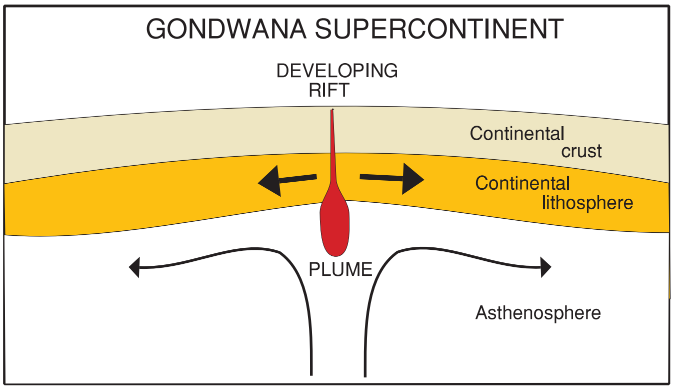
PLATE TECTONICS: Lecture 3

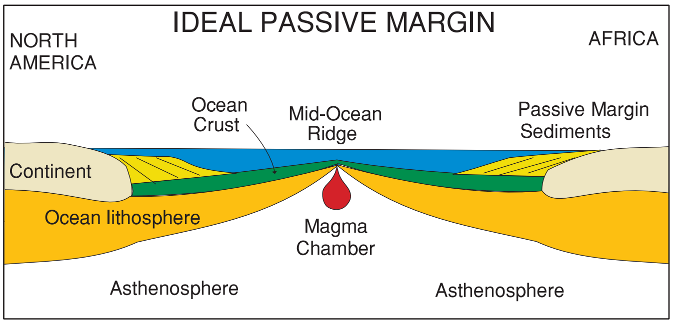
THE WILSON CYCLE: RIFTING AND THE DEVELOPMENT OF OCEAN BASINS

As the concept of sea floor spreading gained acceptance in the late 60's, the consequences for geology gradually began to dawn. One of the first to recognise how plate tectonics could be applied to the geological record was J. Tuzo Wilson. If continents rift apart to form ocean basins, other oceans must close. This may be repeated throughout Earth history. Example: the IAPETUS ocean between England & Scotland in the Lower Palaeozoic, closed in the Caledonian; later opening of the Atlantic, almost in the same place. The cycle is known as the Wilson Cycle:

(1) Rifting of continents by mantle diapirism
(2) Continental drift, seafloor spreading & formation of ocean basins
(3) Progressive closure of ocean basins by subduction of ocean lithosphere
(4) Continental collision and final closure of ocean basin

The two diagrams below (Figs 1 & 2) illustrate some simple (if old) concepts of continental rifting (e.g. the Gondwana continent) at the start of the Wilson Cycle. Uprising plume causes doming of crust with magma chamber developing underneath. As extension continues, an ocean basin forms, and thick sedimentary sequences develop at continental margins as rivers dump sediments in deep water. However in reality may be a bit more complex . . .





CONTINENTAL RIFTING: rrr and RRR triple junctions

Four main stages can be recognised in the tectonic development of a typical rifted passive margin:

(1) The **RIFT VALLEY** stage involves early graben formation prior to continental splitting. This stage may be associated with domal uplift caused by uprise of hot upper mantle material - but this uplift is not ubiquitous and may be connected with underlying mantle hotspots. Example: African Rift Valley.
(2) The **YOUTHFUL** stage, lasting about 50 my after the onsett of seafloor spreading, while the thermal effects are still dominant. This stage is characterised by rapid regional subsidence of the outer shelf and slope, but some graben formation may persist. Example: Red Sea.
(3) The **MATURE** stage during which more subdued regional subsidence may continue. Example: most of the present Atlantic continental margins.
(4) The **FRACTURE** stage when subduction starts and terminates the history of the continental margin.

There are many examples of Stage 1. East African Rift Valley is the classic example. But also the Midland Valley of Scotland, the Rhine Graben, the Oslo Graben. These rifts have never got beyond stage 1. Commonly the volcanism associated with these rifts is highly alkaline and undersaturated in silica.

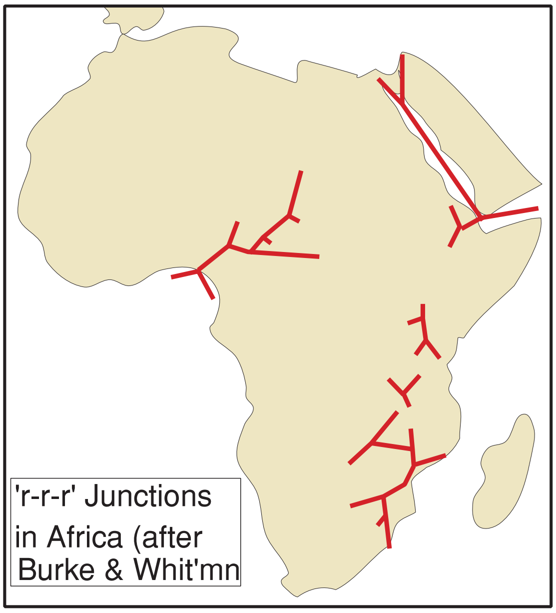


Fig. 3. The continent of Africa is thought to have been split by a series of rift valleys in various states of development. Those in East Africa are still in thick crust.
Those in West Africa are associated with thick oil-bearing sediments. In the Red Sea area the rifting has gone so far as to form a narrow ocean. In the south-east Madagascar has been completely separated from Africa by rifting.

What initiates rifting? There has been considerable discussion on this over the years. Some have ascribed rifting to up-doming of the crust over a hot-spot; certainly parts of the E African rift system are very elevated, compared with other sectors, suggesting that the doming reflects an underlying hot low-density mantle plume. In other cases, geophysical models suggest the asthenospheric mantle is rising to high levels beneath the rift. However it is also apparent that rifting can take place without extensive uplift; in such cases it may be the convective processes in the underlying asthenosphere which are causing the extension. To rift a continent apart it needs the rifts associated with various possible thermal domes to link together. Morgan (1981, 1983) has suggested that as continents drift slowly over hotspots the hotspots weaken the plate - like a blowtorch impinging on the base - and these weakened zones become the sites of continental rifting.

Burke & Whiteman (1973), following the doming hypothesis, suggested that in these domal regions, three rifts would develop, forming an ’rrr’ triple junction. Although it is possible that all three rifts might develop into an ocean (’RRR’), it is more likely that two of these rifts would develop into an ocean (’RRr’), leaving the third rift as a ’failed arm’. They demonstrated / speculated that on many continents it was possible to recognise these RRr junctions. The ’failed arm’ rift would eventually subside as the thermal anomaly decayed and become the site of a major depositional basin, or a major river channel and delta. The Benue Trough in Nigeria is regarded as an example of such a failed arm following the opening of the S. Atlantic. When oceans eventually close it is possible to recognise these failed arms as depositional basins oriented perpendicular to the collision mountain belt (most basins tend to be aligned parallel to mountain belts). These are termed ’aulacogens’.

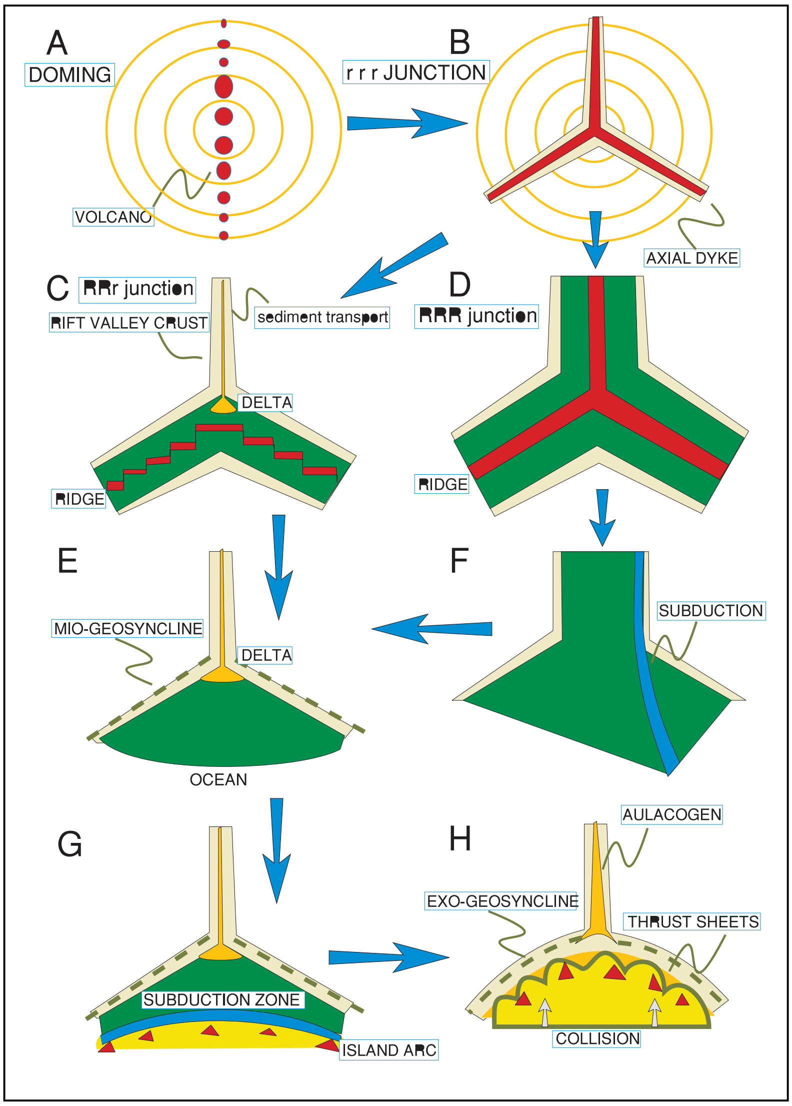


Fig. 4. **A**. Doming by a mantle plume associated with volcanicity. **B**. Rifting (rrr junction) is initiated. **C**. Further development results in two of the rifts developing into an ocean, the third is a failed arm (aulacogen). **D**. Less likely is that all three arms develop into oceans. **E**. A common situation is that the failed arm develops into a major river system feeding the continental margin. **F**. Expansion of oceans on a finite earth is not possible: there must be plate subduction, somewhere, sometime. **G**. Closure of oceans results in island arc development above the subduction zone. **H**. Continued closure results in collision with major fold and thrust belts. But often the failed arm (aulocogen) is still preserved.

Development of Continental Rifts

Early ideas on the development of rifts are conceptualised in the diagram shown in Fig. 5. This is based on the African rift system, where there is significant rift magmatism. There is notable extension, shown by the widening of the diagram block by at least 50 km. At the same time there is uplift or ascent of the more ductile mantle, especially the asthenosphere. The crust, and particularly the upper crust, is assumed to act in a brittle fashion.

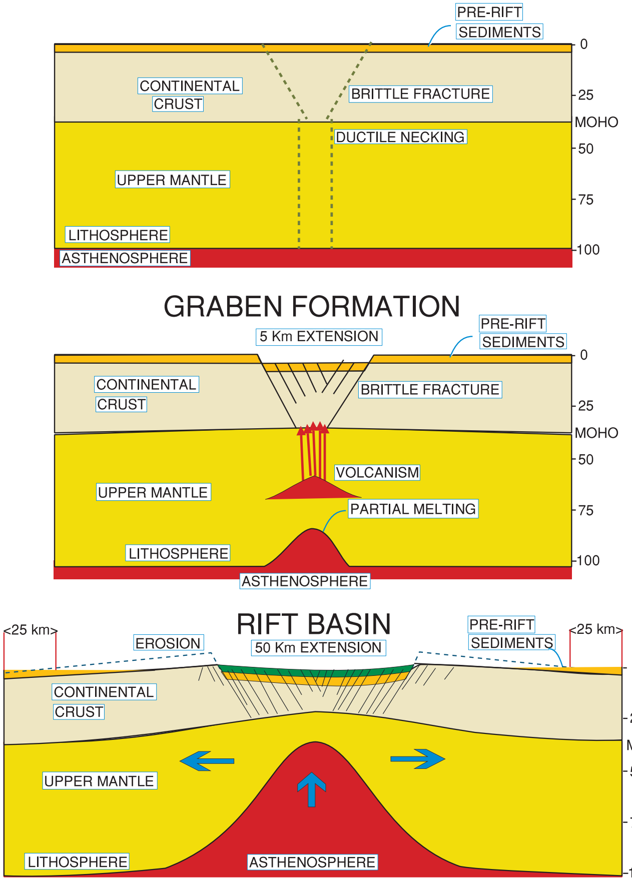
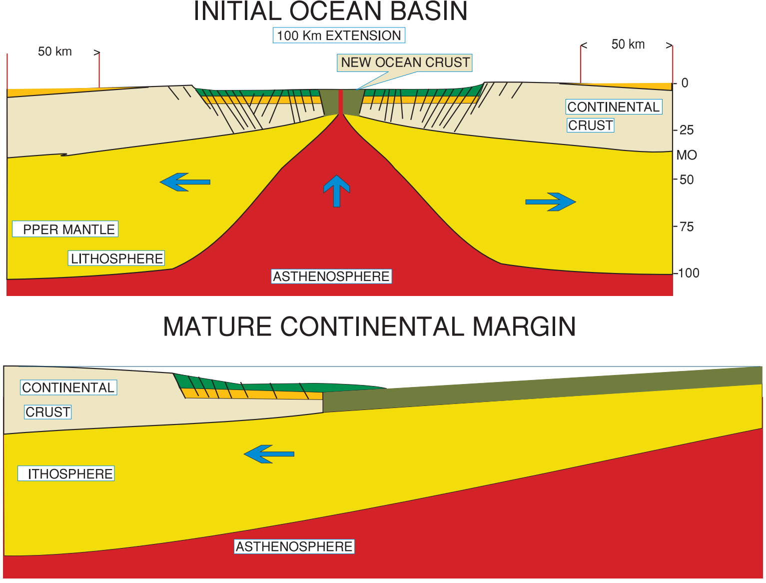


Fig. 5a. Progressive formation of a rift valley through extension of the lithosphere and continental crust (by about 50 km). Note that uprise and decompression of the underlying asthenosphere results in magma formation.
The crust responds by brittle fracture. Early rift sediments are downfaulted into the developing rift (graben). Erosion takes place on the sides of the rift valley.

The first stage assumes that graben-like faults begin to form in the brittle crust.
The second stage shows simultaneous necking of the lithosphere with uprise of an asthenosphere diapir. The decompression associated with the latter causes melting of the mantle to give alkaline basaltic magmas. Pre-existing sediments are downfaulted into the graben.
The third stage is accompanied by significant extension and by more uprise of the asthenosphere. The latter causes doming of the crust (which is evident along the E. African rift system, but is variably devloped. New sediments are deposited within the graben as a result of erosion of the uplifting sides of the graben. So there are both pre-rift and syn-rift sediments within the developing rift valley, but sediments on the flanks are progressively erodied away. Note the complex normal-faulting within the rift valley itself.

The fourth stage (Fig. 5b – below) shows the actually rifting-apart of the continent, so the asthenosphere rises towards the surface, causing decompression and extensice melting. New basaltic oceanic crust is formed.
Finally, sea-floor spreading takes over as the ocean basin widens. The rift sedimentary sequence is buried beneath younger marine sediments.

Note: on this diagram the sediments at the continental margin are shown as not very thick. This is because the model is based on the East African Rift System, which does not have a great deal of subsidence associated with rifting. However, other rifted continental margin sequences are very different, with thick sedimentary sequences.



Continental Shelf Sediments

The real situation at passive continental margins is shown in Fig. 6 (below). This is typical of a number of crustal cross-sections across the continental shelf of the eastern Atlantic seaboard of North America, projected down to 30 km -- based largely on gravity and magnetic evidence, plus some seismic profiles -- and some extrapolation from land geology based on deep drill holes.

The critical point is the huge thicknesses of Mesozoic and Tertiary sediments, here shown as almost 15 km, but in other cross-sections this can be even thicker. Note that at the bottom of this pile are volcanics and volcanogenic sediments, and evaporites, which most likely are shallow water. Also, massive carbonate reef structures, which must also be shallow water, but also must indicate progressive subsidence .. .. slow enough that shallow water sedimentation can keep pace with it.
In many sections of the continental shelf off this eastern seaboard of the USA there is a major coast-parallel magnetic structure, possibly a major intrusion. But its age is unknown.

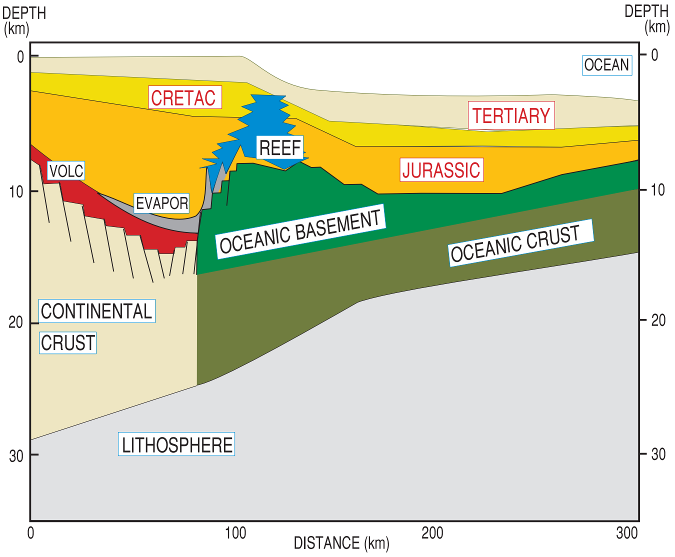


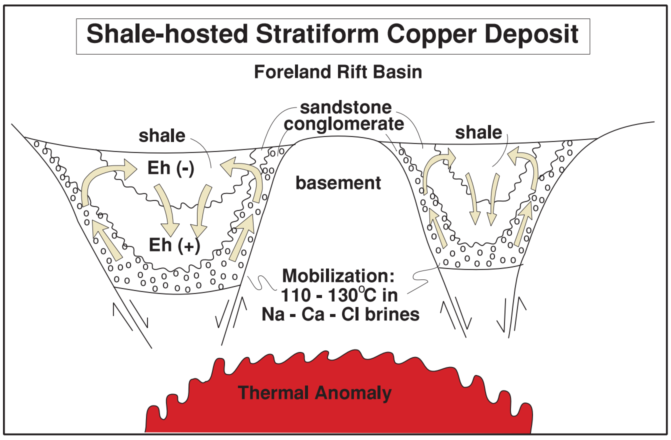
Fig. 6. Profile of deep structure of continental shelf off Atlantic coast of eastern North America -- ?typical of passive continental margins. (Based on gravity, magnetics and seismic data) Critical points regarding this profile are (a) the large thickness of post-rift sediments of Mesozoic-Tertiary age, up to 15 km, and (b) that most of these sediments are shallow-water type.
Note: volcanics and evaporites and reef (or carbonate banks)

Rift Terminology

Continental Rift: elongate tectonic depression with which the entire lithosphere has been modified in extension
Rift System: Tectonically interconnected series of rifts
Modern Rift: A rift that is teconically or magmatically active
Paleorift: A dead or dormant rift
Failed Arm: Branch of a triple junction not developed into an ocean basin
Aulacogen: Paleorift in ancient platform that has been reactivated by compressional deformation
Active Rifting: Rifting in response to thermal upwelling of the asthenosphere
Passive Rifting: Rifting in response to remote stress field

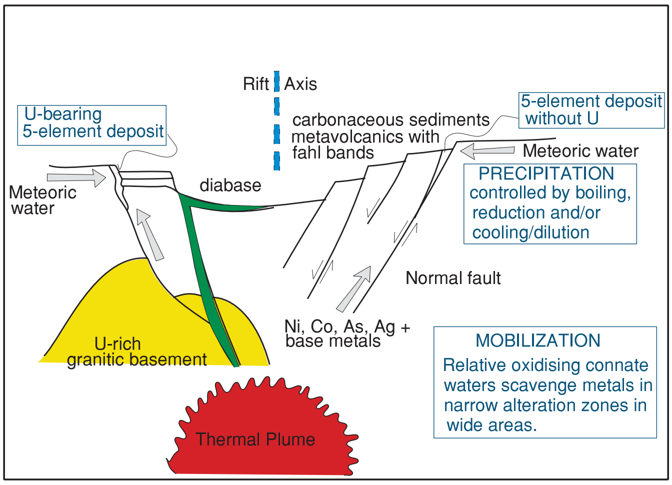
Rifting structures are often good sites for mineralisation. This arises for three reasons:

(1) They can be the sites of thick clastic sedimentation. These sediments hold vast amounts of inter-granular salt water (brines). The brines may be in contact with reducing sediments, such as carbonaceous shales, also a ready supply of sulphur/sulphate. As the sediments compact, these brines are expelled and can move laterally for large distances until they move up the rift faults. Having been buried deep the brines get hot, and can be very corrosive. So en route they can dissolve considerable amounts of metals. However, when they rise up the rift faults and cool, these metals will be precipitated out. This can be enhanced because oxidising meteoric water (groundwater) may also penetrate down these faults, so metals wil be precipitated out when the two meet.



(2) Rift structures are also thermally anomalous hot zones. This is because they are frequently underlain by igneous intrusions -- granite (or perhaps in some cases gabbro) plutons. This magmatic heat drives the hydrothermal systems. Importantly, these hydrothermal systems can last for many millions of years, so the hot fluids in these hydrothermal systems can leach away at the rocks within the rift system and precipitate the leached metals nearer the surface. Because the rift structures remain topographically low structures for many tens of millions of years, these metals concentrations can be preserved, without being eroded, for long periods.

(3) The rift zones may be the sites of diverse rocks, particularly basaltic lavas, which can release their metals on hydrothermal alteration. However, because the rift faults can extend very deep (well into the upper mantle in some cases), there may also be a component of deep fluids and metals in the hydrothermal system.



References

The references below will lead you to some of the discussion on rifting and the Wilson Cycle:

BAKER, B.H., MOHR, P. & WILLIAMS, L.A.J. 1972. Geology of the eastern rift system of Africa*.* *Geological Society of America Special Paper* **136**, 1-67.

BOSWORTH, W. 1985. Geometry of propagating continental rifts. *Nature* **316**, 625-627.

BOSWORTH, W. 1987. Off-axis volcanism in the Gregory rift, East Africa: implications for models of continental rifting. *Geology* **15**, 397-400.

BOTT, M.H.P 1995. Mechanisms ofrifting: Geodynamic modeling of continental rift systems. In: K.H. Olsen (ed.) Continental rifts: evolution, structure, tectonics. *Developments in Geotectonics*, **25**, 27-43. Elsevier, Amsterdam

BRAILE, L.W., KELLER, G.R., WENDLANDT, R.F., MORGAN, P. & KHAN, M.A. 1995. The East African Rift system. In: K.H. Olsen (ed.) *Continental rifts: evolution, structure, tectonics*. Developments in Geotectonics, **25**, Elsevier, Amsterdam

BURKE, K. & DEWEY, J.F. 1973. Plume generated triple junctions: key indicators in applying plate tectonics to old rock. *Journal of Geology* **81**, 406-433.

BURKE, K. & WHITEMAN, A.J. 1973. Uplift, rifting and break-up of Africa. In TARLING, D.H. & RUNCORN, S.K. (eds) *Implications of continental drift to the earth sciences*. Academic Press, London. 735-755.

DEWEY, J.F. & BURKE, K. 1974. Hotspots and continental break-up: implications for collisional orogeny. *Geology* **2**, 57-60.

DUNCAN, C.C. & TURCOTTE, D.L. 1994. On the breakup and coalescence of continents. *Geology* **22**, 103-106.

GURNIS, M. 1988. Large-scale mantle convection and the aggregation and dispersal of continents. *Nature* **332**, 695-699.

MORGAN, W.J. 1981. Hotspot tracks and the opening of the Atlantic and Indian Oceans. In Emiliani, C. (ed*) The Sea. Volume 7*, 443-487. Wiley, New York.

MORGAN, W.J. 1983. Hotspot tracks and the early rifting of the Atlantic. *Tectonophysics* **94**, 123-139.

MURPHY, J.B. & NANCE, R.D. 1992. Mountain belts and the supercontinent cycle. *Scientific American* **266**, 84-91.

OLSEN, K.H. & MORGAN, P. 1995. Introduction: Progress in understanding continental rifts. In: K.H. Olsen (ed.) *Continental rifts: evolution, structure, tectonics.* Developments in Geotectonics, **25**, 3-26. Elsevier, Amsterdam

SPOHN, T. & SCHUBERT, G. 1982. Convective thinning of the lithosphere: a mechanism for the initiation of continental rifting. *Journal of Geophysical Research* **87**, 4669-4681.

WHITE, R.S. & McKENZIE, D.P. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research* **94**, 7685-7730.

WILSON, J.T. 1966. Did the Atlantic close and then re-open? *Nature* **211**, 676-681.