12.740 Paleoceanography
Spring 2008

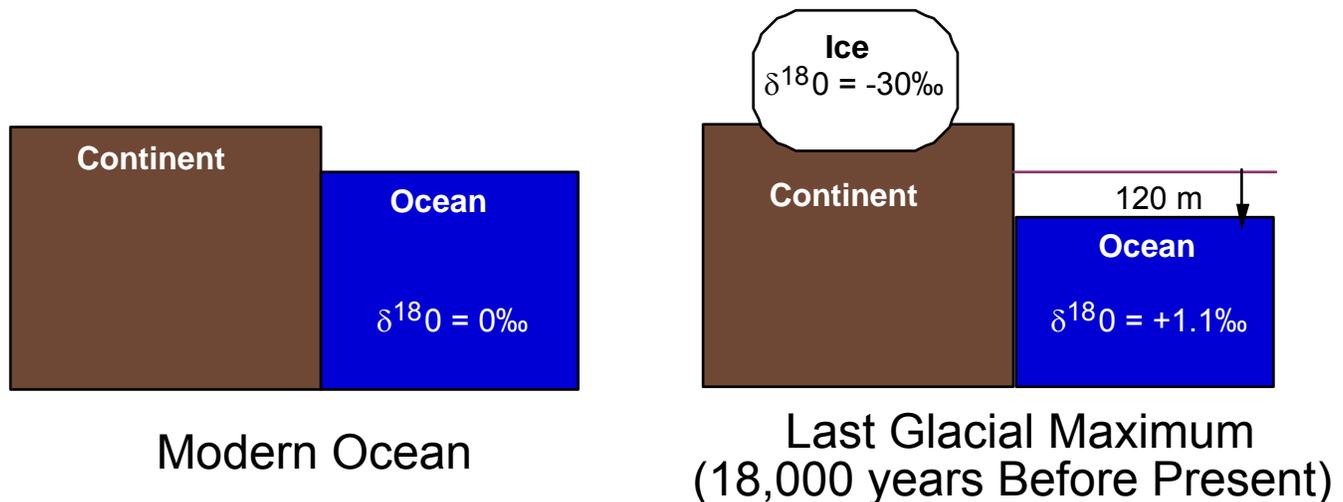PALEOCEANOGRAPHY   12.740   SPRING 2006   Lecture 5

SEA-LEVEL AND CLIMATE CHANGE:
CORAL REEFS ON STABLE AND EMERGING ISLANDS

CARBON-14, TH-230, AND PALEOMAGNETIC GEOCHRONOLOGY

GLOBAL VISCOELASTIC MODELS

I. Introduction: shell position vs. initial absolute depth; local vs. eustatic sea level; crustal rebound, continental tilting, and global isostatic adjustment; down-slope movement of shells.

II. Recall: $\Delta \delta^{18}O_{foram}$ is a function of <u>ice-volume</u>, isotopic composition of ice masses, <u>local</u> salinity, and temperature; probably more a reflection of ice volume rather than changes in ice isotopic composition, local salinity, or temperature; but how can we be more specific? To some extent, paleo-ecological temperature estimates help support this notion, but they do not appear to be sufficiently reliable to constrain sea-level change with confidence.

A. Relation between $\delta^{18}O$ and sea-level:

Ice
$\delta^{18}O = -30‰$

Continent

Ocean

$\delta^{18}O = 0‰$

Continent

120 m

Ocean

$\delta^{18}O = +1.1‰$

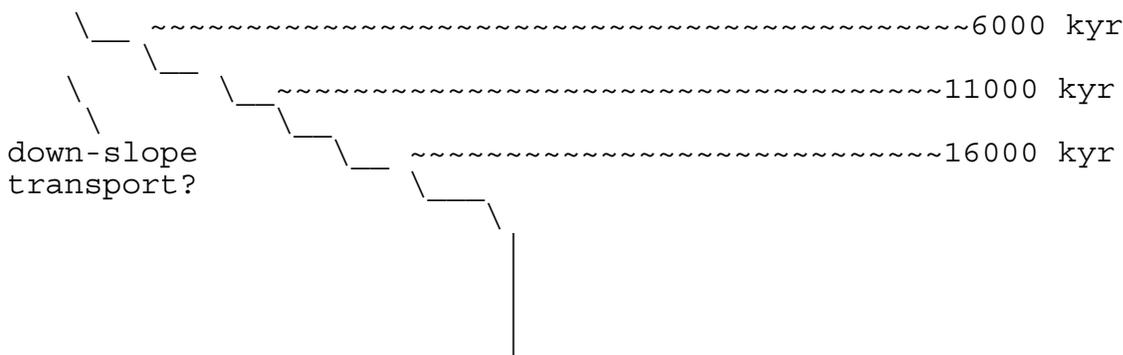Modern Ocean

Last Glacial Maximum
(18,000 years Before Present)

Isotope Mass Balance Equation:

$$M_o\delta_o + M_i\delta_i = M_t\delta_t$$

$\Delta M_i / A_o = \Delta(\text{Sea level})$

B. Glaciologists believe that the area of an ice sheet is <u>not</u> linearly related to its volume; instead, V $\alpha A^{1.5}$.

C. A <u>floating icecap</u> would not significantly change sea level, while it would change the mean isotopic composition of the ocean.

D. So it seems that the most reliable constraint on sea level would be provided by reliable paleo-shoreline evidence.

III. "Direct" approach: sample <u>shells</u> on the continental shelf that can be dated by ^{14}C (or peat bogs, trees, which say that sea level was below a certain level). In the late 1950's and 1960's, many marine geologists obtain grab samples from the continental shelf and attempted to construct sea-level curves.   (e.g. Curray in the late 50's and early 60's; Milliman and Emery in the late 60's)

```
   \__   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~6000 kyr
       \__
    \      \__  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~11000 kyr
     \        \__
  down-slope      \__   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~16000 kyr
  transport?          \
                       \__
                          \
                          |
                          |
                          |
```

A. These studies <u>generally</u> show lowered sea level towards 18K <u>BUT</u>

    1. Large scatter at individual age

    2. Was sea-level comparable to that of the present at 30 kyr? (this seems contrary to the the evidence provided by δ^{18}O). Possible explanations:

        a. Real variations in relative sea level?

            i. Tectonics
            ii. Polar shift (surface imbalance)

        b. Problems with samples? e.g. displacement of shells; erroneous dates (e.g. modern ^{14}C contamination; problems with carbon-14 dating tool?

        c. <u>Or</u> some very basic misunderstanding/mis-assumption?

 B. In-place indicators (e.g. coral reefs) seem more reliable than movable materials. Stable coastlines (especially stable oceanic islands) are of coarse preferable from this point of view.

IV. ^{14}C dating (Part I).

    A. ^{14}C: produced by cosmic rays -> neutron -> ^{14}N -> ^{14}C + proton; production rate is proportional to ^{14}N and cosmic ray flux; affected by solar wind and earth's magnetic field.

        1. ^{14}C $t_{1/2}$ = 5730 years. However, <u>by convention,</u> ^{14}C dates are reported relative to a reported 5570 year half-life! (so as not to divide the literature between dates that are not consistent with the currently-accepted half life, and those that are).

    B. <u>If</u> (^{14}C/^{12}C) in the atmosphere is constant, <u>if</u> the object to be dated obtained its carbon directly from the atmosphere, and <u>if</u> the object to be dated is closed, <u>then</u>

$$\frac{dN}{dt} = -\lambda N$$

$$N/N_0 = e^{-\lambda t}$$

    C. The role of contamination of old artifacts by modern carbon:

1	2	3	4	5	6	(halflives)
1/2	1/4	1/8	1/16	1/32	1/64	(^{14}C left)
5700	11400	17100	22800	28500	34200	(yrs)

        1. Contamination could occur in the laboratory (blanks); by exchange with groundwater ^{14}C; by

exchange with modern seawater; by bacterial growth on raised deep sea cores.

    2. This problem leads to a "practical" limit of 25,000 years for material that was not collected and processed by careful workers. If you don't know who did the work and how careful they are likely to be, distrust all ages older than 25,000 years, and allow a few thousand years potential error at all ages older than about 18,000 years.

    3. Therefore: The 30K high stand reconsidered: BS!

    4. In the use of continental shelf indicators, ^{14}C to reconstruct sea levels. the problems of the wide range of values at glacial maximum and apparent high stand 30-35 kyrBP can be attributed to modern ^{14}C contamination of much older material. Nonetheless, we would still like to know something about older sea level changes.

D. There is a lot more to the ^{14}C story (to be covered later).

v. $U/^{230}Th$ dating of corals.

  A. ^{238}U ----------> ^{234}U --------> ^{230}Th ------->

$t_{1/2}$: 4.5×10^{9}yrs   248,000 yrs   75,200 yrs

        ^{235}U -------> ^{231}Pa ----->
          0.7×10^{9}yrs   32,800 yrs

B. U (VI) is relatively soluble in seawater (carbonato complexes: e.g. $UO_2^{2+}CO_3^{2-}$; $UO_2^{2+}(CO_3^{2-})_2$), occurs at about 13 nmol/kg (2.3 dpm/kg), and appears to be conservative. ^{230}Th is particle-reactive; i.e. it tends to attach to surfaces rapidly, and so it is removed from seawater on a time scale of ~30 years. Hence it occurs at fairly low concentrations in seawater (<0.1 dpm/100kg at the surface; ~1 dpm/100kg in deep waters).

C. Corals incorporate uranium (~2ppm) but very little ^{230}Th.

D. Assumptions for ^{230}Th dating

    1. Closed system : except for radiodecay and production, no uranium or thorium enters or leaves the object.

    2. $^{230}Th_{initial} = O$.

    3. Initial $^{234}U/^{238}U$ activity ratio = 1.15 [this is the ratio observed in seawater; disequilibrium results from alpha-recoil damage in continental rocks and subsequently higher weathering rate of ^{234}U; we assume that this ratio has been stable in the past – but is this justified?]

    4. Then:

$$\frac{\partial^{234}U}{\partial t} = \lambda_{^{238}U}\,^{238}U - \lambda_{^{234}U}\,^{234}U$$

$$\frac{\partial^{230}Th}{\partial t} = \lambda_{^{234}U}\,^{234}U - \lambda_{^{230}Th}\,^{230}Th$$

where the radionuclides are expressed in concentration units (atoms per g); to convert to activity units (dpm/g), must convert each term:
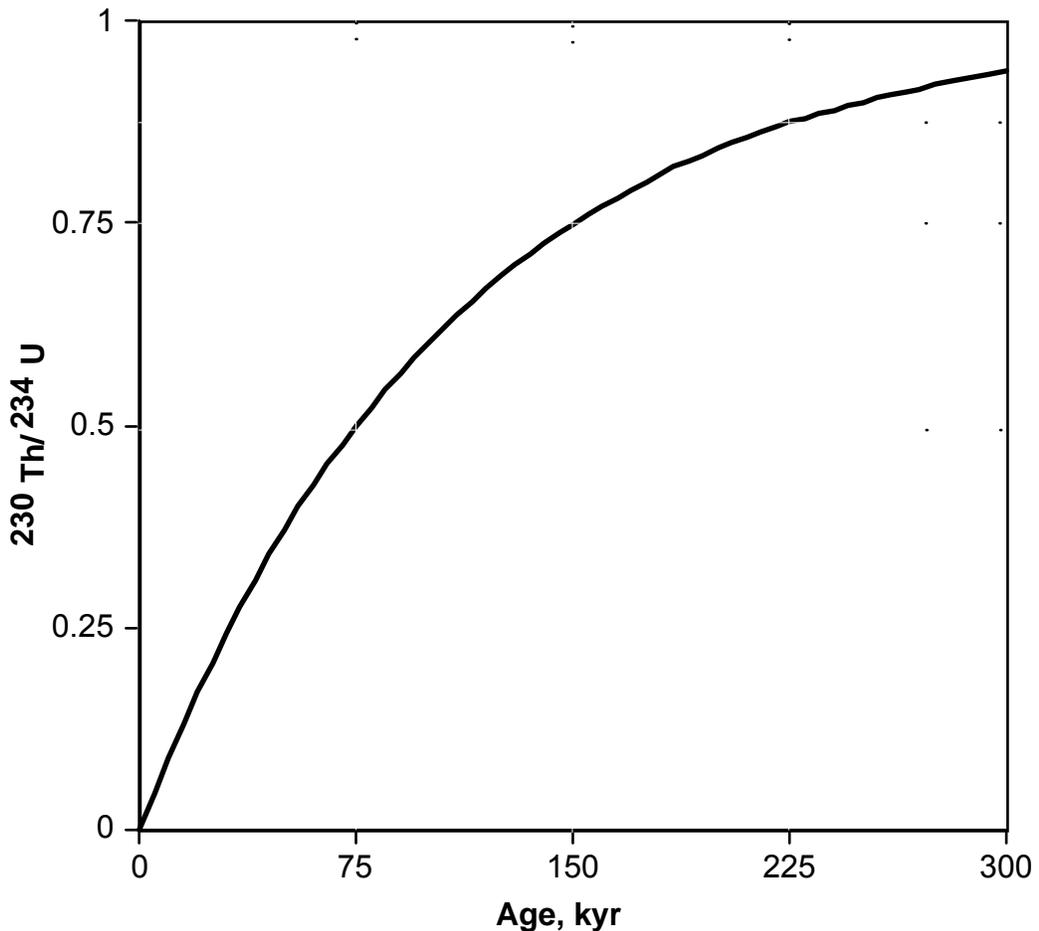
$$^{230}Th = \frac{A_{^{230}Th}}{\lambda_{^{230}Th}} \text{ , etc.}$$

hence:

$$\frac{\partial A_{234_U}}{\partial t} = \lambda_{234_U} A_{238_U} - \lambda_{234_U} A_{234_U}$$

$$\frac{\partial A_{230_{Th}}}{\partial t} = \lambda_{230_{Th}} A_{234_U} - \lambda_{230_{Th}} A_{230_{Th}}$$

Solutions (assume ^{238}U activity is constant (because half-life is 4.5E+9 yr), solve ^{234}U equation first, then plug into ^{230}Th equation) (left as an exercise for the reader!). If we start out with a system where $A_{234_U}/A_{238_U} = 1$, the solution is simple:

this solution can be derived graphically by noting that every ^{230}Th half-life, the $^{230}Th/^{234}U$ ratio approaches 50% closer to 1.00:

5. Because $^{234}U/^{238}U$ is initially above the radioactive equilibrium level, it is necessary to correct for the decay of the initial excess. The complete equations for calculation of ^{230}Th ages are:

$$\frac{A_{230_{Th}}}{A_{238_{U}}} = 1 - e^{-\lambda_{230_{Th}}t} + \left(\frac{\delta^{234}U(t)}{1000}\right)\left(\frac{\lambda_{230_{Th}}}{\lambda_{230_{Th}} - \lambda_{234_{U}}}\right)\left(1 - e^{\left(\lambda_{234_{U}} - \lambda_{230_{Th}}\right)t}\right)$$
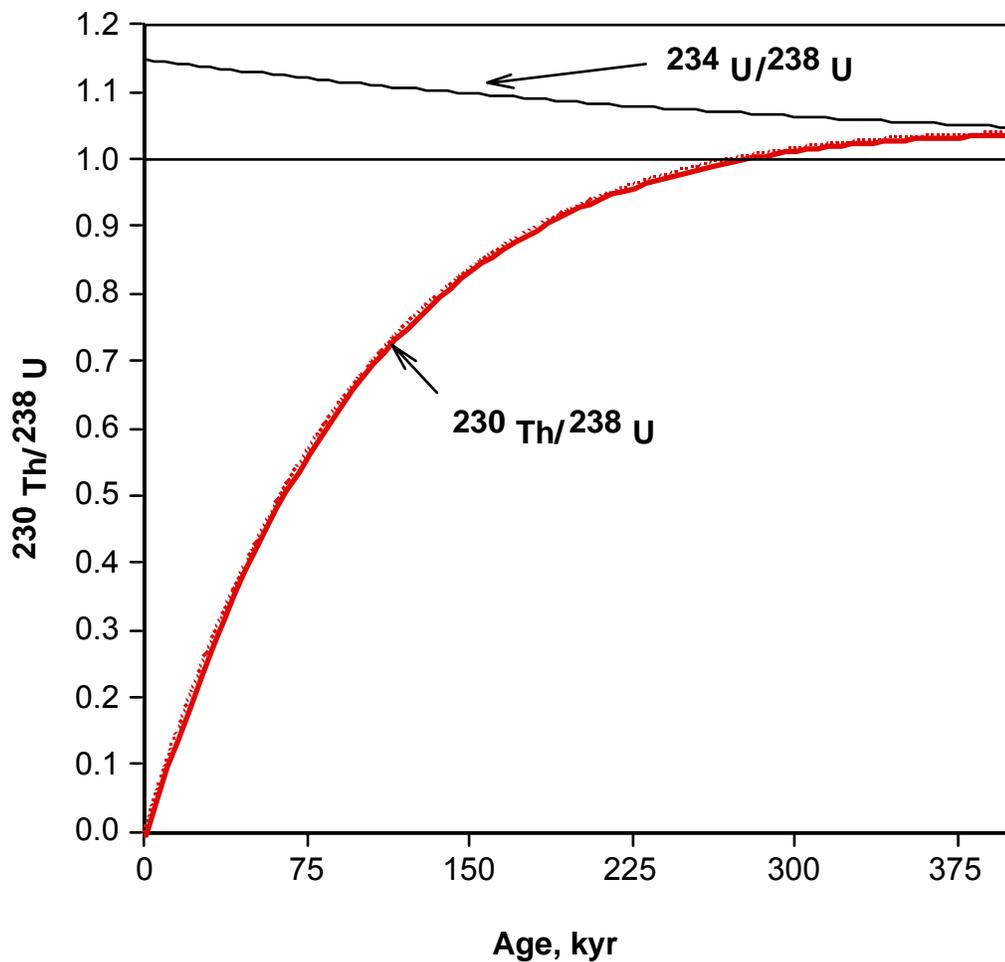
and

$$\delta^{234}U(t) = \delta^{234}U(t=0)e^{-\lambda_{234_{U}}t}$$

where

$$\delta^{234}U = \left(\frac{\left(^{234}U/_{238}U\right)}{\left(^{234}U/_{238}U\right)_{eq}} - 1\right) * 1000$$

and **t** is the age of the sample (kyr before present)

[Note: this treatment differs slightly from that of Edwards et al. in convention on sign and symbol.]

6. Counting statistics: square root of n

7. Although molluscs also incorporate uranium, they cannot be dated because they behave as an open system for uranium.

8. Foraminifera contain very low levels of U (~0.015ppm), so they are not good candidates for U-Th dating. If one could clean excess Th completely from the surfaces (a very difficult task) and could get enough material, it might not be impossible. But a study of $^{234}U/^{238}U$ in foraminifera [Henderson and O'Nions, 1995] suggests that they have excess ^{234}U – complicating any efforts to calculate a ^{230}Th age.

9. Recently, multi-collector plasma mass spectrometry has been shown to be more efficient than TIMS for U-system dating of coral.

VI. Applications of the ^{230}Th dating of corals: alpha-counting era (checked by recent mass-spec measurements)

A. Veeh (1966) found <u>120</u> Kyr bp high stand on Bermuda: +5 ±1 m relative to present.

B. 125±4 kyr high stand found to be present on many oceanic islands.

C. Terrace formation on tectonically uplifted islands

Model for reef terrace formation. In this hypothetical example, reef tract no. 1 forms around Barbados during interglacial high sea stand no. 1. Emergence of reef tract no.1 takes place during an interval of lowered sea level which has a duration of 25,000 years. Interglacial high sea stand no.2 attains the same worldwide level as high sea stand no.1, but, relative to Barbados, high sea stand no.2 appears to be 25 feet lower, due to gradual tectonic uplift of the island at about 1 foot per 1,000 years. Therefore, the record of the eustatic oscillation is the addition of a 25-foot reef terrace to the coral cap.
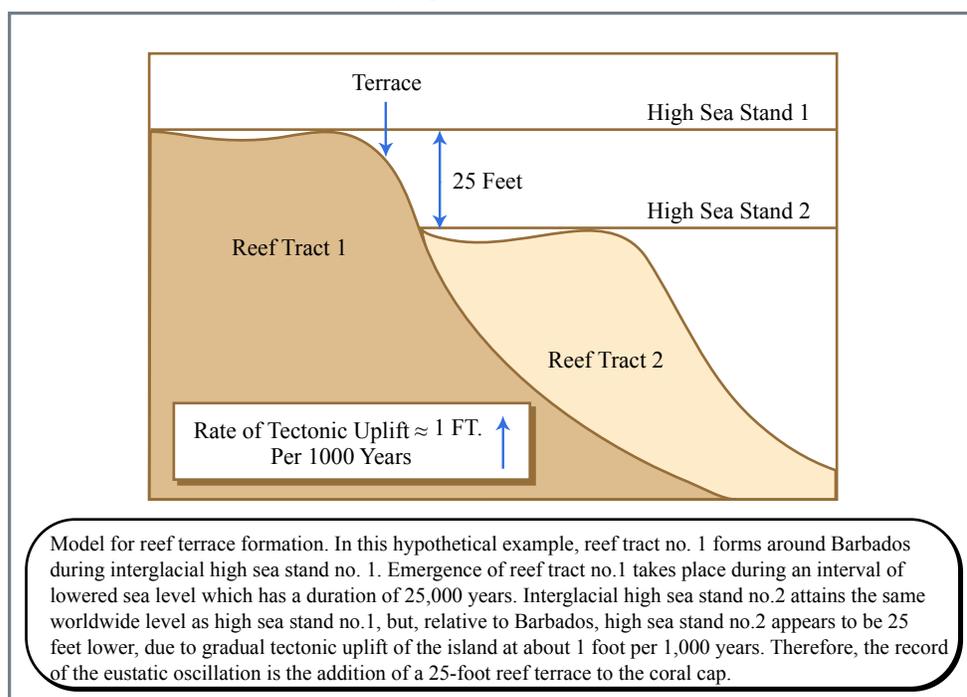
Figure by MIT OpenCourseWare. Adapted from source: Mesolella et al. (1969).

D. Broecker et al. (1968) dated 3 Barbados terrace complexes.

1. The highest (at 40 m elevation) gave ages:

128 ± 6
120 ± 6
124 ± 6
124 ± 6
<u>120 ± 6</u>
Avg. 123, $\sigma = 3$

a. If we assume that this terrace was 5m above present sea level when it was formed (in accordance with Veeh and other stable island data), it implies that Barbados has been rising by $^1/_3$ m kyr^{-1}

2. Two other terraces were dated as well:

```
                    age of formation
   -13m                              -10m    (constant-uplift elevations)
   83 + 4                        103 + 2
   82 + 2                        103 + 4
   81 + 4
   82 + 4
```

And one more problematical one at 111 + 9.

    a. These high stands of sea level occur a few thousand years after Milankovitch <u>precession</u> peaks (highs in Northern Hemisphere summer insolation.

3. Broecker et al. proposed to correlate these terraces with the $\delta^{18}O$ record; they argued that the Emiliani/Rosholt time scale was in error. [A few years later, Shackleton and Opdyke placed this $\delta^{18}O$ record in a paleomagnetic time scale and sealed this age assignment].

4. More recently, Edwards, Chen, and Wasserburg (1986) have redated some of the Barbados corals using mass spectrometry. They obtained ages of 122.1 + 1.1, 122.7 + 1.3, and 124.5 + 1.3 kyr for the major terrace; these ages agree quite well with Broecker et al.'s alpha counting dates.

5. Older high stands are indicated as well (e.g. ~200 kyr bp)

E. Broecker and Van Donk (1968): Proposed to use the 124 kyr date of what Shackleton dubbed "stage 5e" in core V12-122 to extrapolate the age of the most penultimate "termination" as 127,000 kyr ("termination II").

F. New Guinea terraces (Chappell, 1974). A more rapidly rising coastline.

```
Age of formation elevations      -13          -15          (assumed +5m)
(const. uplift model)
                              84 + 4        107 + 9        142 + 8
                              86 + 4        107 + 6        116 + 7
                              ------------  -----------    119 + 7
                                 85            107         140 + 10
                                                           133 + 10
                                                           ----------
                                                              130
```

1. 2.5 m/kyr elevation rate, so there are many terraces above sea level, including some where sea level is 40m or so below present -day sea level at around 30-40 kyr. (-28m for 60 kyr; -38m for 42 kyr; -41 for 28 kyr). Many older terraces as well.

2. (More or less) confirms the two lower Barbados stands, although there is the troublesome older ages "140" kyr (and there do appear to be two separate terraces within this group). Nonetheless, agreement is reasonable for sea-level of the "82" and "105" terraces, assuming constant uplift on both islands.

3. Edwards, Chen, and Wasserburg (1986) have dated two New Hebrides coral samples (a "5e doublet" reef complex) that had been dated at 141+16 kyr by alpha counting. The new mass spec. ages were 129.9+1.1 and 125.5+1.3 kyr. While these are a bit older than the Barbados dates, they are not so deviant as the 141 kyr date made them seem to be. More recent measurements indicate that many samples give ages near 134 kyr (Stein et al., 1993). Larry Edwards (personal communication) argues that the New Guinea terraces are particularly susceptible to diagenetic alteration because of the high rainfall, and that he prefers to disbelieve the New Guinea dates and accept the Barbados dates.

G. Oahu: 122 + 7 high stand. (Update: Szabo et al. results).

H. <u>Haiti</u> (Dodge et al. 1984)

```
Age of formation elevations
(const. uplift model)

            -13m            -10m         (assumed +5 m)

        80 + 3          108 + 5          130 + 6
        82 + 3                           130 + 6
        77 + 3                           132 + 5
        83 + 3                           130 + 6
        ---------                        126 + 6
        81 + 3                           ------------
                                         130 + 2
```

1. Uplift-corrected sea level of 80, 105 stands is the same as that found on Barbados. Hence it appears that we must take the sea level change seriously (unless we are willing to consider the possibility of globally synchronous uplift!).

2. While the older high stand seems a bit older than the Barbados terraces, it has not yet been confirmed by mass spec. measurements. Probably not worth worrying about just yet.

**VII.** Sea level over the past 20,000 years: submerged Barbados drill samples.

A. Fairbanks (1989) drilled three cores into the submerged terraces off Barbados. The corals were dated by ^{14}C. He obtained a good sea level curve for this period; the maximum sea level lowering he found was 120 ± 5 m (ignoring one older, deeper sample of a species which he thought might survive significantly below sea level. Two major rapid rises occur between the core breaks; could this be real or indicate an artifact?

$$\Delta\delta^{18}O$$
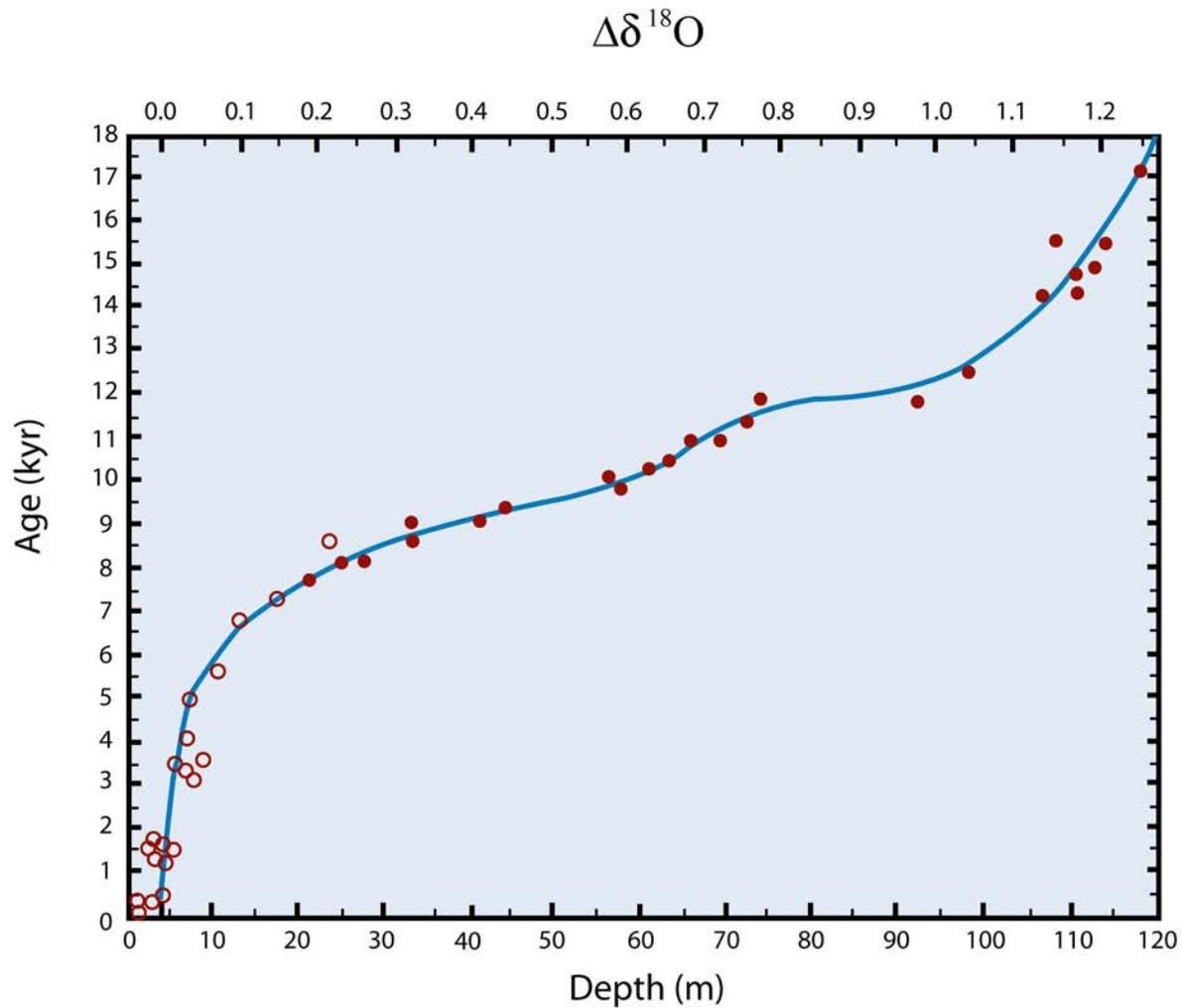
Barbados sea level curve based on radiocarbon-dated *A. palmata* (filled circles) compared with *A. palmata* age-depth data[1] (open circles) for four other Caribbean island locations. All radiocarbon ages in this figure are corrected for local seawater $\Delta^{14}C$ by subtracting 400 yr from the measured radiocarbon ages[8] but they are not corrected for secular changes in atmospheric ^{14}C levels[15]. The Barbados data are corrected for the estimated mean uplift of 34 cm kyr^{-1}. The top axis of the Barbados sea level curve (solid line) is scaled to the estimated $\delta^{18}O$ change of mean ocean water using the calibration in ref. 5.

Figure by MIT OpenCourseWare. Adapted from source: Fairbanks et al. (1989).

B. Edwards et al. (1993) New Guinea drill core

"Fairwards" Sea Level Curve
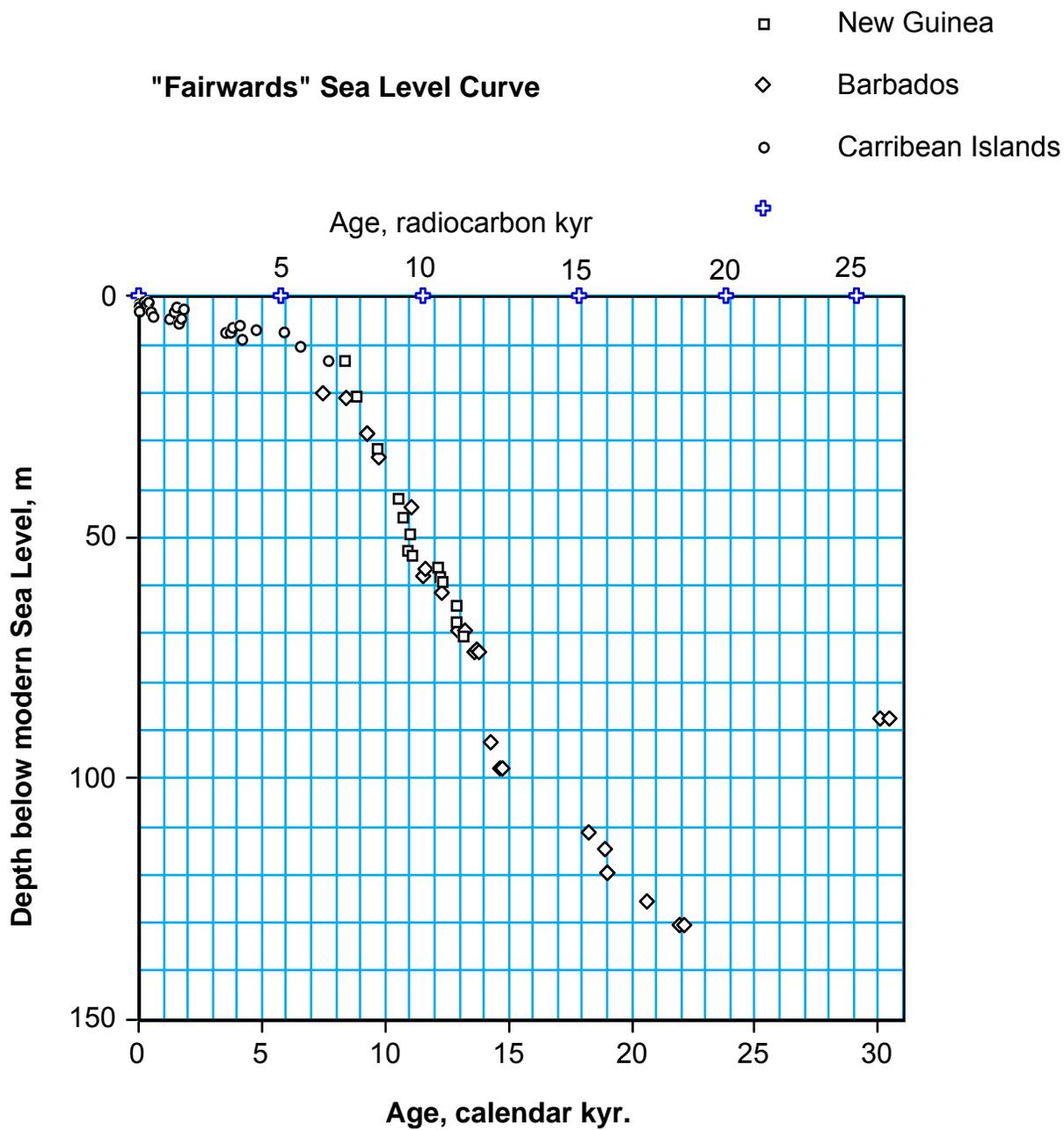
C. Bard Tahiti sea level curve

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Source: Bard et al., 1996.

VIII. Reconciliation of sea level and $\delta^{18}O$: temperature <u>and</u> ice volume

A. If we assume that the discrepancy between $\delta^{18}O$ and the various sealevel indicators is due to the effect of temperature on ice volume, then we can reconstruct paleo-deep-temperature histories from benthic $\delta^{18}O$, which implies that the deep ocean was colder by anywhere from 1.5°C (Pacific) to 3.0°C (Atlantic).

 1. Most of this cooling appears to have taken place going from oxygen isotope stages 5e to 5d, and the greatest warming going from stage 2 and 1. The rest of the time the temperature variations have been more subtle; i.e., the deep ocean must <u>generally</u> have been about 2°C colder than it is at present. This is known because the uplifed coral terraces suggest that sea level change between stages (5a,5c) and 5e was only 10-20m, but benthic $\delta^{18}O$ would have a sea-level change equivalent to more than 40m. So even though the sea level was not very much different during stages 5a,b and 5e, the deep sea temperature was about 2°colder.

 2. Recently Chappell et al. (1996) have shown that the original New Guinea sea level estimates were flawed by an error (the elevations of one transect were confused with that of another), and have remeasured the ^{230}Th/U ages and made revisions to the timing of the sea level highs. Note that the "sea level from $\delta^{18}O$" curve is based on taking the "smoothed" difference between the planktonic RC17-177 record (Shackleton) and the benthic V19-30 record, and determining the difference; i.e., this O18 based sea level record is based on the assumption that there is no temperature (or local salinity) temporal signal in RC17-177.

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Please see:
Figure 1 in Chappell, J., A. Omura, et al. "Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records." Earth Planet Sci Lett 141 (1996): 227-236.

B. The "poetic" Norwegian Sea δ^{18}O stack

> If there was some site where we <u>knew</u> that temperature did not change, then this site could be used to assess <u>relative</u> temperature changes elsewhere. Unfortunately, it is difficult to <u>know</u> that temperature did not change. One constraint occurs in places where the temperature is near the freezing point of seawater. It can't get any colder, although it might have become warmer. It has been argued on various grounds (Labeyrie et al., 1987) that except for the most severe glaciations, NADW formation occurs in the Norwegian/Greenland Sea. In that case, the water must have been near the freezing point (as it is today), so that the temperature must have remained constant. A somewhat poetic "stack" of several N/G sea records was reconstructed (and incorporated with the oxygen isotope and sea level constraint for the last glacial maximum) to obtain a continuous estimate for the mean oxygen isotope composition of seawater. (the poetry involved how the cores were stacked, as the usual 5a-5b-5c-5d-5e sequence was not clearly evident in most of the records).

C. Sea level and chronology for the past 120,000 years: the state of the art as of 2006. Cutler et al. (2003) eliminated all samples with inconsistent δ^{234}U, U/Th, U/Pa ages.

Image removed due to copyright considerations.
Source: Cutler et al. (2003).

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Please see:
Figure 7 in Cutler K. B., R. L. Edwards, F. W. Taylor, H. Cheng, J. Adkins, C. D. Gallup, P. M. Cutler, G. S. Burr,
and A. L. Bloom. "Rapid sea-level fall and deep-ocean temperature change since the last interglacial period."
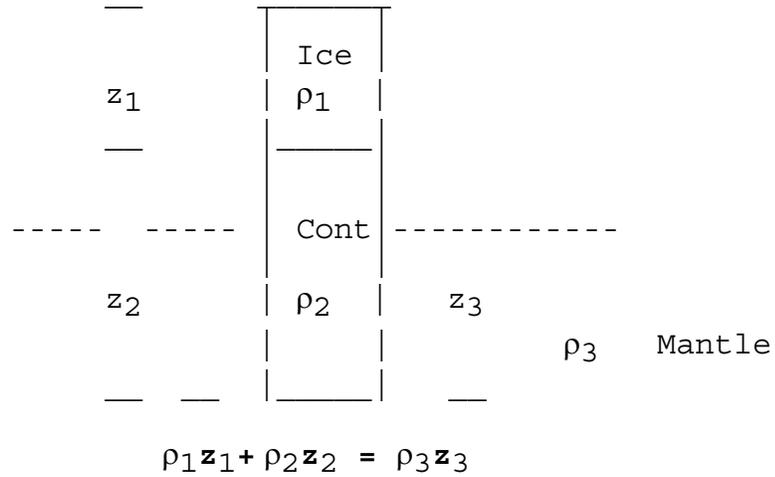Earth Planet Sci Lett 206 (2003): 253-271.

     D. One of the remaining problems in interpreting foraminiferal $\delta^{18}O$ records is the role of local salinity (and isotopic) variations in contributing to individual isotopic records. (Not to mention the role of temperature- or depth- related foraminifera and flux-rate effects...)

IX. Sea level, isostasy, and the viscoelastic earth.

     A. Eustatic vs. Relative Sea level changes

          1. Relative sea level is what you measure: the position where the sea meets the land (relative to some benchmark). Relative sea level includes a component of the vertical movements of the land.

          2. Eustatic sea level is the level of the ocean corrected for the vertical movements of the land – and generally assumed to be the same everywhere on earth (except for some corrections – see later).

B. Isostasy: As major ice sheets build up on the earth's surface, the solid earth below sinks to maintain isostatic equilibrium: in effect, the (continental block + ice sheet) is floating in the mantle:

```
 ___                _____
                   |           |
                   |   Ice     |
                   |           |
   z1              |   ρ1      |
                   |           |
 ___               |  _____  |
                   |           |
  - - - -   - - - -|   Cont    |- - - - - - - - -
                   |           |
   z2              |   ρ2      |    z3
                   |           |
                   |           |        ρ3    Mantle
                   |           |
 __   __   |_____|    __
```

$$\rho_1 z_1 + \rho_2 z_2 = \rho_3 z_3$$

    1. One complication: continental plates can flex or tilt

C. A second complication is that the earth's mantle acts like a very viscous fluid. So image putting your ice cube on a boat floating in molasses: it takes a while (many thousands of years) for the system to reach its equilibrium level.

Image removed due to copyright considerations.
Source: Fairbridge and Hillaire-Marcel, 1977.

Image removed due to copyright considerations.
Source: R.F. Flint, Glacial and Quaternary Geology (QE696 .P6245), figure 13.13.

Image removed due to copyright considerations.
Source: Vanicek and Nagy (1980) Trans. Am Geophys. Union 61:146, figure 3.

D. A third complication: the earth is somewhat like a toothpaste tube: if you squeeze it in one place, it tends to pop up somewhere else!

E. These considerations lead to the use of visco-elastic models of the earth's interior. Basically, removing water from the ocean basins causes them to start moving up a little bit (because of the decreased overburden of water). Putting the ice sheets on Europe and North America of course causes the underlying continent to sink significantly (e.g. ice sheets were about 5 km maximum thickness; density of ice ~1 and mantle ~3, so continent must sink about 5/3 km) and to flex near the margins. The displaced mantle then flows elsewhere, causing other places to move up. This all takes place on a finite time scale by laws of fluid dynamics, and depends heavily on the viscosity (structure) of the mantle (in fact, the only way we know the viscosity of the mantle is from studies of the rates of crustal rebound). All of this is reversed as the ice melts. Most of the isostatic adjustment occurs within a few thousand years, but there are parts of Hudson's bay that are still rebounding at rate of 1 m/century.

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Please see:
Clark, J.A., W.E. Farrell, and W.R. Peltier. "Global changes in postglacial sea level: a numerical calculation." Quaternary Res 9 (1978): 265-287.

1. An interesting sidelight of this process is that estimates for how fast modern sea level is rising must take into account this crustal rebound and the associated mantle flows.

2. The ongoing rebound can be estimated from precise surveys; ancient rebound can be estimated by (^{14}C) dating shells of organisms that grow in the shallow seashore.

ADD: RECENT PELTIER PAPERS

READING LIST:

Bard, E., B. Hamelin, and R.G. Fairbanks, U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years, *Nature*, *346*, 456-458, 1990.

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Cutler K. B., Edwards R. L., Taylor F. W., Cheng H., Adkins J., Gallup C. D., Cutler P. M., Burr G. S., and Bloom A. L. (2003) Rapid sea-level fall and deep-ocean temperature change since the last interglacial period. Earth Planet. Sci. Lett. 206, 253-271.

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Edwards, R.L., Chen, J.H. and Wasserburg, G.J. (1987) Precise timing of the last interglacial period from mass spectrometric determination of Thorium-230 in corals. Science, 236:1547-1553.

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