature fluctuations of at least 3 °C. This is because, although fluctuations of this magnitude have greatly affected mountain glaciers, they have had little effect on the remaining ice sheets, those of Greenland and Antarctica.

A long-occupied higher interglacial absolute sea level, if glacially controlled, requires an analogous situation, and implies that the whole of one of the present ice sheets had disappeared, after which the remaining ice sheets were still climatically secure against moderate temperature fluctuations. Consideration of the differences between an ice sheet based on land and one based below sea level indicates that the Antarctic Ice Sheet comprises two distinct ice sheets with different histories and characteristics: the East Antarctic Ice Sheet and the much smaller West Antarctic Ice Sheet. Of the three existing ice sheets, the West Antarctic Ice Sheet is the most vulnerable to a rise in temperature, and there is evidence that during at least one Pleistocene interglacial, temperatures in the Antarctic were high enough to destroy it.

A WARM "INTERGLACIAL" INTERVAL IN CENTRAL ANTARCTICA

The Reedy Glacier flows from the East Antarctic Ice Sheet through the Transantarctic Mountains to the southeastern extremity of the Ross Ice Shelf. Alongside the glacier at latitude 86° S and 1400 m elevation, at least 90 m of sediments were laid down in an ice-marginal lake in which icebergs floated, indicating open water during summer; average temperature of the warmest month at this site today is estimated to be about minus 10 °C (Mercer, 1968). Although this is anomalously warm for the latitude and elevation, probably because of the adiabatic heating of the prevailing down-glacier winds (at Byrd, 1530 m above sea level and at latitude 80° S, average temperature of the warmest month is minus 15 °C), nevertheless, in the vicinity of the lake sediments, meltwater now accumulates only on clear, calm days after snowfalls, in shallow pools that last for a few hours while the sun is in a favorable direction and then refreeze. Lakes similar to that formerly existing at 1400 m and latitude 86° S are now confined to areas close to sea level and at lower latitudes, where average midsummer temperatures are only slightly below freezing point; for example, Lake Radok, about latitude 71° S, longitude 68° E (Mellor and McKinnon, 1960, p. 32) and the lakes in the Bunger Hills, latitude 66° 20′ S, longitude 101° E. Therefore, when the ice-marginal lake existed by the Reedy Glacier, summer temperatures were at least 7 °C higher than they are today. Inactive solifluxion flows also occur adjacent to the Reedy Glacier, at elevations between 2000 m and 2200 m where summer temperatures are now about minus 16 °C, at least 10 °C too low for the existence of an active layer.

The inferred surface profile of the Reedy Glacier at the time the lake sediments and the solifluxion flows were formed suggests that both are of northern hemisphere interglacial age; the solifluxion flows are believed to be older than the Sangamon Interglacial and the lake sediments are of uncertain age (Mercer, 1968). These deposits are evidence that at least once during the Pleistocene, but not necessarily during the last interglacial, temperatures in the Reedy Glacier area were 7 °C to 10 °C, or more, higher than they are today. This does not imply that average world temperatures were so much higher, because temperature fluctuations tend to be most pronounced at high latitudes (Fairbridge, 1964, p. 440; Butzer, 1964, p. 324). Evidence of warm episodes during the Pleistocene in the McMurdo Sound area is discussed by Nichols (1965).

THE EFFECT ON ANTARCTIC ICE OF A 10 °C RISE IN SUMMER TEMPERATURE

The present minus 10 °C isotherm for January lies inland but close to the coast throughout Antarctica except in the Antarctic Peninsula (Tolstikov and others, 1966) Pl. 76), so that an increase in temperature of 10 °C would cause only marginal increase in ablation by melting. However, Robin and Adie (1964, p. 105) note that ice shelves are polar or subpolar in type; subpolar glaciers on land reach sea level slightly north of where ice shelves can exist. Therefore, ice shelves that are close to the climatic limit are sensitive to changes in summer temperatures. The limits of most Antarctic ice shelves such as the Ross and Filchner are determined by the positions of lateral anchors and other topographic factors (cf. Swithinbank, 1955, p. 65) and not by temperature. However, in the Antarctic Peninsula some ice shelves do extend to the climatic limit. In that area the limit is apparently near the 0 °C isotherm for January because embayments and sounds that are topographically suitable for occupation by ice shelves are open water in summer if they lie north of this isotherm but contain ice shelves if they lie to the south (Tolstikov and others, 1966, Pl. 76).

At present, average January temperature along the fronts of both the Ross and Filchner ice shelves is about minus 4 °C. Consequently, these ice shelves would not be affected if summer temperature rose as much as 4 °C, but they must have receded far to the south when summer temperature was 7 °C higher and probably disappeared altogether if it was 10 °C higher.

As Hollin (1962, p. 185) and Robin and Adie (1964, p. 116) point out, the disappearance of ice shelves during a warm interval would also entail the disappearance of all ice grounded more than about 170 m below sea level, and a stable coastline would develop (fig. 1), similar in character to the present west coast of the Antarctic Peninsula north of latitude 69° S, where ice cliffs end between high and low water level. In West Antarctica, where the Ross and Filchner ice shelves are the floating extensions of the grounded West Antarctic Ice Sheet with which they are in equilibrium, changing horizontal forces would cause the grounded ice sheet to thin and decrease in area as the ice fronts receded until the whole of it had lifted off the

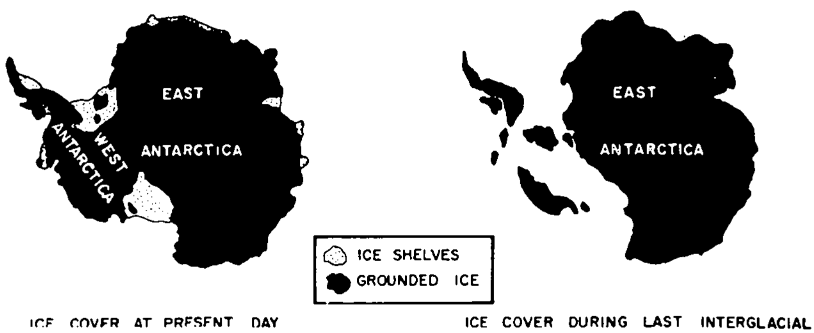

FIG. 1.

sea bottom and reverted to a single ice shelf, at which point the glacio-eustatic rise in sea level would cease. If warming continued, this ice shelf would be replaced by pack ice. This would be, in reverse, the process postulated by Bentley and Ostenso (1961, p. 891) for the formation of the ice sheet.

Thus the West Antarctic Ice Sheet is an uniquely vulnerable and unstable body of ice which cannot exist unless composed of "cold" ice throughout. Although it reaches 2000 m above sea level, the elevated portions would in no way help it to survive if average summer temperature rose above freezing point at sea level. Furthermore, compared to the slow melting away of an ice sheet of similar size on land, its disappearance by disintegration into the sea would be rapid, perhaps even catastrophic.

The topography of the rock surface beneath the ice of East Antarctica is not yet well known. Extensive areas of ice grounded below sea level are known or suspected, but they appear to be in enclosed basins and are not in equilibrium with ice shelves; an almost complete rim of land above sea level encircles the continent (Kapitza, 1967; Tolstikov and others, 1966, Pl. 66). If the existing ice shelves of East Antarctica disappeared, this would not cause those parts of the ice sheet that are below sea level to spread horizontally, in contrast to the grounded West Antarctic Ice Sheet. More detailed information about the ice-rock interface may change this picture, but with present knowledge the volume of the East Antarctic Ice Sheet would be only slightly affected by a 10 °C rise in summer temperature, although the ice near the coast would become temperate.

West Antarctic ice volume

If summer temperatures in Antarctica during a Pleistocene interglacial have in fact been high enough to cause the disappearance of the part of the West Antarctic Ice Sheet that is grounded below sea level, as the evidence from the Reedy Glacier suggests, absolute sea level would have risen as a result. Much of the ice sheet and all its peripheral ice shelves are merely displacing their own weight of water, and their melting would not affect sea levels. A calculation based on available maps of ice surface and rock surface contours (Thiel, 1962, fig. 3-5; Tolstikov and others, 1966, Pl. 64-66) indicates that about 1.5 to 1.8 million km^3 of ice represents water substracted from the oceans. Taking the area of the oceans as 360×10^6 km^2, and the density of ice as 0.9, this would raise absolute sea level by 4-4.5 m, ignoring flooding of lowlands and thermal expansion of the oceans. The eustatic effect of the recovery of the ocean floor that the ice sheet had rested on would probably be counterbalanced by the depression of the remainder of the ocean floor caused by the increase in the mass of the oceans.

Greenland ice sheet

The Greenland Ice Sheet contains about 2.6 million km^3 of ice, so that its complete melting would raise absolute sea level by about 6.5 m. It is land-based like the East Antarctic Ice Sheet and could consist of temperate ice throughout, and is thus less vulnerable to a rise in temperature than is the West Antarctic Ice Sheet. Its behaviour during an Antarctic warm episode is not known. Because the ice sheet extends through such a wide range of latitude, severe ablation would start in the southern half and extend progressively north with rising temperature so that sea level would rise slowly. There is no evidence that the Arctic regions have experienced Pleistocene summer temperatures so far above today's as have the Antarctic regions, although why this should be so is not clear. Probably, interglacial sea levels can provide the best evidence about the contemporary volume of the Greenland Ice Sheet, if they can be interpreted correctly.

Flint (1966, p. 674) rightly insists that comparison of former sea levels in different parts of the world should be based on factors other than altitude, and he notes that radiometric dating of marine features offers a means of long-distance correlation. Radiometric dating indicates a worldwide high stand of the sea about 120,000 years ago. The study of deep-sea cores indicates that this was near the end of an interglacial (Rosholt and others, 1961, p. 182; Broecker, 1965, p. 745) which Ericson and others (1964) believe was the last (Sangamon) but which Emiliani (1964, p. 141) believes was the next to last (Yarmouth). This difference of opinion results from the interpretations of a later climatic warming from about 95,000 to 60,000 years ago. Emiliani contends that this interval was at least as warm as today and was, therefore, a full interglacial, whereas Ericson and others believe that it was a Wisconsin interstadial and cooler than today. Although the ages of two samples of raised coral from the Florida-Bahamas area (Broecker, 1965, p. 747; Broecker and Thurber, 1965, p. 59; Thurber and others, 1965) and one sample from the Red Sea (Berry and others, 1966, p. 125) fall in this interval, the evidence at present is on the whole against a repetition of the worldwide high sea stand of 120,000 years ago, suggesting that that date did, in fact, fall in the Sangamon.

Veeh (1966, p. 3379), using the uranium series inequilibrium method, has dated raised corals from several parts of the Indian and Pacific oceans. The elevations of the samples above mean low tide, which give a minimum estimate of former relative sea levels, were between 1.5 m and 9 m, depending upon the site, but the ages were all about 120,000 years. Veeh ascribes the spread of elevations to the different diastrophic histories of the sites, and believes that the similarity of ages is strong evidence of eustatic control. Because of the evident instability of most of the sites, Veeh was unable to estimate the change in absolute sea level.

Russell (1964 a and 1964 b), who has studied coasts facing all the world's oceans, concludes that there has been minimal deformation in parts of Western Australia and the Seychelles Islands, on opposite sides of the Indian Ocean. The west coast of Australia, he believes, is perhaps the best place in the world from which to infer absolute changes in sea level. His criterion for sea level is the height of former reef growth above the present reef flat, and he emphasizes that beach deposits connected with the same sea stand can extend several metres higher. He finds (personal communication) a conspicuous stand at about 6 m; coral from this stand is about 120,000 years old and, therefore, probably Sangamon in age. Russell also has evidence of a 6 m stand in South and East Africa and the West Indies. (Daly [1920, p. 256, 260; 1934, p. 157] also notes evidence of former shorelines at about 6 m in Western Australia, Samoa, Norfolk Island, St. Helena, southern Africa and the West Indies, but he had no means of dating them and believed that they were Hypsithermal in age.)

In the central reaches of the English Channel, an area thought to have been fairly but not completely stable since the late Pleistocene, relative sea level reached about 7.5 m during the Ipswichian (Sangamon) Interglacial. The final rise in sea level took place during the interglacial hypsithermal when summers were warmer than they are today, and was exceptionally rapid (West and Sparks, 1961).

All the foregoing is either evidence for, or is consistent with, the concept that the highest absolute sea level during the Sangamon Interglacial was about 6 m. However, some other observations suggest a higher level. Butzer and Cuerda (1962) have studied shore features in Majorca and find evidence of Sangamon sea levels up to 11.5 m; the area, they claim, was undoubtedly stable throughout the Pleistocene. In the southeastern United States, the Key Largo limestone and the Miami Oolite of Florida which have been radiometrically dated at 120,000 to 130,000 years (Osmond and others, 1965, p. 1846; Broecker and Thurber, 1965, p. 59), are believed to have been formed when sea level was about 10 m higher relative to the land. In southeast Virginia inferred relative sea levels at several elevations between 5 m and 15 m are thought to be Sangamon in age (Oaks and Coch, 1963, p. 982; Flint, 1966, p. 677). However, although some consider that the Atlantic coastal plain has been free from diastrophic movement during the late Pleistocene, others (Hack, 1955, p. 38; Harrison and others, 1965; Hoyt and Hails, 1967, p. 1542) believe that at least parts of it have been affected. The southeastern United States is, therefore, probably not a good area from which to estimate absolute changes in sea level. In northwest Alaska, Sainsbury and others (1965, p. 240) conclude that sea level was formerly between 8.5 m and 12 m higher relative to the land at a time beyond the range of C-14 dating and thought to be Sangamon. They believe that the area has not been tectonically uplifted.

Thus, the problem of absolute Sangamon sea level is far from solved, but, with the evidence at present available, a level of about 6 m 120,000 years ago seems the most probable.

THE ANTARCTIC ICE DURING THE HOLOCENE

Three views are held about Holocene absolute sea levels. The first is that sea level oscillated and reached 3 m to 5 m during the Hypsithermal Interval, after which it fell (Fairbridge, 1961, p. 161, 165; Butzer and Cuerda, 1962, p. 414). However, the dates on which this concept depends are suspect (Russell, 1964 a, p. 39). Jelgersma (1966) reviews and discusses the problem and concludes that evidence for high postglacial sea level is questionable. Glacial control of such high hypsithermal sea levels would be difficult to explain; not only has insufficient time passed since the hypsithermal maximum for the West Antarctic Ice Sheet to have re-formed if much of it had disintegrated, but West Antarctica would not be in its present state of isostatic equilibrium. The second view is that sea level has been rising continuously during recent millennia at the rate of about 0.75-1 m every 1000 years and at no time since the Sangamon has it stood higher than at present (Shepard, 1964; Redfield, 1967). The third view, which appears to be gaining favour, is that sea level is now at a maximum postglacial level, but has remained virtually unchanged for the past 4000 to 5000 years (Russell, 1964 a; Shepard and others, 1967).

If hypsithermal sea levels were little or no higher than today's, summer temperatures in the Antarctic can then have been no more than 5 °C higher than they are today. However, temperatures perhaps came close to the critical level, because in temperate northern latitudes they may have approached Sangamon values. The warmest part of the postglacial hypsithermal interval in middle latitudes was probably 2 °C to 3 °C warmer than today (Charlesworth, 1957, p. 1493) and a mean interglacial annual temperature at least 3 °C higher than today's is indicated by the fossils of the Don beds near Toronto, believed to be Sangamon in age, though not necessarily from the warmest part (Terasmae, 1960, p. 39). Europe was probably at least 3 °C warmer than today during the warmest part of the last interglacial (Butzer, 1964, p. 326).

What is the likelihood that the West Antarctic Ice Sheet will disintegrate during the present interglacial, as during the Sangamon? There is evidence that ice shelves in the Antarctic Peninsula, where they are sensitive to climatic change, may have receded southward quite recently; Fleming (1940, p. 95, 99), Fuchs (1951, p. 405), and Thomas (1963, p. 27) believe that island ice caps and ice fringes existing in west coastal regions of the Antarctic Peninsula could only have formed in conjunction with ice shelves which have since vanished. Ice shelves lying just south of the 0 °C January isotherm have receded recently, although climatic warming is perhaps not the cause in every case. The Larsen Ice Shelf extends along most of the east coast of Graham Land, and at its northern extremity nearly 1000 km^2 has broken away in recent years (Koerner, 1964, p. 39). Ice shelves are confined to the southern part of the warmer west coast, and in King George VI Sound the ice front retreated about 45 km during the 1940s at both the northern and southwestern ends (Fuchs, 1951, fig. 2, 4). In East Antarctica Buinitskii (1964/1960, p. 217) notes that many of the ice shelves are becoming smaller. In the late 1950s Mellor and McKinnon (1960, p. 32) noted that the Amery Ice Shelf, which is close to the 0 °C isotherm for January, was subject to greater melting than were most other ice shelves: melt pools lay in hollows between pressure ridges, and the banding of icebergs indicated summer melt layers. This indicates that the ice shelf was subpolar in its northern parts, and thus vulnerable to climatic warming. In 1963, 11,000 km^2 of the ice shelf broke away, the largest breakout ever recorded from any ice shelf (Swithinbank, 1966, p. 467). However, this is perhaps a regularly repeated event caused by structural failure (Budd, 1966, p. 355) rather than by climatic warming.

The recent recession of these ice shelves is thus not conclusive evidence of climatic warming of Antarctica. Instrumental records suggesting that a warming has taken place during the present century are also inconclusive because observations were not made at exactly the same site. Wexler (1961, p. 57) estimates that average annual temperature increased by 2 °C between 1912 and 1957 at Little America on the edge of the Ross Ice Shelf, and over virtually the same interval (1912 and the years 1956-59) Averyanov (1965) estimates that summer temperatures in the vicinity of Mirnyy rose nearly 3 °C. If the apparent warming trend is real and continues until hypsithermal conditions are reached and exceeded, whether because of industrial pollution of the atmosphere (see Abelson, 1967) or for any other reason, the unstable West Antarctic Ice Sheet will become a threat to coastal areas of the world within 6 m of sea level.

Summary and conclusions

Field evidence indicates that summer temperatures in the Antarctic were too high for the existence of the West Antarctic Ice Sheet during at least one Pleistocene interglacial; in the absence of this ice sheet alone, absolute sea level would have been 4-4.5 m higher than it is today. There is considerable evidence from the Pacific and Indian oceans and elsewhere that a stand at about 6 m occurred about 120,000 radiometric years ago, which was probably during the last interglacial. If so, this strongly suggests cause and effect: that the disappearance of the West Antarctic Ice Sheet was mainly responsible for the high interglacial sea level. Increased melting of mountain glaciers, marginal melting of the Greenland Ice Sheet and thermal expansion of the oceans, added the remainder. The evidence given by West and Sparks (1961) that the rise in sea level to above present levels took place during the Sangamon Hypsithermal and was very rapid, suggests possible catastrophic disintegration of the West Antarctic Ice Sheet at that time, but further evidence is needed. Most of the Greenland Ice Sheet remained in existence, partly because it is land-based, and, therefore, less vulnerable to rise in temperature; but also, perhaps, because temperature in the Greenland area did not rise so much as it did in West Antarctica.

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DISCUSSION

C. BULL

In the areas of S. Victoria Land where present highest monthly average temperatures are about 0 °C the present amount of solifluxion is very small.

In the absence of a Ross Ice Shelf one might expect penguin rookeries - which could give datable evidence of the absence of the Shelf.

J. HOLLIN

Progress on this problem might be made by way of the micro-palaeontology, if any, of Dr. Mercer's sediments. On their age: tree or grass pollen would favour the Tertiary; moss spores a Quaternary interglacial. On their environment, pollen or diatoms might yield information about the proximity of the sea. If the sediments are both Quaternary and quasi-marine, they may indeed account for a few metres of the known higher sea levels of the Quaternary.

C. SWITHINBANK

If the remains of a penguin rookery were found in the Transantarctic Mountains south of Minna Bluff I would not be prepared to conclude that the Ross Ice Shelf was absent from the area at the time the penguins were occupying it. I have seen an Adélie rookery with nesting penguins 100 km inland from the Antarctic coast. If they will nest that far inland, why not further?