ORIGINAL ARTICLES.

A Recent Worldwide Sinking of Ocean-level

By REGINALD A. DALY, Harvard University, Cambridge,
Massachusetts.

Introduction.

Field Observations.

First Contact with the Problem.

Gulf of St. Lawrence.

Maine.

Samoa.

Difficulties of an Inductive Study of Records.

British Isles.

Atlantic Coastal Plain of the United States.

Florida Keys and West Indies.

South America.

Graham Land.

New Zealand.

Australia.

Pacific Islands.

California.

Amount of the Eustatic Change.

Contemporaneity and Age of the Strands.

Cause of the Eustatic Change.

Conclusion.

LOCAL uplift and local sinking of the earth's surface have been fully demonstrated for past geological epochs. The amounts of these movements have generally been stated with reference to the present sea-level, and for the greater movements the statements of magnitudes are not seriously impaired by the fact that general sea-level itself has been shifting, upwards and downwards, through geological time. Among the causes for general or "eustatic" shifts of sea-level are: appropriate crustal movements whereby the volume of the ocean basin has been changed; delta-building and volcanic eruption on the sea-floor, the displacement of sea-water not being compensated by crustal sinking; volcanic addition of new water to the ocean; subtraction of water which becomes chemically bound during the alteration of rocks; glaciation on land, lowering sea-level by the abstraction of water from the ocean; deglaciation on land, raising sea-level; changes in the earth's centre of gravity and in her speed of rotation.¹

Numerous as these possibilities are the proof of a eustatic change in shore-levels is not easy. In the following pages are recorded some field facts which suggest the probability of a sinking of general sea-level to the extent of about 20 feet during the human period. The

¹ The writer has recently found that A. Tylor (*GEOL. MAG.*, 1868, p. 576, and 1872, p. 392) anticipated even Belt in relating the origin of coral reefs to the shift of ocean-level consequent on deglaciation. W. B. Wright (*The Quaternary Ice Age*, London, 1914, p. 417) believes the submerged forests of the British Isles prove a eustatic shift of 55 to 60 feet, if not of considerably greater amount, and attributes it to deglaciation.

suggestion is published, not to express a fixed conclusion, but to invite criticism by those familiar with shorelines in different parts of the world, for the testing of the idea is manifestly a worldwide problem.

The matter is important because it affects judgment as to the reality of many so-called uplifts of land or sea-bottom, and because a close study of the latest shift of sea-level may help to systematize the criteria for earlier and larger eustatic shifts.

FIELD OBSERVATIONS.

First Contact with the Problem.—The hypothesis of a Recent, negative shift of sea-level first suggested itself to the writer nearly twenty years ago, while engaged in the correlation of post-Glacial elevated strands in Labrador and Newfoundland with those of Quebec. The highest strand mapped between Newfoundland and Nachvak Bay, 500 miles to the north-west, was found to be strongly warped; its gradient varies from 1 to 3 feet per mile, measured along the coast and thus not at right angles to the isobases. The highest strand in Maine has maximum gradients of 5 or more feet per mile. Ice attraction fails to account for such high values and even for the lower gradients of the old strands around the Great Lakes, where also crustal warping is generally credited. On the other hand, the lowest emerged terrace along the shores of the Gulf of St. Lawrence was seen to be conspicuously level throughout a distance of 300 miles or more below Quebec City. The apparent uniformity of level prompted the question whether this particular strand had been abandoned by the waves because of a sinking of general sea-level. For lack of accurate levelling, definite correlation with the more closely studied, lowest beaches of Labrador was impossible, and with the data in hand serious belief in the hypothesis of a eustatic change was withheld.

However, that explanation was recalled by the discovery of new facts during recent field studies on the shores of New England, Florida, and the Samoan Islands. Meantime, Goldthwait had made a careful study of the St. Lawrence strand, to which he gave the name "Micmac terrace"; the results of his levelling agree so well with those made in the other regions mentioned that the suspicion of past years has become a hypothesis that seems to deserve more attentive consideration.

For the opportunity to collect data from the two tropical regions the writer is indebted to Dr. A. G. Mayor, Director of the Marine Laboratory of the Carnegie Institution of Washington.

Gulf of St. Lawrence.—In his excellent account of the Micmac terrace, Goldthwait writes: "Traces of wave work along the south coast of the Saint Lawrence were found at all altitudes below the upper limit of submergence. Contrary to expectation, again, there proved to be no shoreline below the highest one, with the exception of the twenty-foot [Micmac] strand, which possesses enough

individuality of character, enough strength of expression, or enough continuity to indicate a long stand of the sea at any level. Distinct beach fragments were found at all altitudes, in such places as were peculiarly favorable to exposure to the open sea, or in supply of beach material. This is believed to indicate that the emergence of the Saint Lawrence valley from the Champlain sea was not accomplished by spasmodic uplifts, separated by intervals of repose, but was fairly steady and continuous. . . . In marked contrast with the weak beaches at higher levels, the shoreline which stands 20 feet above the sea is strong and continuous.”¹ Similarly, the present writer could find no sure evidence of pronounced halts in the uplift of Labrador, where, however, the great strength of the bed-rocks and the general absence of thick glacial drift would in any case forbid the development of continuous beaches or benches in the time available. For the same reasons the topographic equivalent of the Micmac terrace would not be expected in Labrador, except quite locally, even if the emergence took place at identical rates in the two regions. The width of the Micmac terrace varies from a few feet to 1.5 miles or more. Though only a part of its width is due to wave-cutting, and though the formations affected are relatively weak, the 20 ft. higher level of the sea must have been steadily kept for a large fraction of post-Glacial time.

Farther east in the Gulf of St. Lawrence, at Anticosti, Twenhofel found elevated shorelines at intervals up to 350 feet above sea. “The lowest is between eight and fifteen feet above high tide.” The corresponding terrace “reaches a maximum width of more than two miles and will average more than one-fourth mile”. On the eastern two-thirds of the south coast for about 80 miles, this terrace is two or more miles wide, and is described as occurring in many other parts of the island.²

At Arisaig, Nova Scotia, on Northumberland Strait, Twenhofel noted a “raised” beach, roughly estimated to be 25 feet above sea (mean water-level?).³

Maine.—“Throughout the region of Penobscot Bay the best defined and most widely developed terrace has an elevation of 20 to 25 feet above sea-level.”⁴ In the Rockland folio of the United States Geological Survey Bastin writes (1908): “The most widely developed terrace stands about 15 to 25 feet above mean tide.” Along the Maine coast in general Stone noted evidence of a pause in the post-Glacial “fall of the sea” at an elevation of 20 feet above (mean?) sea-level.⁵ The present writer’s field observations accord with these published statements, which indicate a recent,

¹ J. W. Goldthwait, *Amer. Journ. Sci.*, vol. xxxii, 1911, pp. 293-4.

² W. H. Twenhofel, *Amer. Journ. Sci.*, vol. xxx, 1910, pp. 66, 69.

³ *Ibid.*, vol. xxviii, 1909, p. 147.

⁴ G. O. Smith, E. S. Bastin, and C. W. Brown, Penobscot Bay folio, U.S. Geol. Survey, 1907, p. 13.

⁵ G. H. Stone, *Monograph 34*, U.S. Geol. Surv., 1899, p. 53.

lengthened stand of the sea along the Maine coast at a level nearly 20 feet higher than the existing high-tide level.

The similarity of levels for the lowest terraces in areas so widely separated as the Maine coast and the Gulf of St. Lawrence, and the failure of the 300-mile Micmac terrace to show a distinct tilt, although it runs athwart the isobases of post-Glacial uplift, are both difficult of explanation by assuming crustal uplifts. Confidence in the alternative hypothesis of a eustatic shift was greatly increased by 1919 studies of shorelines in Samoa, about 7,000 miles from the St. Lawrence.

Samoa.—Mayor had already found wave-cut rock-benches, about 8 feet above high tide on all sides of Tutuila, the largest island of American Samoa.¹ The island is 16 miles long. At its eastern end is Aunuu Island, and about 60 miles farther east is Tau Island of the Manua sub-group. The writer found very fine wave-cut benches at 8 to 10 feet above high tide on Aunuu and Tau, and others at the same general elevation on Olosega Island, 7 miles west of Tau. The distance between the most widely separated benches is 75 miles; nowhere in that long line did the bench crests depart essentially from a constant level. Explanation by local uplift was at once seen to be highly improbable, for crustal uplift of such uniformity is unknown to geology.

Eight or ten feet of bench elevation does not, however, measure the total of recent emergence in Samoa. At several points in Tutuila large sea-caves were found. Their floors varied in height above high tide, from 14 or 15 feet at their mouths to 25 feet at the back walls of the caves. Many caves of similar forms and cut in similar rocks are being made by the surf of the present day. The lower lips of the newer caves are characteristically 4 to 6 or more feet below high-tide level, and the floors rise inwards to heights of a few feet above high tide. Hence the emerged caves were cut when the sea-level was nearly 20 feet higher than now. That assumption also explains the 8 ft. benches, for the cliffs now being cut on the Samoan headlands (where not protected by coral reefs) have regularly about 12 feet of water directly at their feet during high tide. The writer fully agrees with Mayor's conclusion that reef corals were not living on any of these Samoan shores when the emerged caves and benches were developed.² Hence the reefless, or nearly reefless, headlands of the present time are those where the relation between sea-level and bench-level of the earlier period is best determined. It may be added that no evidence of a negative shift of sea-level greater than about 20 feet could be found in the Samoan Islands. If they ever were submerged more deeply, the evidences have been removed by erosion.

The equivalence of the negative shift of sea-level in Samoa and along the east coast of North America is shown not only by its

¹ A. G. Mayor, *Proc. Nat. Acad. Sci.* vol. iii, 1917, p. 523.

² *Ibid.*, p. 522.

amount, but also by the state of preservation of the strand marks. Allowing for lithological differences, cliffs, benches, caves, and chasms have comparable strength of development in the two regions, in each of which the sea must have worked a relatively long time at the 20 ft. level. Since the shift of level the surf has destroyed a part of each bench in Samoa, therewith doing work roughly equal to the destructive wave-work already performed on equally hard rocks in Maine.

Difficulties of an Inductive Study of Records.—The hypothesis of a eustatic change must meet the obvious test of matching the facts observable on the shores of every continent and nearly all islands. That the application of the test is not easy will be clear from the following considerations.

1. Most shores have not been studied with requisite thoroughness. The compilation of the published, appropriate records, incomplete as they are, is a herculean job. Apart from the time and physical labour involved, the compiler is baffled by the psychology of many authors, who have observed in the field and then written their records under the more or less unconscious control of the uplift hypothesis. Relevant and perfectly accessible facts have therefore not been noted. Moreover, the selection of data in statistical study has its own obvious danger for the compiler.

2. Writers have not always been careful to give the datum from which the level of each "raised" strand was measured. In general "sea-level" is mentioned without specifying mean level or high-tide level or any other unequivocal datum. The omission is serious for the compiler dealing with a shift of only 20 feet.

3. The marks of a higher stand of sea-level depend for their clearness on several highly variable factors, including: the strength and other characters of the shore rocks; the exposure of the coast as it affects the fetch and power of the waves; the power of tidal currents; the position of wave-base at the old shore, especially the depth of the rock-bench cut by the waves at the foot of a receding sea-cliff; the degree to which the records of the higher stand of the sea have been destroyed by the waves acting at present sea-level.

The influence of rock variation is well illustrated in New England, where glacial deposits were distinctly cliffed at the 20 ft. level, while the massive granites suffered little benching. As already stated, the contrast between the shores of the St. Lawrence and those of Labrador in this respect is very striking. Even where the shore materials were quite incoherent, as along young coastal plains, sea-cliffing might not have taken place systematically at all. Modern examples show prograding, rather than retrogression, of the shoreline. Thus the sea-cliffs of the 20 ft. strand would vary in height from zero upwards.

The crest of a storm beach is not sea-level. The more powerful the waves the greater is the difference of these two levels. From published texts one can not always be sure that due allowance

has been made for the difference in estimating former sea-level from emerged beaches.

Variation in the position of wave-base is worthy of special attention. Waves running in on a flat shallow shelf are damped, so that wave-base approaches a minimum depth inshore. Wave-base is deeper along a steep-to shore, other things being equal. In the former case the foot of the sea-cliff is characteristically at or near high-tide level; in the latter case it is typically well below high-tide level, as exemplified in Samoa, where many headland cliffs plunge into water about 2 fathoms deep. Generally old strand-levels on oceanic islands are likely to be notably higher than the corresponding wave-cut benches, as well as 2 to 10 or more feet lower than the level crests of storm beaches.

4. Wherever a coastal region is now undergoing, or has recently undergone, a crustal movement, the search for local evidences of an earlier eustatic sinking of ocean level may give negative or doubtful results. The marks of the old strand may be drowned, or else elevated to heights which are not to be directly correlated with the heights of the old strand in undisturbed rocks.

5. In special cases the eustatic shift may locally cause a change in the tidal range, affecting the datum if this be high tide.

6. Finally the height of the old strand line above mean sea-level may depend on the cause of the eustatic shift. Suppose, for example, that a shift of level averaging 20 feet were due to a recent increase of the ice-cap on the Antarctic continent. Near the ice-cap sea-level would be kept, through gravitative attraction by the new ice, a little higher than it would be if abstraction of water from the ocean were the only cause for the change of level. In the northern hemisphere the lowering of sea-level would be all the greater because of attraction to the new ice.

For many reasons, therefore, the search for complete proof of the eustatic shift here postulated is bound to be prolonged. Meantime a preliminary study of some records made in separate mutually distant regions has been made, with results that also show the hypothesis to merit discussion and further testing. Certain examples may now be briefly reviewed.

British Isles.—The raised beaches of Scotland and Ireland are celebrated, and like the American cases already noted, occur in an area of uplift following deglaciation. In Scotland the uplift was differential, but according to most published statements the lowest beach is at nearly constant level, which is sometimes described as about 20 feet or about 25 feet above Ordnance datum. Ordnance datum is mean water-level at Liverpool, so that the beach varies from 15 to 20 feet above local high tide, according to these statements. Geikie writes: "The most prominent of all the raised beaches is that which lies at a height of about 20 or 25 feet above high water . . . varying in breadth from 6 or 7 miles to not more than a few feet." Along its inner edge are sea-cliffs, caves, sea-stacks,

and skerries. "This beach must be more or less familiar to every one who has visited almost any part of the coast-line of Scotland."¹

Many memoirs of the Geological Survey of Scotland bear references to this beach, which is described as seen "at frequent intervals", or as "conspicuous" or as the "best developed". In the Clyde area, the Loch Fyne area, Skye, and elsewhere, its fossil shells are those of species now living in Scottish waters. Clough writes: "With regard to the age of the 25-foot beach, the consensus of opinion seems to be that the elevation of the beach was completed in Neolithic times."²

In Jamieson's early account of the strand he states that a rise of 25 or 30 feet (above Ordnance datum?) is indicated, and that it "seems to have been very general along the shores of this country". He concluded that the uplift was unequal; "consequently it is the land that has risen, and not the sea that has sunk."³ Fifty years later Wright published a sketch-map of the "25-foot beach", showing a maximum height (above Ordnance datum?) of over 35 feet near Loch Linnhe, in Western Scotland, from which point the elevation declines—to reach zero on the south-east and north-west shores of Ireland, in northern Wales, and in the North Sea.⁴ Wright's placing of this strand-line does not altogether agree with the descriptions published by A. Geikie, Kinahan, Hull, and others, but would indicate late Neolithic warping.

According to Kinahan, "the 25-feet sea beach all around Ireland rises and falls very similarly to the levels of the present sea-margin," though he adheres to the uplift hypothesis as the only one to be considered in explanation. The old level is marked by cliffs, stacks, sea-caves, and beaches; on open seaboards they have been largely destroyed by waves breaking at present sea-level. From Wicklow, southward, the strand is at about the 22 ft. contour. North of Dublin Bay it is below the 20 ft. contour. In the old estuaries it has been placed nearly on the 25 ft. contour, perhaps illustrating the influence of the tides in causing different initial levels. Human relics and shells of species now living in the Atlantic have been found in the Irish beaches also.

Hull described the "25-feet terrace" as the most striking and continuous of all the "raised" beaches of Ireland, and correlates it with the 25 ft. strand in Scotland. However, he gives the average elevation of the Irish beaches as 15 feet.⁵ The contrast in elevations

¹ A. Geikie, *The Scenery of Scotland*, 2nd ed., London, 1887, pp. 381–2.

² C. T. Clough, *The Geology of the Glasgow District* (Mem. Geol. Surv. Scotland), 1911, p. 192.

³ T. F. Jamieson, *Quart. Journ. Geol. Soc.*, vol. xxi, 1865, pp. 188–90.

⁴ W. B. Wright, *The Quaternary Ice Age*, London, 1914, p. 422. According to a personal communication from Mr. Wright (November, 1919) the zero isobase should be drawn considerably farther south in Ireland and Wales.

⁵ G. H. Kinahan, *Manual of the Geology of Ireland*, London, 1878, pp. 251–8; E. Hull, *The Physical Geology and Geography of Ireland*, 2nd ed., London, 1891, p. 137.

may be connected with the difference of datum-levels assumed in the two countries. Ordnance datum in Ireland is 8 feet below Ordnance datum for Great Britain (mean water-level at Liverpool, which is practically the same as in Ireland). In general, 25 feet above Ordnance datum in Scotland means 20 feet or less above high tide, the significant level.

For a total distance of about 1,000 miles along the southern shores of England, Wales, and Ireland, a "pre-glacial" terrace "has been traced almost continuously". It occurs also in France, from Calais to beyond Brittany. "Throughout the greater part of this district it stands uniformly some 10 or 12 feet above the present high-water mark, and maintains a remarkable parallelism with the present sea-level. This parallelism proves almost beyond a doubt that no permanent deformation by folding or faulting has taken place over this wide area since pre-glacial times."¹ The "pre-glacial" age is deduced from the presence of boulder-clay and early "Pleistocene" fossils on the rock-bench cut when the sea stood at the higher level. Wright holds that the old strand owes its position to a eustatic oscillation of sea-level.

The progress of discoveries and ideas concerning the lowest strands in the British Isles shows one kind of danger into which a compiler may run if the record of relevant facts is inadequate. Considering the many statements by good observers as to the continuity of the 20 ft. level or of the 25 ft. level all around both Great Britain and Ireland, it would look as if these islands could afford excellent corroboration of the eustatic hypothesis. When, however, strand-lines of about the right elevation are found to be partly "pre-Glacial" and partly post-Glacial, and when it is further suggested that the later beach-level has been deformed, the difficulty of using the British data is clear. If Wright's view as to the warping of the Neolithic beach (the 25 ft. or 20 ft. beach of Scotland and Ireland) is correct, then the relation of this very extensive strand-line to the eustatic hypothesis could only be established after the dates of the warping and the eustatic shift become known. Meantime the British Isles represent a region where the ascertained facts, in spite of their complexity, point to these islands as a field where special tests of the eustatic hypothesis should be made.

Atlantic Coastal Plain of the United States.—Other questions arise in connexion with the lower parts of Atlantic coastal plains recently emerged. For example, the Cape May formation of New Jersey and Pennsylvania and the correlated Talbot formation of Maryland emerged from the sea not many thousand years ago. Their surfaces lie in general below the 20 ft. contour, but strata with surfaces at 40 or 45 feet have been included in each formation. In the north

¹ W. B. Wright, *The Quaternary Ice Age*, London, 1914, p. 423; *The Geology of the British Isles*, edited by J. W. Evans (*Handbuch der regionalen Geologie*, iii. 1), The Hague, 1918, p. 299. Cf. J. Prestwich, *Quart. Journ. Geol. Soc.*, vol. xlviii, 1892, p. 263.

the "lower Cape May terrace" does not rise beyond the 20 ft. contour. Is there evidence of such a halt in the emergence of the Talbot formation?¹

Similarly, the lower division of the Pensacola terrace in Florida, like the Satilla terrace in Georgia, seems to correlate with the Recent 20 ft. eustatic shift. The Pensacola terrace "is a broad plain, rising less than 40 feet above sea level, and apparently including two divisions, one being less than 20 feet above, and the other from 20 to 40 feet above sea level."² The greater part of the Satilla terrace, which merges into the Pensacola terrace, "is 15 to 25 feet above sea level, but there are a few places which reach an elevation of about 40 feet. . . . If the coast region were uplifted 15 or 20 feet above its present elevation, a plain now submerged beneath the ocean waters would appear as an emerged terrace lying east of and parallel to the Satilla terrace, and separated from it by an escarpment. This plain would be analogous to the Satilla plain in all its essential features."³ Since the Pensacola-Satilla terrace keeps a practically uniform set of levels for an air-line distance of 500 miles, the hypothesis of its emergence by crustal uplift seems hardly credible.

Florida Keys and West Indies.—Vaughan has deduced a recent sinking of sea-level of from 10 to 15 feet along the coral-reef keys of Florida, and "perhaps 10 to 20 feet" along the keys west of Bahia Honda.⁴ He described New Providence Island of the Bahama group as "mostly a platform from sea-level to 20 feet in elevation", and the neighbouring Andros Island as having the same range of emergence. On New Providence Island he discovered a wave-cut scarp at 10 feet above "water-level", and other benches at only 3 or 4 feet above the sea, but he also found a sea-cave at Nicollstown Light, which indicates an emergence of about 18 feet.⁵ This case of apparent conflict in the testimony of bench and sea-cave as to the amount of level-shifting is strikingly like that at Tutuila, Samoa, already described.

In Cuba the Seboruco "reef" represents a recent "uniform" emergence; it "borders the coast in most places" and constitutes many islets surrounding the main island. "Generally these are low, standing only a few feet above the water." In Jamaica Hill found "elevated reefs" at 25 feet and 10 feet above "sea-level",

¹ Cf. M. Fuller, Prof. Paper No. 82, U.S. Geol. Surv., 1914, p. 222.

² G. C. Matson and S. Sanford, Water-supply Paper No. 319, U.S. Geol. Surv., 1913, p. 34.

³ O. Veatch and L. W. Stephenson, Bull. 26, Geol. Surv. of Georgia, 1911, pp. 36, 437.

⁴ T. W. Vaughan, "A Contribution to the Geological History of the Floridian Plateau": Papers of the Marine Laboratory, Carnegie Institution of Washington, 1910, p. 180. "Preliminary Remarks on the Geology of the Bahamas": *ibid.* 1914 p. 50. Yearbook No. 13, Carnegie Institution of Washington, 1914, p. 230.

and states that they are persistent on the north, east, and south-west shores.¹

South America.—According to Branner, the Brazilian coast shows features indicating recent emergence, the amount of which is variously described as “a few meters” to 8 meters.² Halle found a “very distinct terrace at 6 meters above sea-level on Gable Island”, Patagonia, and another at 6 meters at the mouth of the Rio Grande River, 48 kilometres from Gable Island. The sands of the former terrace bear fossils showing that the contemporary sea had a temperature higher than that now reigning offshore. Halle adds: “These low terraces do not afford any unquestionable evidence of an unequal upheaval.”³ Andersson describes a sea-cut terrace at 3·5 meters on Beagle Channel, Tierra del Fuego, and says that it is the “same beach” as those on Gable Island and Navarin Island. He quotes Nordenskjöld’s discovery of a very marked terrace at “about 10 meters above sea-level” on Usuaia Peninsula, Straits of Magellan.⁴

Graham Land, Antarctica.—Andersson also discovered a terrace at 7 meters “above sea-level” on Graham Land, Antarctica, indicating “upheaval” which “does not exceed a few meters”.⁵

New Zealand.—Considerable attention has been given by the Government Geological Survey to proofs of recent emergence in New Zealand, with results which may be tabulated as follows:⁶—

District.	Elevation of “raised beaches” or benches.
Thames subdivision . . .	Maximum “over 25 feet” (datum?).
Miranda, across Firth of Thames . . .	10 to 12 feet above high-water mark.
Waihi-Tairua subdivision . . .	Benches “several feet above high-water mark”.
Aroha subdivision . . .	Correlated with the last.
Oamaru subdivision . . .	12 ft. bench; accompanying beach with Recent fossils; Papakaio coastal plain at “15 to 25 feet above sea-level”.

Australia.—According to Andrews, the numerous coastal plains, emerged beaches, and rock-benches of New South Wales “suggest an apparent elevation of the shoreline to the extent of a few feet in very recent time”. The heights of the beaches vary from 1 to 15 feet above high-water mark. “Similar indications of the apparent elevation of the shoreline for a few feet are to be found along the whole eastern side of Australia.” The cause is attributed to “either an apparent rise of the land, or a retreat of the sea, to the extent of a few feet”.⁶ Süßmilch believes that the New South Wales

¹ R. T. Hill, *Amer. Journ. Science*, vol. xlviii, 1894, p. 203; *Bull.* 34, Museum Compar. Zoology, Cambridge, Mass., 1899, p. 99. Systematic discussion of the Atlantic Islands would include Bermuda, where R. S. Tarr (*Amer. Geol.* vol. xix, 1897, p. 293) found a recent terrace reaching 15 or more feet above sea.

² J. C. Branner, *Bull.* 44, Museum Compar. Zoology, Cambridge, Mass., 1904, p. 170 *et ante*.

³ T. G. Halle, *Bull. Geol. Inst. Univ. Upsala*, vol. ix, 1910, pp. 99, 117.

⁴ J. G. Andersson, *Bull. Geol. Inst. Univ. Upsala*, vol. viii, 1908, p. 182.

⁵ *Ibid.*, p. 57.

⁶ *Bulletin* No. 10, 1910, p. 29; No. 15, 1912, p. 50; No. 16, 1913, p. 77; No. 20, 1918, pp. 112–13 and p. 4.

coast belt shows recent "uplift" to the extent of "about 10 to 20 feet." An estuarine deposit at Largs, with surface at 15 feet above high-water mark, has yielded more than 30 species of shells of animals now living in the adjacent water. Similar discoveries on the coast of Queensland are reported by Jack and Etheridge, the emerged beaches and plains (locally with recent fossils) having heights of from 10 feet to 20 feet above "sea-level".¹

Cadell notes that the "raised beaches" of Western Australia are from 10 to 15 feet above sea-level. One of these is from 12 to 18 miles wide, and extends 25 miles inland. The beaches contain recent marine shells.²

Pacific Islands.—Many local, recent, negative shifts of sea-level have been recorded in the Pacific archipelagoes, where synthetic studies are needed in so many lines. A few of the records will suffice to raise the question whether the last shift of level in Samoa affected the whole Pacific basin. After his reconnaissance of the Paumotus, Agassiz wrote: "Nearly all the islands have been elevated a very moderate height and probably to about the same height." He gives the figure for Niau as "no greater than 20 feet" and for Rangiroa as 15 to 16 feet.³ At Funafuti of the Ellice group, David and Sweet found the recent negative shift of level to be "at least 6 feet and almost certainly 16 feet". In another passage they write: "There must have been a land-elevation or a sea-sinking of at least 9 to 10 feet."⁴ For the New Hebrides Mawson reports sea terraces, benches, and "raised" shore debris or coral in Santo, Efate, Epi, Malekula, Pakea, and Hui Islands, at heights of from 5 to 15 feet.⁵ In his Murray Island report Mayor writes: "In common with other islands of the Torres Straits region, whether volcanic, calcareous, or continental in character, the Murray Islands exhibit a recently emerged shore platform about 3 feet above the present high-tide level."⁶ On Bird Island of the Hawaiian Chain, Elschner found a "level terrace" a few feet above sea-level.⁷

As shown in Samoa and in the Bahamas, the observed heights of wave-cut benches on oceanic islands are likely to be 6 to 12 or more feet below the high-tide level ruling at the time of their cutting. "Raised" coral, too, is liable to give too small a value for a negative

¹ E. C. Andrews, *New South Wales Handbook*, Brit. Assoc. Adv. Science, 1914, pp. 525, 532; C. A. Süßmilch, *Introduction to the Geology of New South Wales*, Sydney, 1911, p. 154; R. L. Jack and R. Etheridge, *Geology and Paleontology of Queensland and New Guinea*, London, 1892, pp. 614 ff.

² H. M. Cadell, *Trans. Edinburgh Geol. Soc.*, vol. vii, 1897, p. 179.

³ A. Agassiz, *Memoirs*, Museum Compar. Zoology, Cambridge, Mass., vol. xxviii, 1903, p. 20.

⁴ T. W. E. David and G. Sweet, *The Atoll of Funafuti*, London, 1904, pp. 68, 84, 85.

⁵ D. Mawson, *Proc. Linn. Soc. New South Wales*, 1905, pt. iii, pp. 400 ff.

⁶ A. G. Mayor, *Papers from the Department of Marine Biology*, Carnegie Institution of Washington, vol. ix, 1918, p. 9.

⁷ C. Elschner, "The Leeward Islands of the Hawaiian Group": reprint from the *Sunday Advertiser*, Honolulu, 1915, p. 9.

shift. Until the delicate problem of the relation between the emerged forms and the corresponding sea surface has been worked out, both as to general criteria and as to the local application of those principles, the actual amount of delevelling registered in the Pacific Islands cannot be definitely stated.

California.—Japan, Alaska, and California are examples of the lands where local movement of the earth's crust, upwards or downwards, have taken place during the last few decades. Strand-marks of an ocean-level, which some thousands of years ago was higher than now, must there have altitudes different from contemporaneous markings in more stable regions. Identification of the 20 ft. strand is thereby made specially difficult. Yet Lawson's observations on the emerged zone at Carmelo Bay and Monterey, California, are suggestive for future research. He notes that the emerged terrace reaching 25 or 30 feet above sea-level is the "most defined and persistent elevated terrace in this coastal region", and concludes that the sea beat on the higher shore about as long as it has worked at the existing level.¹ Has the emerged terrace a height slightly greater than that of the Micmac and other terraces because California has been specially affected by diastrophism during the recent period?

AMOUNT OF THE EUSTATIC CHANGE.

Without further multiplying examples, those so far mentioned may be reviewed conveniently by the use of the following table.² Its full meaning cannot be understood without recalling certain principles. In each case where the author of a record uses "sea-level" or "water level" as his only datum, reference to the more significant and less equivocal high-tide level is not directly possible. The fifth column of the table therefore has many blanks. A wave-cut bench is likely to give too low a value for the emergence; a storm-beach, too high a value. Coral reefs give too low a value unless they can be shown to have grown up to the sea surface (mean or high-tide level) before the emergence began. Even in that instance their crests may have been somewhat abraded by storm waves just after the sea-level began to sink, for a dead coral reef is a friable structure. Special note should be taken of W. B. Wright's view that the British 25 ft. beach has been warped.³

In spite of all uncertainties, columns 4 and 5 of the table show that the negative eustatic shift of ocean level which suffices to explain the facts, is close to 20 feet. It may have been a little less; it was probably not as much as 25 feet.

¹ A. C. Lawson, Bull. Dep. Geol. Univ. California, vol. i, 1893, p. 53.

² In a verbal communication Dr. E. O. Hovey has stated that at many parts of the Greenland coast he observed beaches with crests 15 to 20 feet above mean sea-level.

³ See reference above, and also GEOL. MAG., Vol. viii, 1911, p. 99.

SUMMARY OF DATA REGARDING RECENT EMERGENCE.

Region.	Features.	Heights given (feet).	Datum stated.	Height above high tide (feet).	Remarks.
Gulf of St. Lawrence	Micmac terrace	14-23	High tide.	14-23	Specially developed.
Anticosti	Terrace	8-15	" "	8-15	Ditto.
Arisaig	Beach	25	Sea-level.	—	Roughly estimated.
Maine	Benches, benches . . .	15-25	Mean tide.	10-20	Specially developed.
Scotland	" " " " " "	20-25	Ordinance.	15-20	Ditto.
" (Wright)	" " " " " "	20 (?) - 35 +	Ordinance (?)	(?)	Ditto.
Ireland	" " " " " "	15-25	Ordinance.	15-20 (?)	Ditto.
" (Wright)	" " " " " "	0-25 (?)	Ordinance (?)	(?)	Uniform levels for long distance
New Jersey	Lower C. May terrace . .	20	Sea-level.	—	Ditto.
Maryland	Talbot terrace (in part) .	20	" "	—	Ditto.
Georgia	Satilla terrace (greater part)	15-25	" "	—	Ditto.
Florida	Lower Pensacola terrace .	20	" "	—	Ditto.
Bahamas	Keys	10-20	High tide (?).	—	Platforms wide; sea-cave at 18 feet.
	Benches, sea-caves . . .	3-20	Water-level.	—	Persistent.
Cuba	Reef	" Few feet."	Sea-level.	—	"
Jamaica	Reefs	10, 25	" "	—	Accord at distant points.
Brazil	Beaches, terraces . . .	20-25	" "	—	See table above.
Patagonia	Terraces	12-32	" "	—	
Graham Land	Terrace	23	" "	—	
New Zealand	Beaches, benches, coastal plain	10-25	" "	—	
East Australia	Ditto	10-20	" "	—	Uniform emergence.
West Australia	Ditto	10-15	" "	—	Uniform emergence.
Samoa	Benches, sea-caves . . .	8-15 +	High tide.	8-15 +	
Panmotus	Emerged limestone . . .	15-20	Sea-level.	—	
Funafuti	Reef coral	6-16 (?)	High tide.	6-16 (?)	
New Hebrides	Terraces, benches . . .	5-15	Sea-level.	—	
Murray Island	Benches	" Few feet "	High tide.	—	
Bird Island	Terrace (level)	" "	Sea-level.	—	
Carmelo Bay	Terrace	25-30	" "	—	Persistent.

CONTEMPORANEITY AND AGE OF THE STRANDS.

A second test of the eustatic change is naturally to be found in the expectation that the delevelling should be essentially synchronous in all parts of the ocean. In fact, observers dwell on the recency of the sea-level shifts registered in all of the illustrative cases. Fossils in the St. Lawrence, Scottish, Irish, Cuban, Patagonian, New Zealand, Australian, Funafuti, Murray Island, New Jersey, Maryland, Georgia, and Florida beaches, reefs, or coastal plains belong to species now living in the adjoining seas, or, exceptionally, to species now living in slightly warmer water. Great recency is also shown by the relatively small damage done by erosion to the strand marks, except in the case of those exposed to powerful surf.

The beaches of the higher latitudes are clearly post-Glacial, and also of date later than the post-Glacial uplifts following deglaciation. Brögger puts the completion of the last 4 metre to 8 metre emergence of the Christiania region at about the year 500 B.C. The development of the corresponding sea-cliffs, benches, and other strand marks is referred by him to the late Tapes (Neolithic) period, between 1400 B.C. and 2400 B.C. All Tapes time is taken to lie, between 1400 B.C. and 6700 B.C. During the late Tapes period the Christiania climate was about 2° C. warmer than now.¹ Traces of Neolithic man have been found in the 25 ft. beaches of the British Isles. The emergence of this beach in North Ireland seems to have been completed during Neolithic times.²

Perhaps fuller direct evidence for contemporaneity among the lowest beaches may be discovered through the use of fossils. It is significant that the fossils in the Patagonian beaches, like those of Norway, betoken water warmer than the adjacent sea.

Simultaneous emergence for the many separate regions is the more credible because of the similarity in the histories of their respective coasts before emergence. Repeatedly one encounters the description of terrace, bench, or beach near the 20 ft. level as the best developed, the most conspicuous, or the most persistent in a region characterized by "raised" strand marks; illustrations are noted in the foregoing table. Thus, the different regions must have had sea-level nearly constant for a considerable time, during which the strand marks were well incised. This widespread accordance itself must deepen suspicion that local diastrophism has not been responsible for the recent emergence of so many continental and island coasts.

In conclusion, the facts in hand appear to permit belief in the possible synchrony of the different strand markings and emergences here considered, but this second test of the general hypothesis also leads more surely to questions than to definite answers.

¹ W. C. Brögger, *Norges geol. Unders.*, No. 31, 1901, p. 713, and No. 41, 1905.

² W. B. Wright, *The Quaternary Ice Age*, London, 1914, pp. 384-5.

CAUSE OF THE EUSTATIC CHANGE.

Before the fact is established it would be idle to dwell overmuch on the explanation of a 20 ft. drop in ocean level. If lands in both hemispheres, in high and low latitudes, emerged simultaneously and to a nearly equal amount, the cause of the emergence cannot be found in a change in the earth's centre of gravity nor in a change in the speed of her rotation. There is no evidence compelling belief that the ocean basin has been so enlarged in recent time as to cause a negative 20 ft. shift of sea-level. More hopeful is the hypothesis of an increase in the volume of existing, non-floating glaciers, an increase taking place a few thousand years ago. If the Antarctic ice-cap were then thickened to the average amount of about 700 feet, an average sinking of sea-level to the extent of nearly 20 feet would be inevitable.

In favour of this suggestion would be evidence of a worldwide oscillation of climate, like that which seems to have affected the Christiania region in Recent time. If the whole earth was in the Tapes period a little warmer than now, less water may have then been taken from the ocean to build the ice-caps; sea-level was a little higher than at present. The oscillation as a whole would be but an incident in a series of climatic changes which began with the opening of the Glacial period.

CONCLUSION.

The facts on which the hypothesis of a general post-Glacial fall of sea-level is based belong to three groups.

Because of the recency of strand lines now about 20 feet above high-tide level, many of these lines should not have undergone important deformation, and if their emergence was due to the eustatic shift their accordance of level should be observable. Notwithstanding the difficulties attending a canvass of the world's coast-lines, a comparison of published observations seems to show that the speculation will bear the test of a fuller induction founded on special field work.

Naturally less troubled by the danger of subjectivity, the conclusions drawn from a study of the Micmac terrace or the lowest coastal-plain terrace to the southward of New York City are now perhaps more compelling. Practical uniformity for the terrace level along 300 miles of coast in the one case and along nearly 1,000 miles of coast in the other is certainly not expected on the uplift hypothesis, which likewise does not easily explain the strikingly accordant levels of Samoan benches at points only 75 miles apart.

A third group of facts, relating to the necessity of synchrony for the different strands abandoned by the sea, is meagre, but so far as it goes this evidence permits the main hypothesis, and its analysis suggests methods for future research.

The combination of all three groups of observations is much

stronger than any one of them. For that reason the eustatic hypothesis has seemed worthy of statement. The search for proof of eustatic shifts during more remote periods might be easier if even a small modern movement of the kind were proved, especially if its cause were also determined.

Note on the Age of the Milburn Group.

By A. D. N. BAIN, B.Sc.

ON the western side of Cross Fell lies a group of beds consisting of andesitic lavas and ashes, with intercalated beds of shale. The shales are tranquilly bedded, testifying to their having been deposited in quiet water. It has therefore been inferred that the igneous material is volcanic, and was poured out on a sea-floor. The beds were first described by Harkness,¹ later by Goodchild,² who gave the name "Milburn Group", and subsequently by Professors Nicholson and Marr.³

The exact age of these beds could only be approximately determined because of the scarcity of determinable fossils obtained from them. Goodchild recorded *Didymograptus munchisoni* (Boeck), and Professors Nicholson and Marr recorded *Diplograptus dentatus* (Brongn.).³ Professor Marr assigned them to either the Lower Llandeilo or the uppermost part of the Arenig, at the same time expressing a hope "that local observers will pay special attention to the fauna of these beds, as the exact determination of their age is a matter of considerable importance".⁴ Later Goodchild grouped them with the Ellergill Beds, a group of earthy slates underlying the Milburn Group and of about the same age, as being equivalent to the lower part of the Volcanic Series of Borrowdale.⁵

It is in Wythwaite Hole that these beds are best exposed and where they have been generally studied. A good exposure occurs in a similar "hole" to the east of Wythwaite Hole proper, where a band of shale is exposed, quite regularly bedded and lying between masses of andesitic lava. It is about 3 feet thick and dips to the south-east. The lavas above show regular parallel banding, dipping at a greater angle in the same direction.

From this band of shale the following graptolites have been collected by the author⁶:—

¹ Quart. Journ. Geol. Soc., vol. xxi, 1865, pp. 235, 340-1. Cf. Harkness, Quart. Journ. Geol. Soc., vol. xix, p. 127.

² Proc. Geol. Assoc., vol. ix, No. 7.

³ "The Cross Fell Inlier": Quart. Journ. Geol. Soc., vol. xlvii, 1891, p. 502.

⁴ GEOL. MAG., 1894, p. 128.

⁵ *The Geology of the Country between Appleby, Ullswater, and Hawes Water.* Mem. Geol. Surv. England and Wales, Sheet 30 (New Series), 102 S.W. (Old Series), pp. 34 and 39.

⁶ A *Phyllograptus*, the species of which has not yet been determined, has also been obtained.