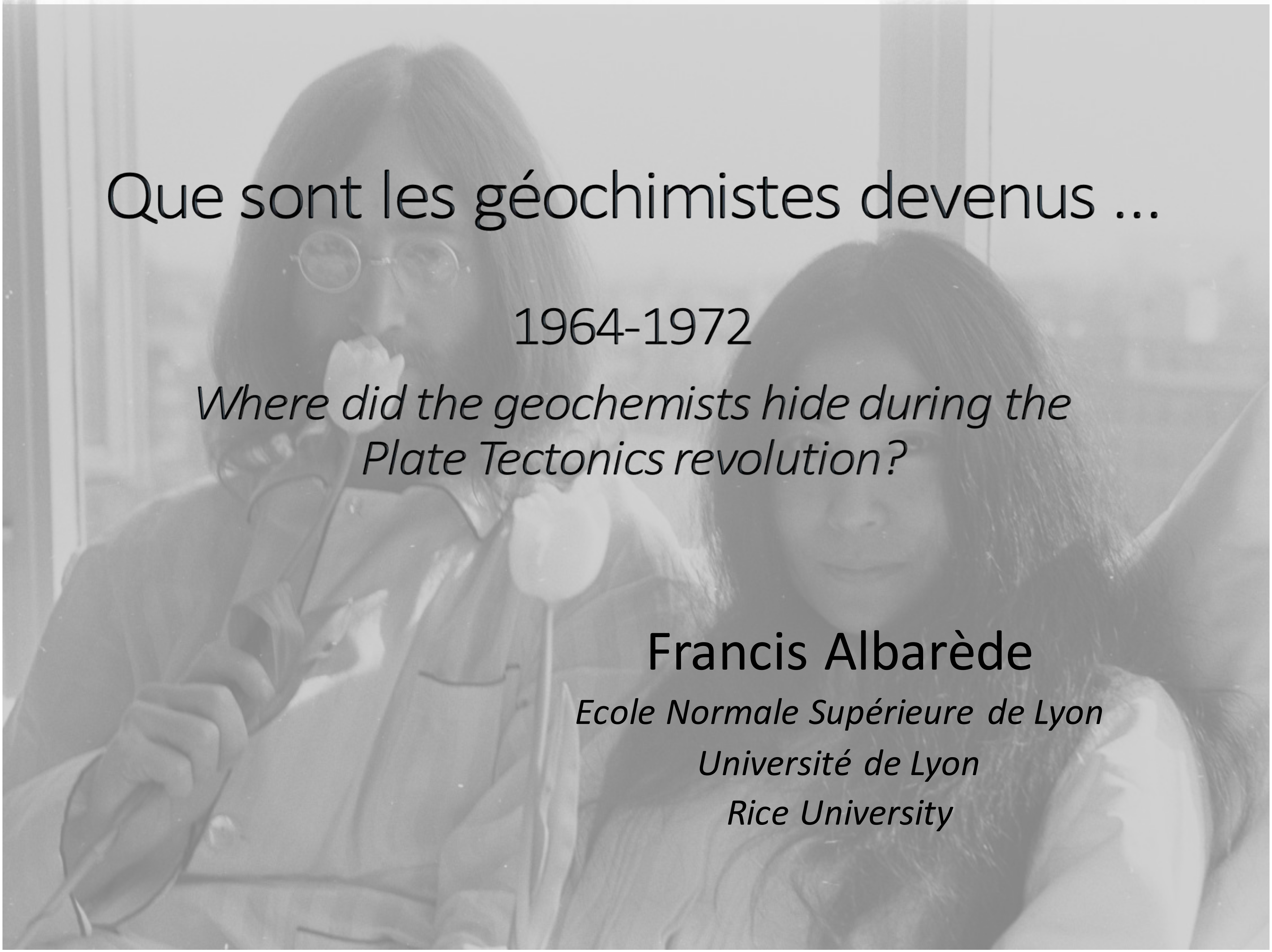


Que sont les géochimistes devenus …

1964-1972

Where did the geochemists hide during the Plate Tectonics revolution?

Francis Albarède

Ecole Normale Supérieure de Lyon
Université de Lyon
Rice University

What were they thinking about?

The context: the evolution of techniques

- Instrumental Neutron Activation Analysis (Schilling and Winchester, 1966)
- Electron probe (Castaing, 1958; Bence and Albee, 1968)
- Thermal ionization mass spectrometers (Papanastassiou and Wasserburg 1969)

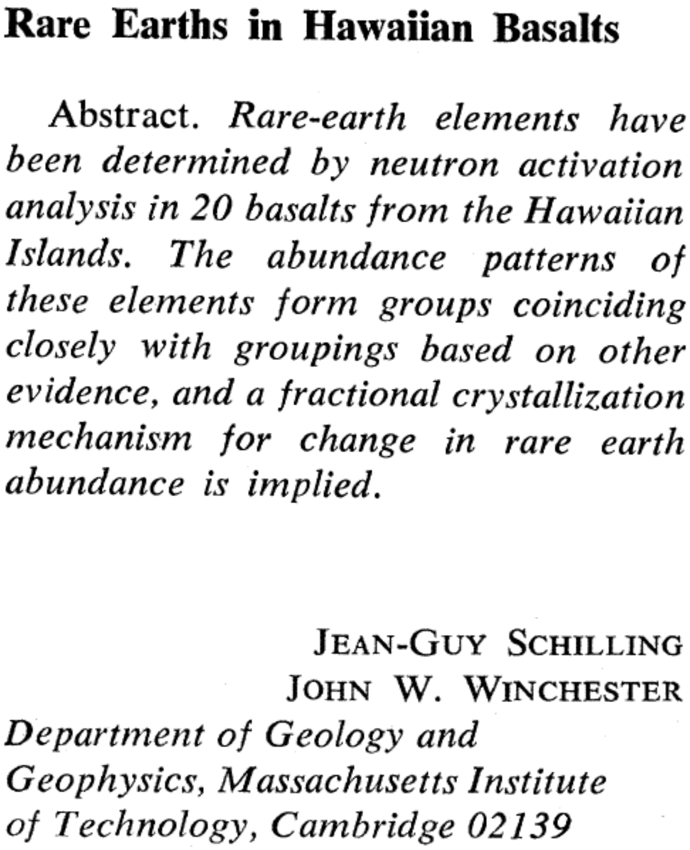
The interior of the Earth

- The different types of basalts and how they relate to each other
- The nature of the mantle and its heterogeneity
- Mid-ocean ridges and back-arcs
- Subduction zones

Crustal growth

- The nature of the Moho
- Continent assembly

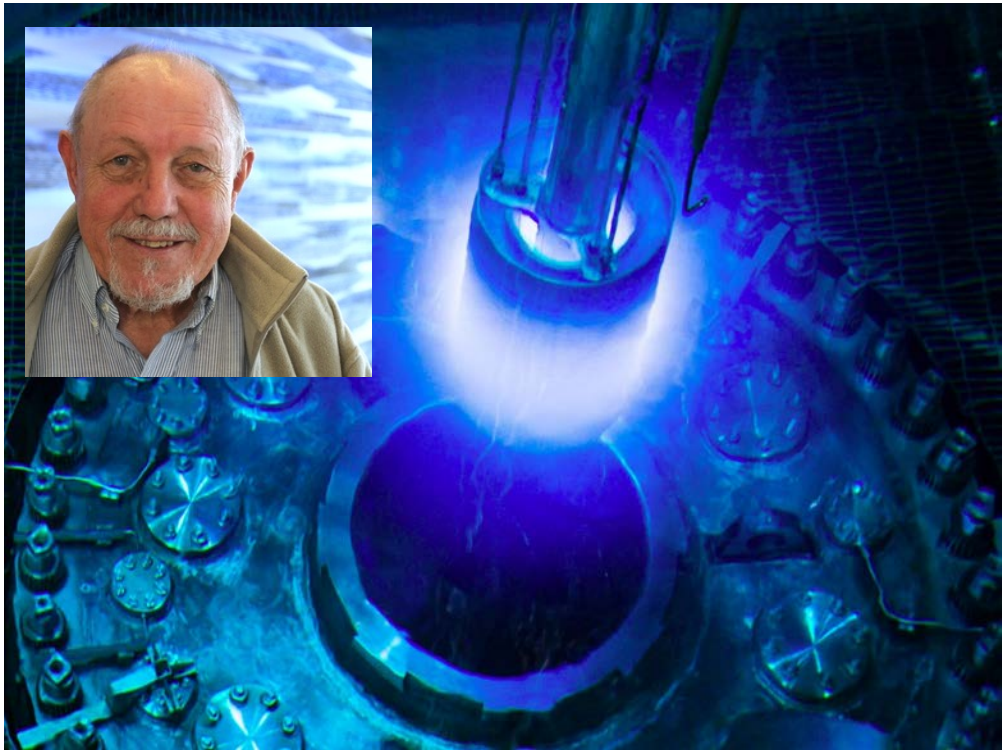
1966: First reliable trace element analyses (Neutron Activation)



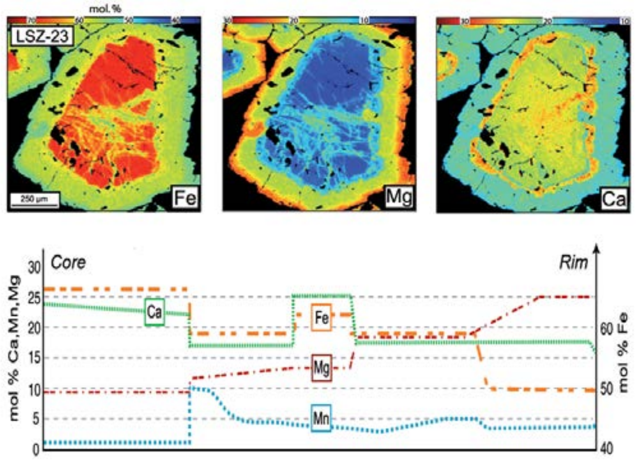
Rare Earths in Hawaiian Basalts

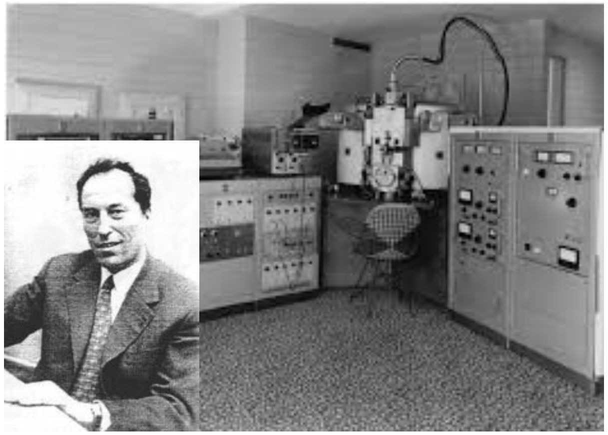
Abstract. *Rare-earth elements have been determined by neutron activation analysis in 20 basalts from the Hawaiian Islands. The abundance patterns of these elements form groups coinciding closely with groupings based on other evidence, and a fractional crystallization mechanism for change in rare earth abundance is implied.*

JEAN-GUY SCHILLING
JOHN W. WINCHESTER
Department of Geology and
Geophysics, Massachusetts Institute
of Technology, Cambridge 02139

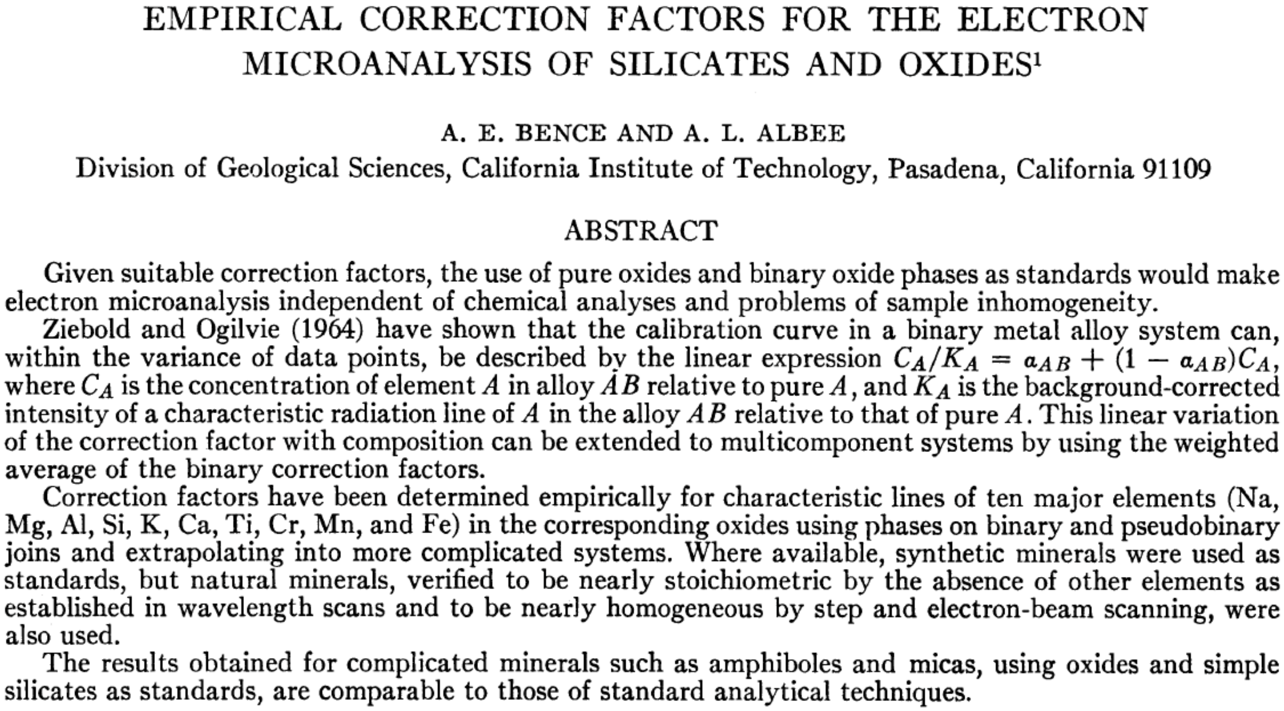


1968: The coming of age of in situ *analysis*





R. Castaing



EMPIRICAL CORRECTION FACTORS FOR THE ELECTRON MICROANALYSIS OF SILICATES AND OXIDES[1]

A. E. BENCE AND A. L. ALBEE
Division of Geological Sciences, California Institute of Technology, Pasadena, California 91109

ABSTRACT

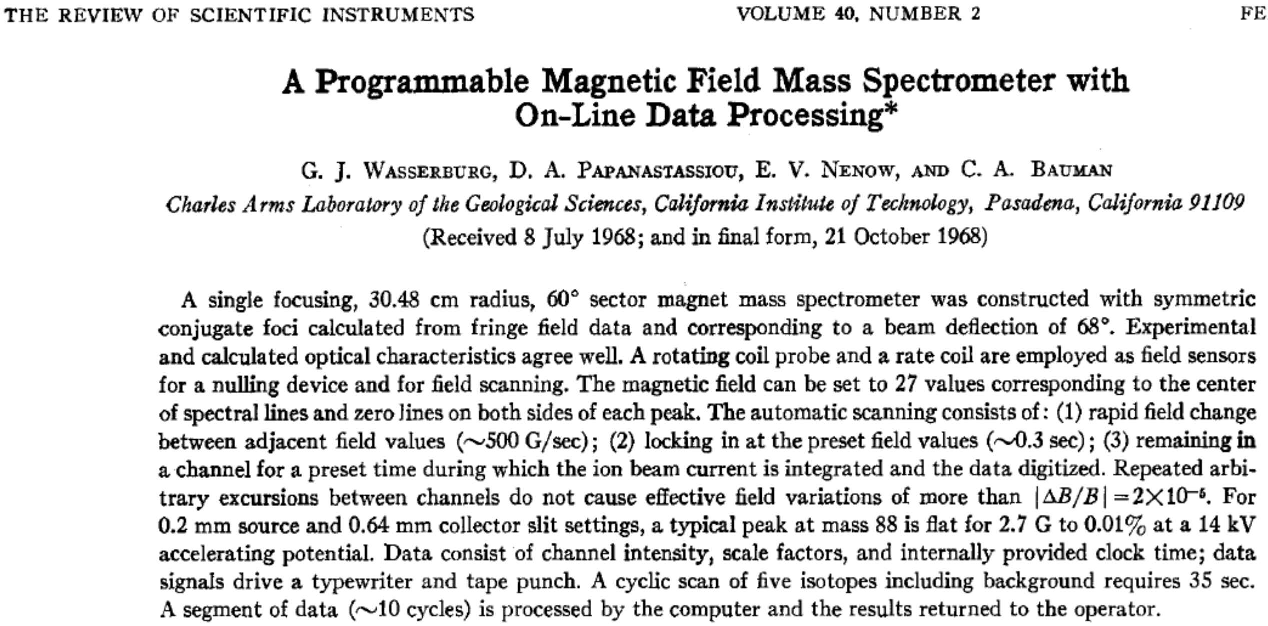
Given suitable correction factors, the use of pure oxides and binary oxide phases as standards would make electron microanalysis independent of chemical analyses and problems of sample inhomogeneity.

Ziebold and Ogilvie (1964) have shown that the calibration curve in a binary metal alloy system can, within the variance of data points, be described by the linear expression $C_A/K_A = \alpha_{AB} + (1 - \alpha_{AB})C_A$, where C_A is the concentration of element A in alloy AB relative to pure A, and K_A is the background-corrected intensity of a characteristic radiation line of A in the alloy AB relative to that of pure A. This linear variation of the correction factor with composition can be extended to multicomponent systems by using the weighted average of the binary correction factors.

Correction factors have been determined empirically for characteristic lines of ten major elements (Na, Mg, Al, Si, K, Ca, Ti, Cr, Mn, and Fe) in the corresponding oxides using phases on binary and pseudobinary joins and extrapolating into more complicated systems. Where available, synthetic minerals were used as standards, but natural minerals, verified to be nearly stoichiometric by the absence of other elements as established in wavelength scans and to be nearly homogeneous by step and electron-beam scanning, were also used.

The results obtained for complicated minerals such as amphiboles and micas, using oxides and simple silicates as standards, are comparable to those of standard analytical techniques.

1969: The first high-precision mass spectrometer



THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 40, NUMBER 2 FEBRUARY 1969

A Programmable Magnetic Field Mass Spectrometer with On-Line Data Processing*

G. J. Wasserburg, D. A. Papanastassiou, E. V. Nenow, and C. A. Bauman

Charles Arms Laboratory of the Geological Sciences, California Institute of Technology, Pasadena, California 91109

(Received 8 July 1968; and in final form, 21 October 1968)

A single focusing, 30.48 cm radius, 60° sector magnet mass spectrometer was constructed with symmetric conjugate foci calculated from fringe field data and corresponding to a beam deflection of 68°. Experimental and calculated optical characteristics agree well. A rotating coil probe and a rate coil are employed as field sensors for a nulling device and for field scanning. The magnetic field can be set to 27 values corresponding to the center of spectral lines and zero lines on both sides of each peak. The automatic scanning consists of: (1) rapid field change between adjacent field values (~500 G/sec); (2) locking in at the preset field values (~0.3 sec); (3) remaining in a channel for a preset time during which the ion beam current is integrated and the data digitized. Repeated arbitrary excursions between channels do not cause effective field variations of more than $|\Delta B/B| = 2\times10^{-6}$. For 0.2 mm source and 0.64 mm collector slit settings, a typical peak at mass 88 is flat for 2.7 G to 0.01% at a 14 kV accelerating potential. Data consist of channel intensity, scale factors, and internally provided clock time; data signals drive a typewriter and tape punch. A cyclic scan of five isotopes including background requires 35 sec. A segment of data (~10 cycles) is processed by the computer and the results returned to the operator.

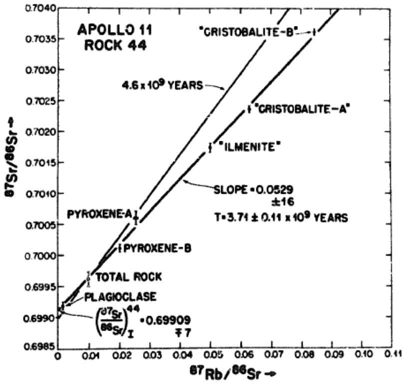


Fig. 3. Rb-Sr evolution diagram for low-K rock # 44. Best fit isochron and parameters shown; 4.6×10^9 yr reference isochron also shown. Range of enrichment of $(^{87}Sr/^{86}Sr)$ is 0.6%.

What were they thinking about?

The context: the evolution of techniques

- Instrumental Neutron Activation Analysis (Schilling and Winchester, 1966)
- Electron probe (Castaing, 1964; Bence and Albee, 1968)
- Thermal ionization mass spectrometers (Papanastassiou and Wasserburg 1969)

The interior of the Earth

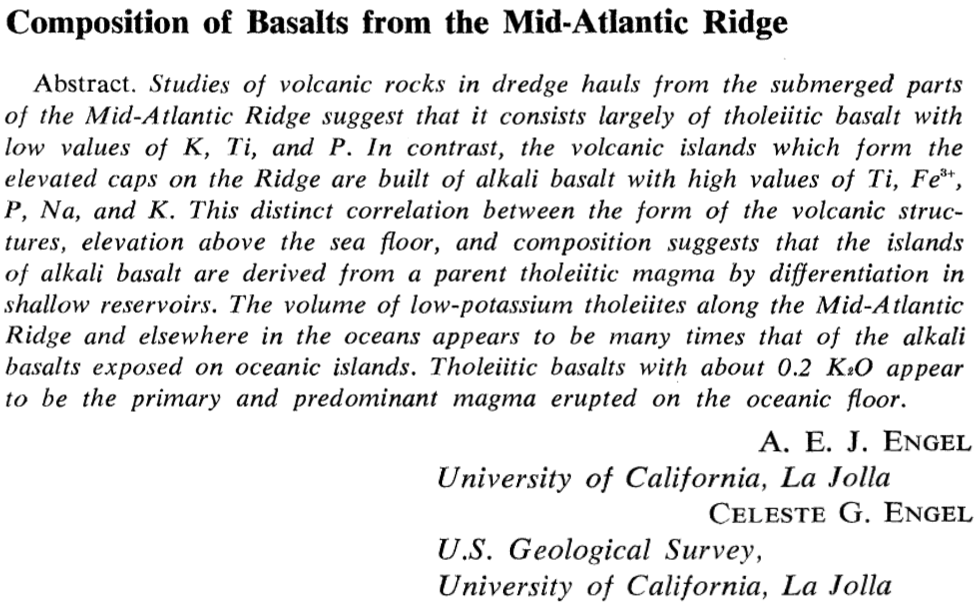
- The different types of basalts and how they relate to each other
- The nature of the mantle and its heterogeneity
- Mid-ocean ridges and back-arcs
- Subduction zones

Crustal growth

- The nature of the Moho
- Continent assembly

Ocean island arc basalts: a differentiation product of mid-ocean ridge basalts ?

Engel and Engel (1964)
who discovered the mid-ocean ridge basalts

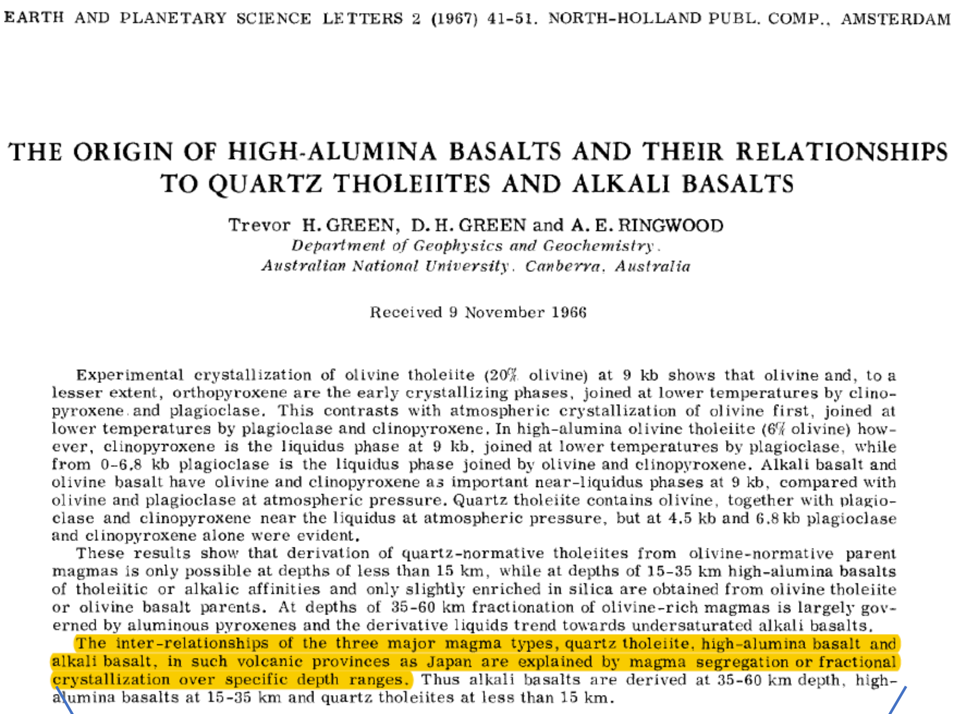


Composition of Basalts from the Mid-Atlantic Ridge

Abstract. *Studies of volcanic rocks in dredge hauls from the submerged parts of the Mid-Atlantic Ridge suggest that it consists largely of tholeiitic basalt with low values of K, Ti, and P. In contrast, the volcanic islands which form the elevated caps on the Ridge are built of alkali basalt with high values of Ti, Fe^{3+}, P, Na, and K. This distinct correlation between the form of the volcanic structures, elevation above the sea floor, and composition suggests that the islands of alkali basalt are derived from a parent tholeiitic magma by differentiation in shallow reservoirs. The volume of low-potassium tholeiites along the Mid-Atlantic Ridge and elsewhere in the oceans appears to be many times that of the alkali basalts exposed on oceanic islands. Tholeiitic basalts with about 0.2 K_2O appear to be the primary and predominant magma erupted on the oceanic floor.*

A. E. J. ENGEL
University of California, La Jolla
CELESTE G. ENGEL
U.S. Geological Survey,
University of California, La Jolla

'This seeming dependence of composition upon elevation appears to argue eloquently for the **derivation of the elevated alkali basalt cones from a parent tholeiitic magma** by gravity differentiation. '



EARTH AND PLANETARY SCIENCE LETTERS 2 (1967) 41-51. NORTH-HOLLAND PUBL. COMP., AMSTERDAM

THE ORIGIN OF HIGH-ALUMINA BASALTS AND THEIR RELATIONSHIPS TO QUARTZ THOLEIITES AND ALKALI BASALTS

Trevor H. GREEN, D. H. GREEN and A. E. RINGWOOD
Department of Geophysics and Geochemistry,
Australian National University, Canberra, Australia

Received 9 November 1966

Experimental crystallization of olivine tholeiite (20% olivine) at 9 kb shows that olivine and, to a lesser extent, orthopyroxene are the early crystallizing phases, joined at lower temperatures by clinopyroxene and plagioclase. This contrasts with atmospheric crystallization of olivine first, joined at lower temperatures by plagioclase and clinopyroxene. In high-alumina olivine tholeiite (6% olivine) however, clinopyroxene is the liquidus phase at 9 kb, joined at lower temperatures by plagioclase, while from 0-6.8 kb plagioclase is the liquidus phase joined by olivine and clinopyroxene. Alkali basalt and olivine basalt have olivine and clinopyroxene as important near-liquidus phases at 9 kb, compared with olivine and plagioclase at atmospheric pressure. Quartz tholeiite contains olivine, together with plagioclase and clinopyroxene near the liquidus at atmospheric pressure, but at 4.5 kb and 6.8 kb plagioclase and clinopyroxene alone were evident.

These results show that derivation of quartz-normative tholeiites from olivine-normative parent magmas is only possible at depths of less than 15 km, while at depths of 15-35 km high-alumina basalts of tholeiitic or alkalic affinities and only slightly enriched in silica are obtained from olivine tholeiite or olivine basalt parents. At depths of 35-60 km fractionation of olivine-rich magmas is largely governed by aluminous pyroxenes and the derivative liquids trend towards undersaturated alkali basalts.

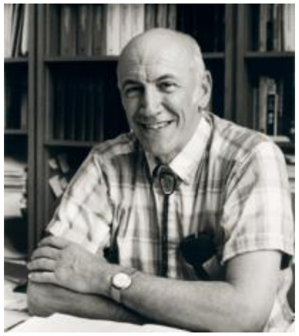
The inter-relationships of the three major magma types, quartz tholeiite, high-alumina basalt and alkali basalt, in such volcanic provinces as Japan are explained by magma segregation or fractional crystallization over specific depth ranges. Thus alkali basalts are derived at 35-60 km depth, high-alumina basalts at 15-35 km and quartz tholeiites at less than 15 km.

The inter-relationships of the three major magma types, quartz tholeiite, high-alumina basalt and alkali basalt […] are explained by magma segregation or fractional crystallization over specific depth ranges.

During much of the 60s, a deep-running vision of the mantle as a chemically homogeneous entity was shared by petrologists and geochemists

The advent of mantle heterogeneities

Frey and Haskin (1964) discovered the **dichotomy of rare-earth element distributions** between mid-ocean ridge and ocean island basalts but still thought that the MORB source was primordial.



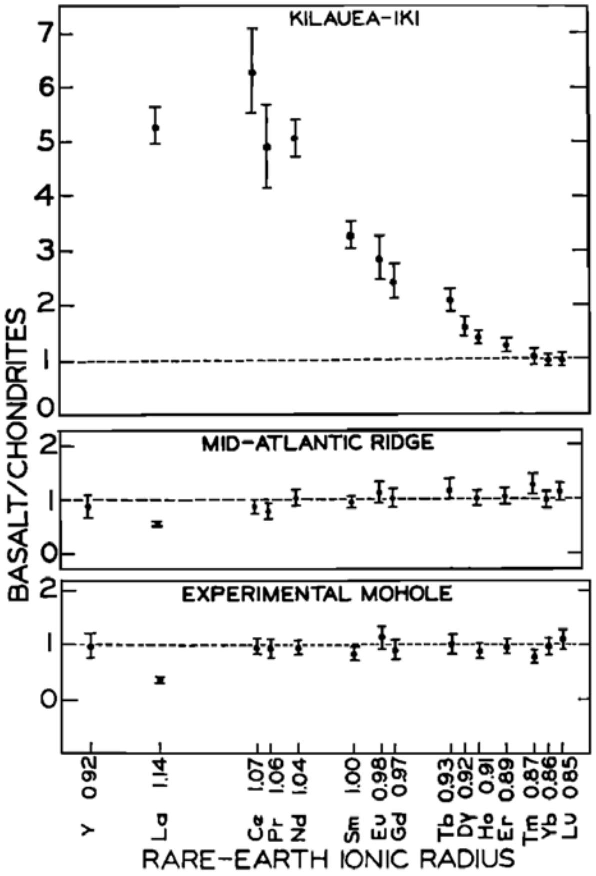
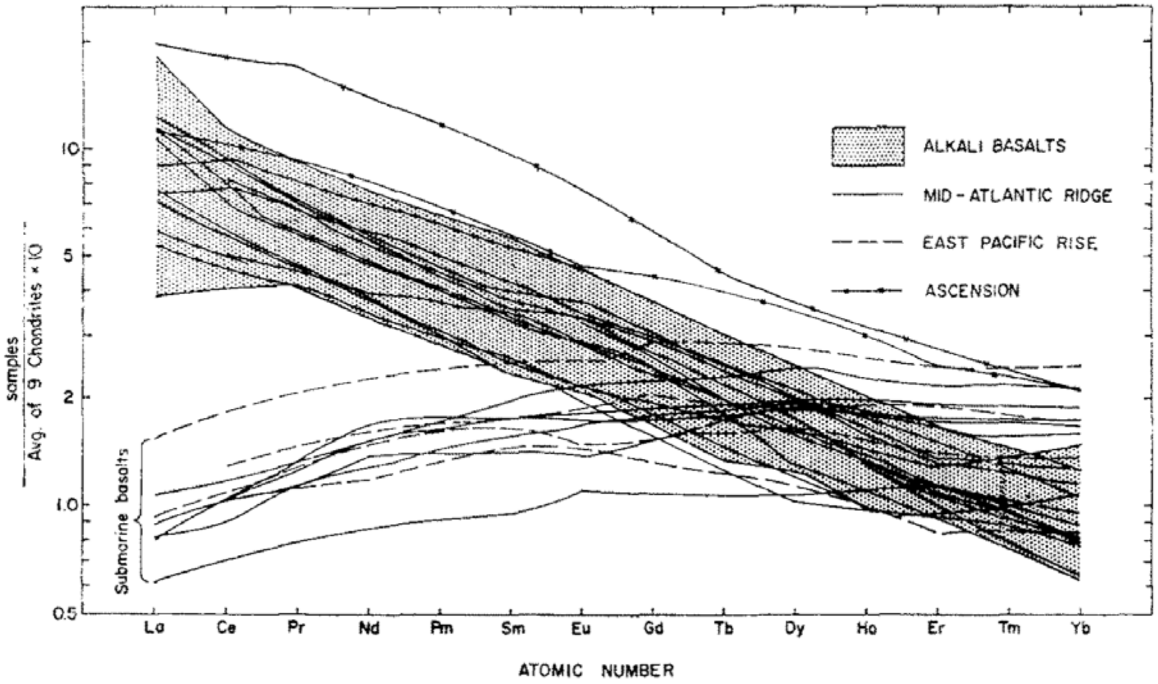


Fig. 3. The Yb-normalized distributions of the Kilauea-Iki and experimental Mohole basalts and the average of the Yb-normalized distributions for the three mid-Atlantic ridge basalts are compared with the chondrite pattern.

Gast (1968) demonstrated that **ocean island basalts cannot be derived from mid-ocean ridge basalts**. In addition, MORBs are derived from a mantle that has **a long history of magma extraction**. He founded the modern vision of the mantle.



Mantle heterogeneities were isolated for billions of years

Tatsumoto (1966)

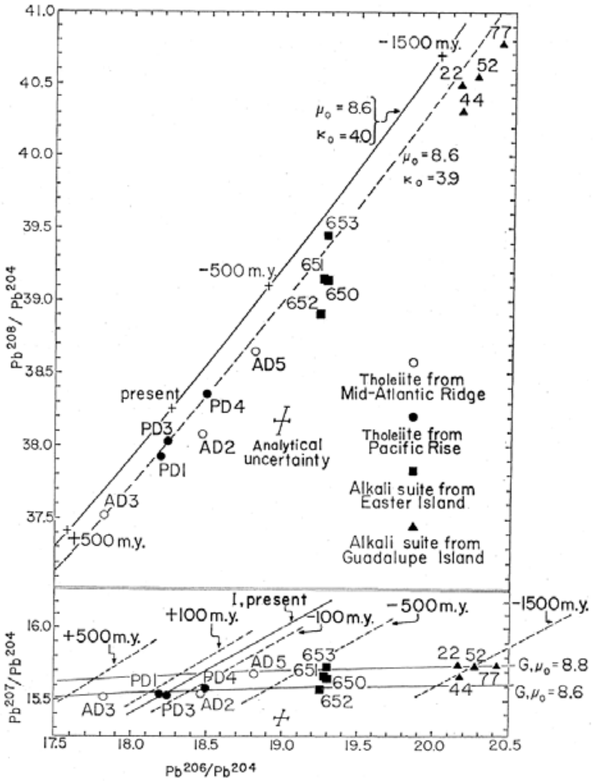
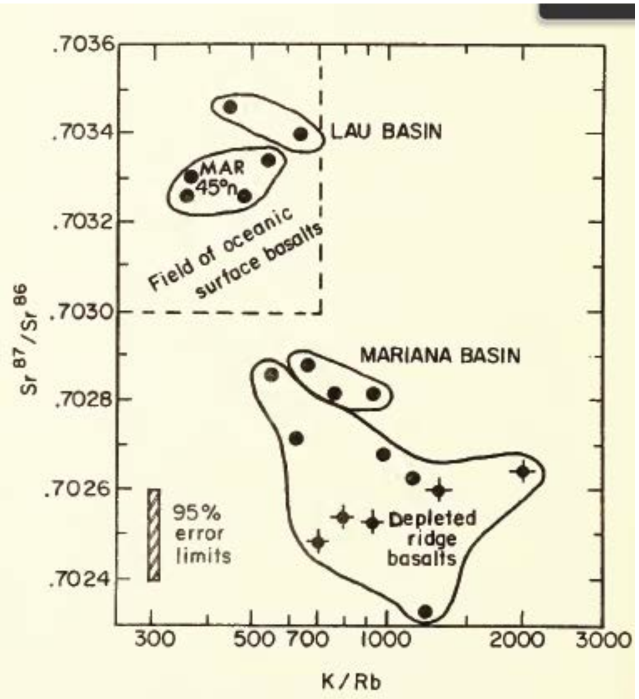


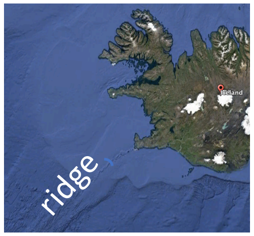
Fig. 2. Ratios of Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} (lower part) and Pb^{206}/Pb^{204} versus Pb^{208}/Pb^{204} (upper part) in tholeiites and rocks from Easter and Guadalupe Islands. The primary growth curves having $\mu_0 = 8.6$ and 8.8 (lower part), $\mu_0 = 8.6$ and $\kappa_0 = 4.0$ and $\mu_0 = 8.6$ and $\kappa_0 = 3.9$ (upper part) are given by *G*. The primary isochrons (*I*) are also given for present, ± 100 million years, ± 500 million years, and − 1500 million years.

Tatz' visionary assessment: 'the isotopic composition of lead in oceanic tholeiite suggests that **the upper mantle source region of the tholeiite was differentiated from an original mantle material more than 1 billion years ago** and that the upper mantle is not homogeneous at the present time,'

Hart (1970)



Mantle heterogeneities: localized plumes vs overall convection



Hart, Powell, and Schilling (1973)

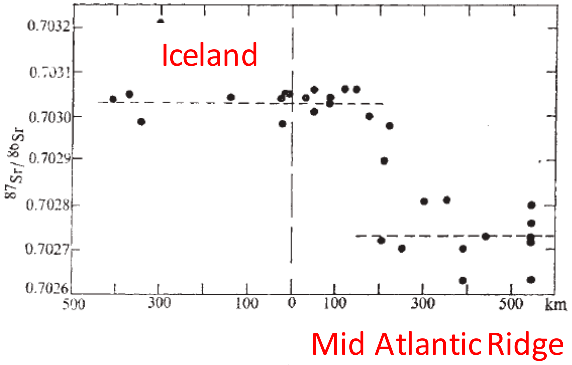
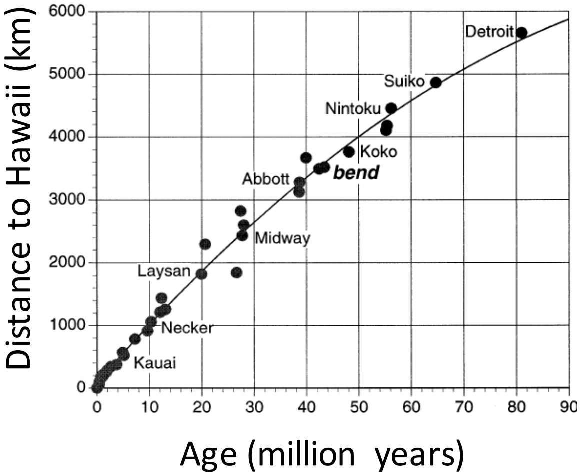
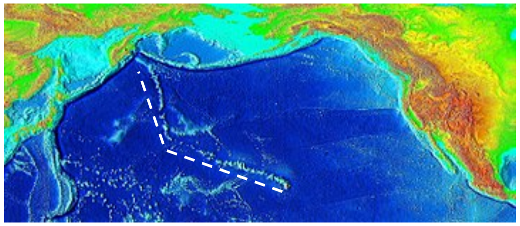
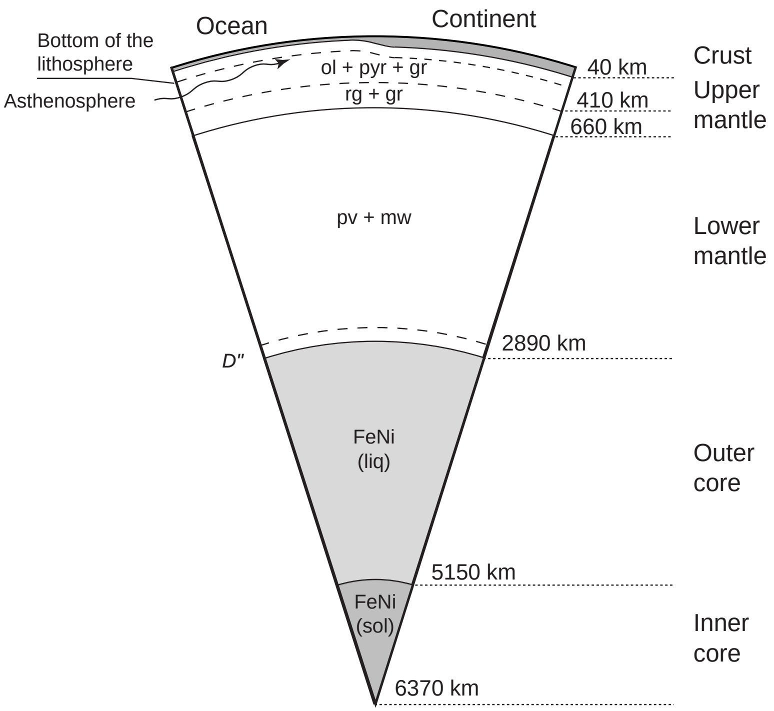


Fig. 2 Sr isotope ratios of tholeiitic basalts plotted as a function of distance from the tip of the Reykjanes Peninsula.

Wilson and Morgan's deep mantle plumes







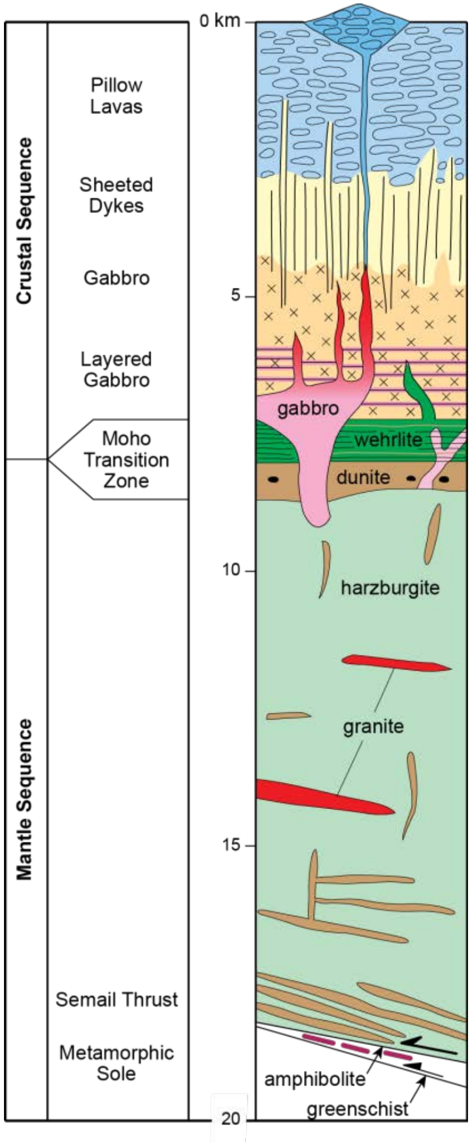
Conclusion: When the Wilson-Morgan concept of deep mantle plumes was combined with isotopic evidence of long-lived mantle heterogeneity, it became clear that Plate Tectonics manifests that the oceanic lithosphere is the ***thermo-mechanical boundary layer*** *of the upper mantle. Plumes are short-lived features from the lower mantle burning through the upper mantle.*

Magmatic activity at mid-ocean ridges and the canonical ophiolite model

Pillow-lavas

The sheeted-dyke complex

Accumulative gabbros



Evidence for a magma chamber at ridge crests

Inspired by the first results of the Apollo missions ..

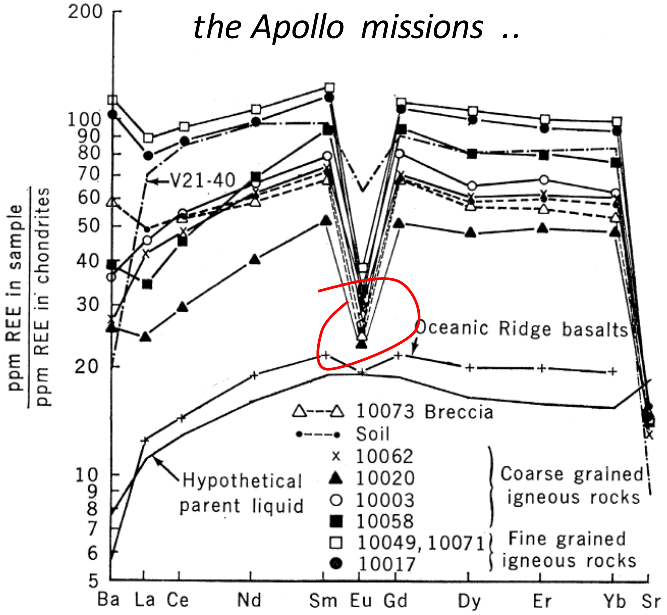
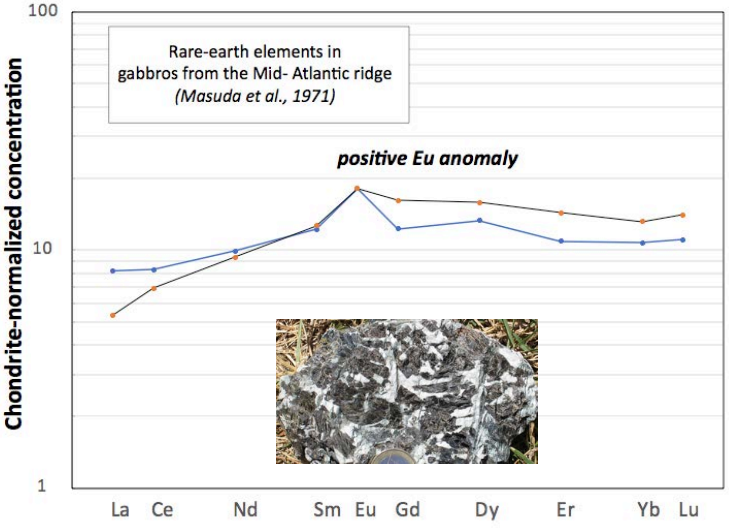


Fig. 2. Isochron diagram for six lunar rocks ($\lambda = 1.39 \times 10^{-11}$ year^{-1}).

Large europium anomalies in **Apollo 11 basalts** provided evidence of massive accumulation of plagioclase within the Moon (Gast and Hubbard, 1970). This observation was the basis for the interpretation of lunar highlands and the concept of the lunar magma ocean.



Accumulation of plagioclase in magma chambers under **mid-ocean ridges** is attested to by positive Eu anomalies in mid-ocean ridge gabbros. Plagioclase precipitation is a relatively shallow-pressure feature (<15 km).

Mid-ocean ridges are underlain by magma chambers

The complementary nature of negative (basalts) and positive (gabbros) Eu anomalies reveals the magmatic differentiation of the ophiolitic equivalent of mid-ocean ridges

The Vourinos ophiolite
(Montigny et al., 1973)

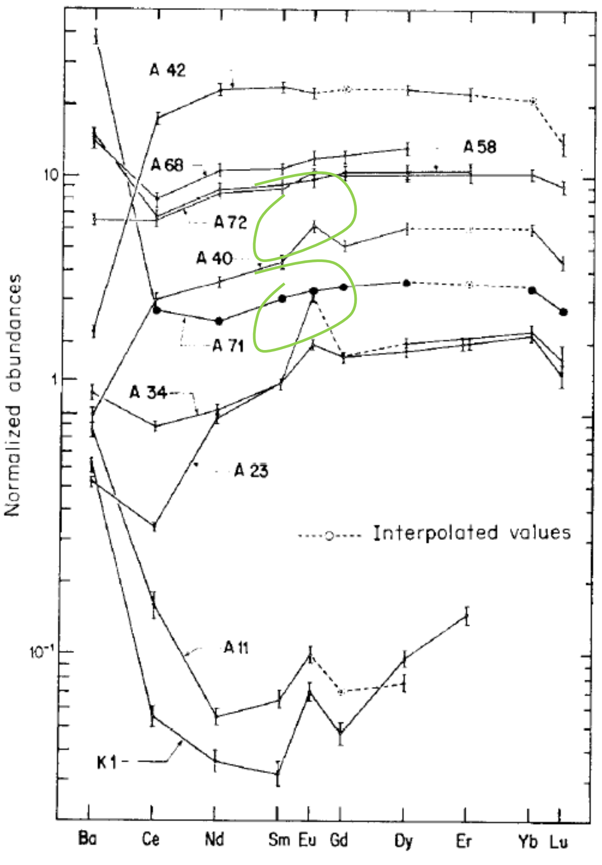
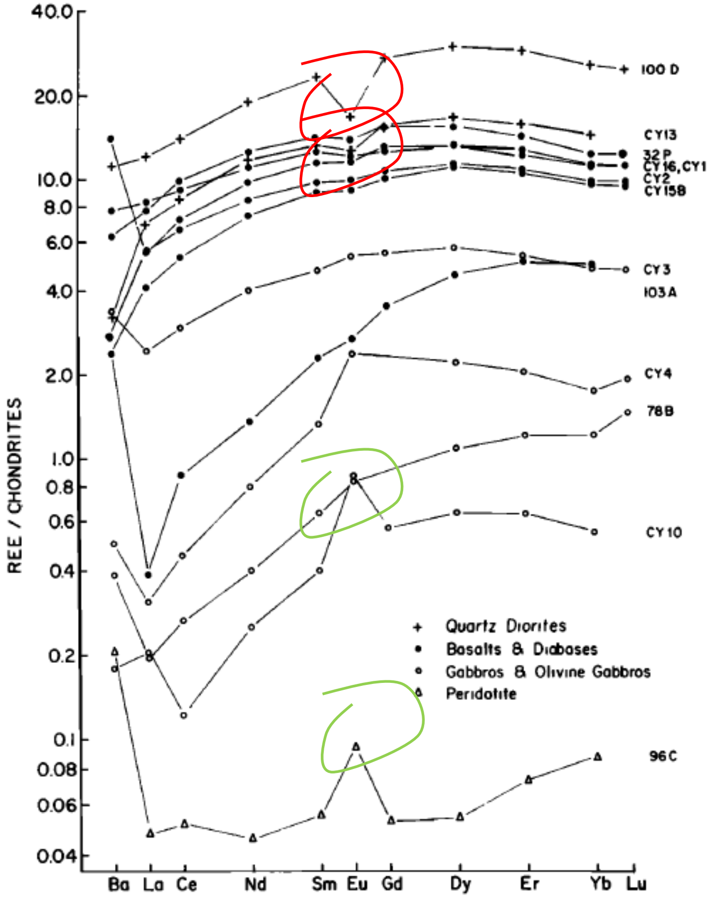


Fig. 2. Chondritic normalized REE abundances.

The Troodos ophiolite
(Kay and Sénéchal, 1976)



The first steps toward the ‘subduction factory’

Kuno (1966)

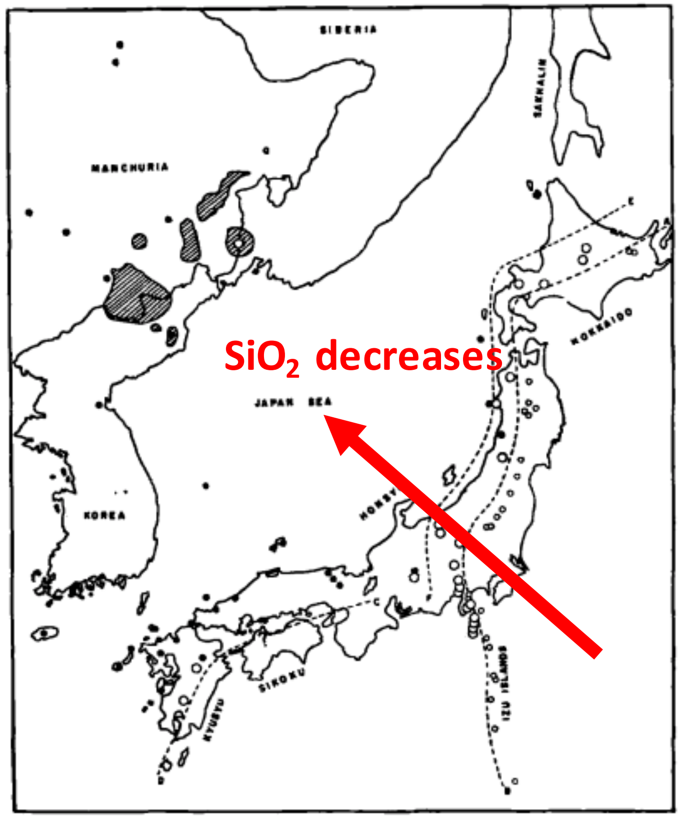
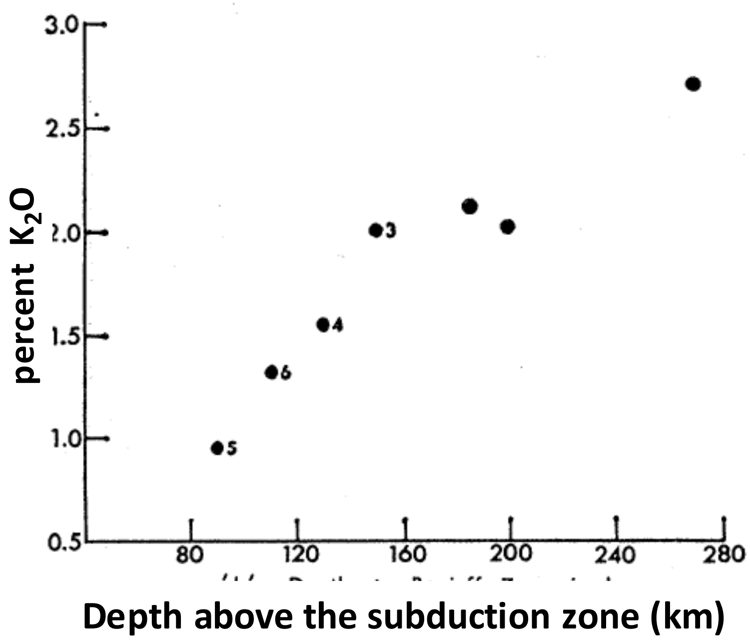


FIG. 1 - Distribution of tholeiite (small open circles), high-alumina basalt (large open circles), and alkali olivine basalt (solid circles) in Quaternary volcanoes of Japan, Korea, and Manchuria. The shaded areas in Manchuria are basalt plateaus mostly of alkali olivine basalt of younger Tertiary age. Lines *AB* and *CD* are boundaries between the tholeiite and high-alumina basalt zones and line *EF* is that between the high-alumina basalt and alkali olivine basalt zones.

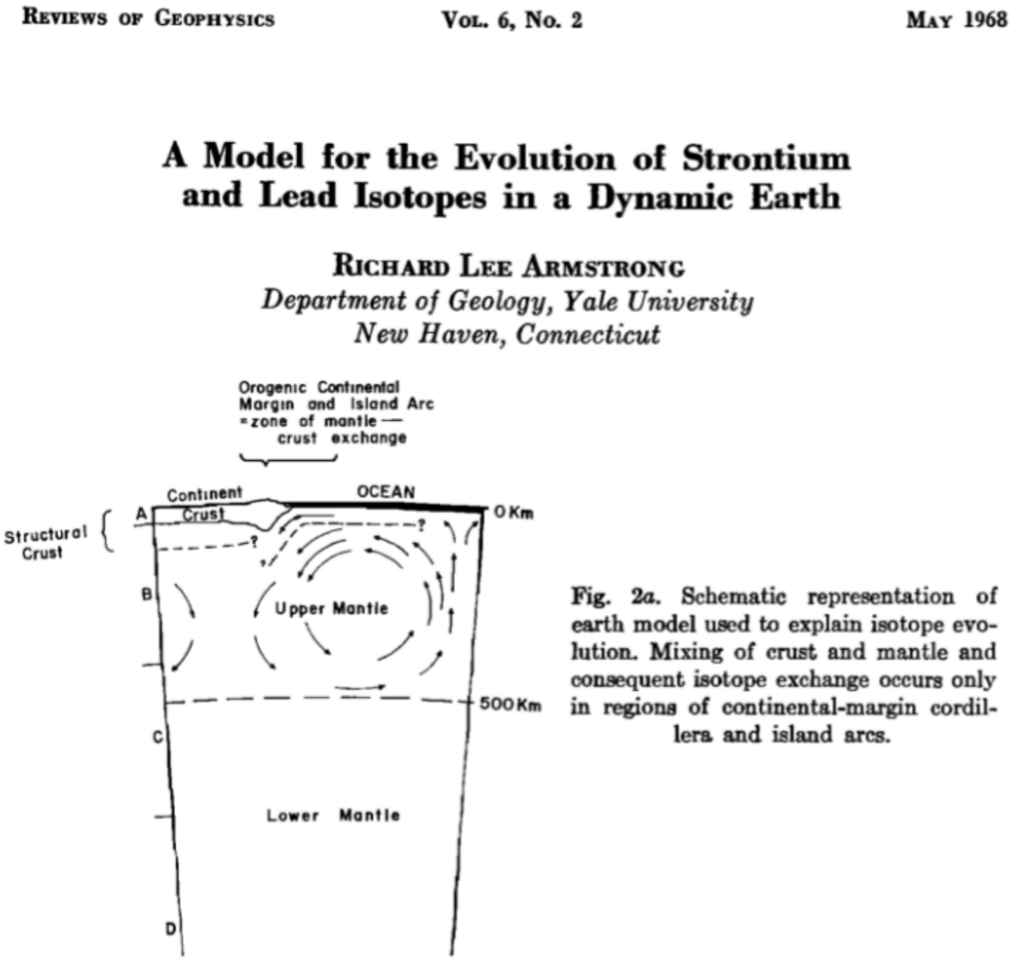
Dickinson and Atkinson (1967)



Tatsumoto (1967): ‘the [Pb] isotopic variation in basalts across the Japanese island arc result(s) from different proportions of the **plate material and the upper mantle** of continental side in the partial melt.’

Armstrong and Copper (1971): ‘oceanic sediments are dragged into the mantle, mixed to some degree with mantle material, and partially melted to form calc-alkaline magmas’.

A bold and visionary approach to global geochemistry



Reviews of Geophysics Vol. 6, No. 2 May 1968

A Model for the Evolution of Strontium and Lead Isotopes in a Dynamic Earth

Richard Lee Armstrong
Department of Geology, Yale University
New Haven, Connecticut

Fig. 2*a*. Schematic representation of earth model used to explain isotope evolution. Mixing of crust and mantle and consequent isotope exchange occurs only in regions of continental-margin cordillera and island arcs.

The Earth at steady-state:
Subduction of the altered oceanic crust (including sediments) and orogenic volcanism balance magma extraction at mid-ocean ridges

What were they thinking about?

The context: the evolution of techniques

- Instrumental Neutron Activation Analysis (Schilling and Winchester, 1966)
- Electron probe (Castaing, 1964; Bence and Albee, 1968)
- Thermal ionization mass spectrometers (Papanastassiou and Wasserburg 1969)

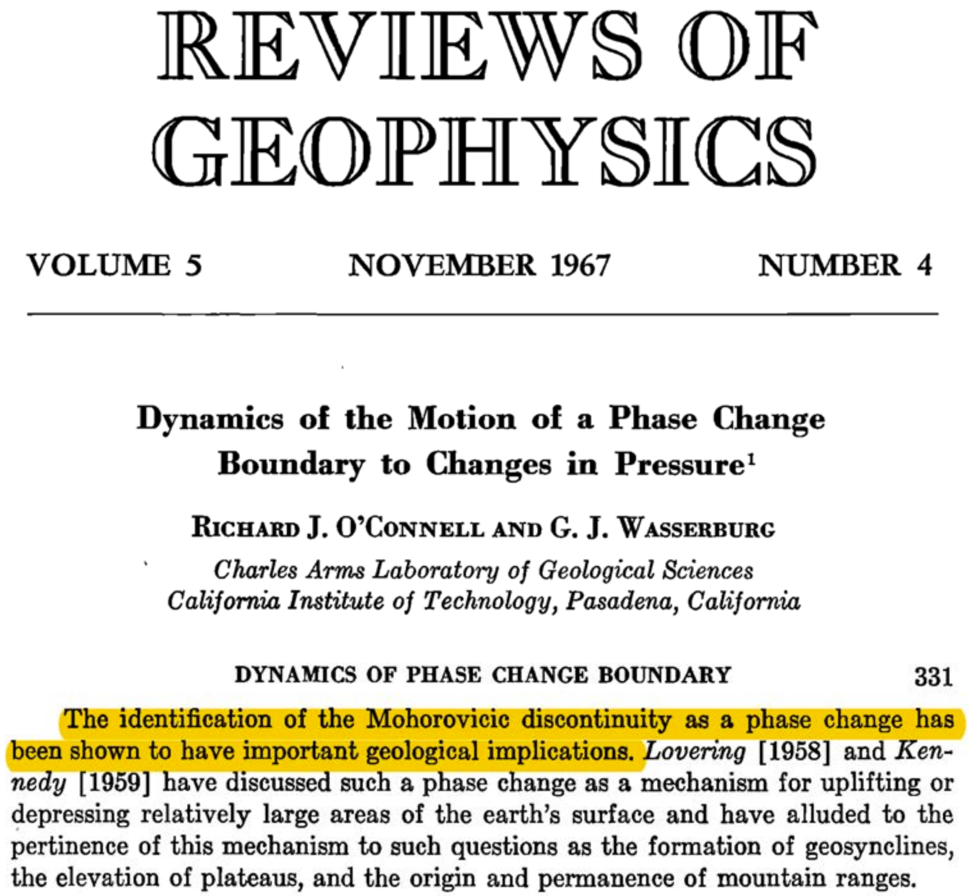
The interior of the Earth

- The different types of basalts and how they relate to each other
- The nature of the mantle and its heterogeneity
- Mid-ocean ridges and back-arcs
- Subduction zones

Crustal growth

- The nature of the Moho
- Continent assembly

The nature of continents: Is the Moho a gabbro-eclogite phase boundary?



REVIEWS OF GEOPHYSICS

VOLUME 5 NOVEMBER 1967 NUMBER 4

Dynamics of the Motion of a Phase Change Boundary to Changes in Pressure[1]

Richard J. O'Connell and G. J. Wasserburg

Charles Arms Laboratory of Geological Sciences
California Institute of Technology, Pasadena, California

DYNAMICS OF PHASE CHANGE BOUNDARY 331

The identification of the Mohorovicic discontinuity as a phase change has been shown to have important geological implications. *Lovering* [1958] and *Kennedy* [1959] have discussed such a phase change as a mechanism for uplifting or depressing relatively large areas of the earth's surface and have alluded to the pertinence of this mechanism to such questions as the formation of geosynclines, the elevation of plateaus, and the origin and permanence of mountain ranges.

EXPERIMENTAL INVESTIGATIONS BEARING ON THE NATURE OF THE MOHOROVIČIĆ DISCONTINUITY

By Prof. A. E. Ringwood and Dr. D. H. Green
Department of Geophysics, Australian National University, Canberra

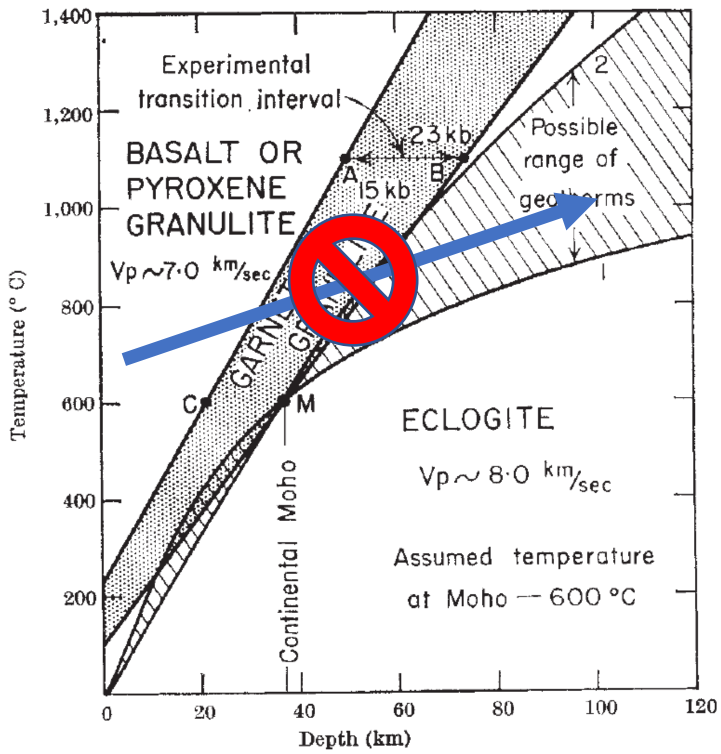


Fig. 1. Stability fields of basalt, garnet granulite and eclogite of tholeiitic composition as defined by (I) direct experimental data at 1,100° C, (II) the assumptions that the Moho is caused by a basalt–eclogite transformation, with eclogite stable beneath the Moho and that the temperature at the Moho is 600° C, and (III) the assumption that the width of the garnet granulite field is proportional to absolute temperature

The growth and assembly of continental crust

Hurley (1962)

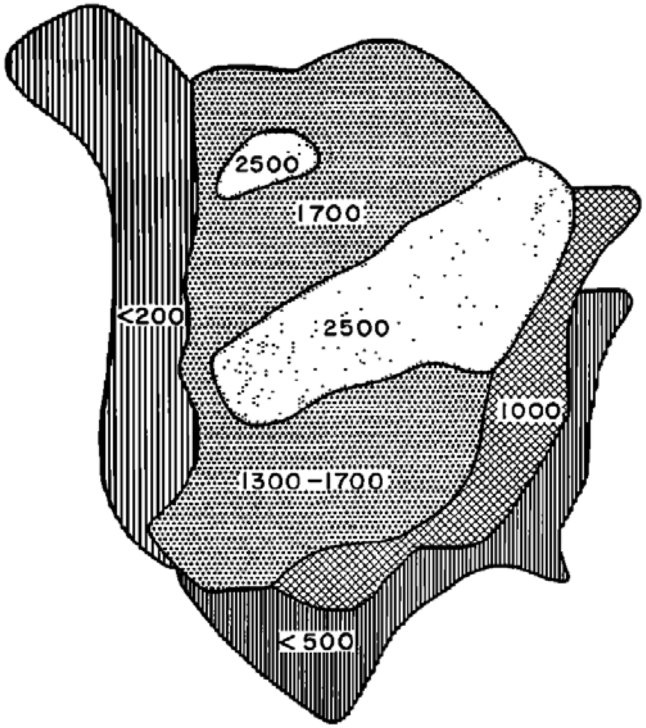


Fig. 2. Approximate relative areal extent of geologic age provinces in North America.

Putting Bullard's fit to good use:
Hurley and Rand (1969)

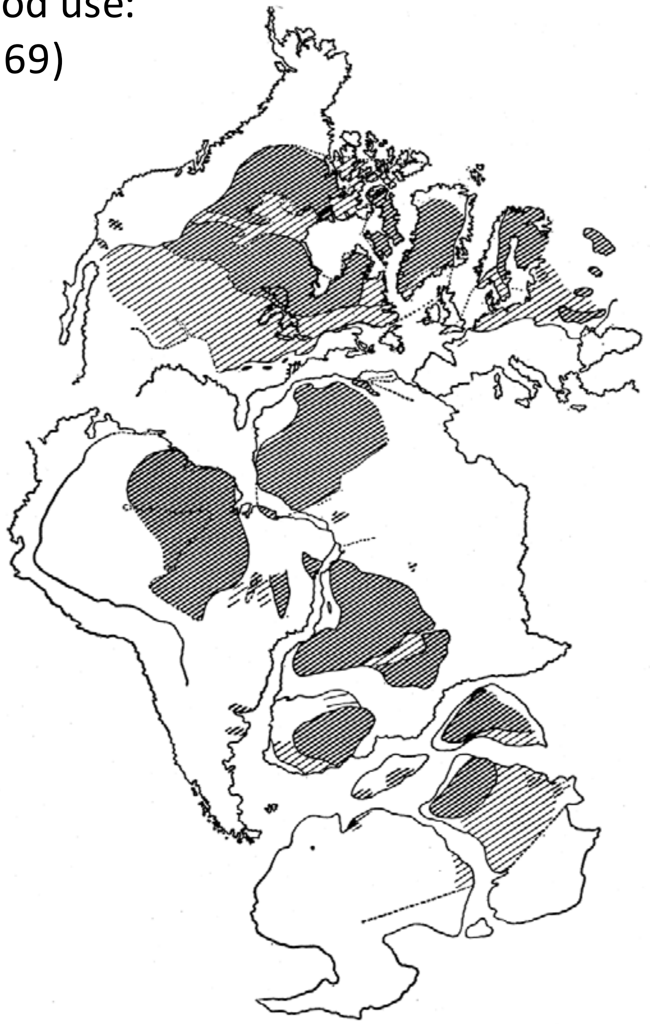
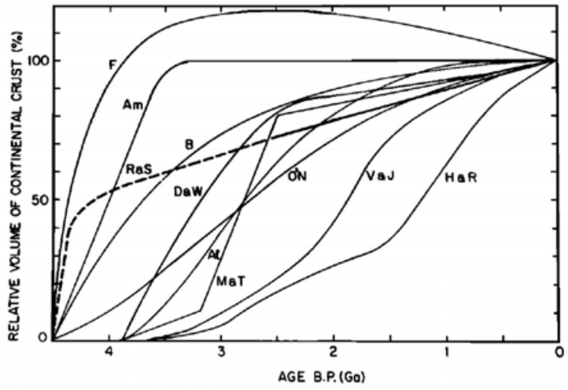
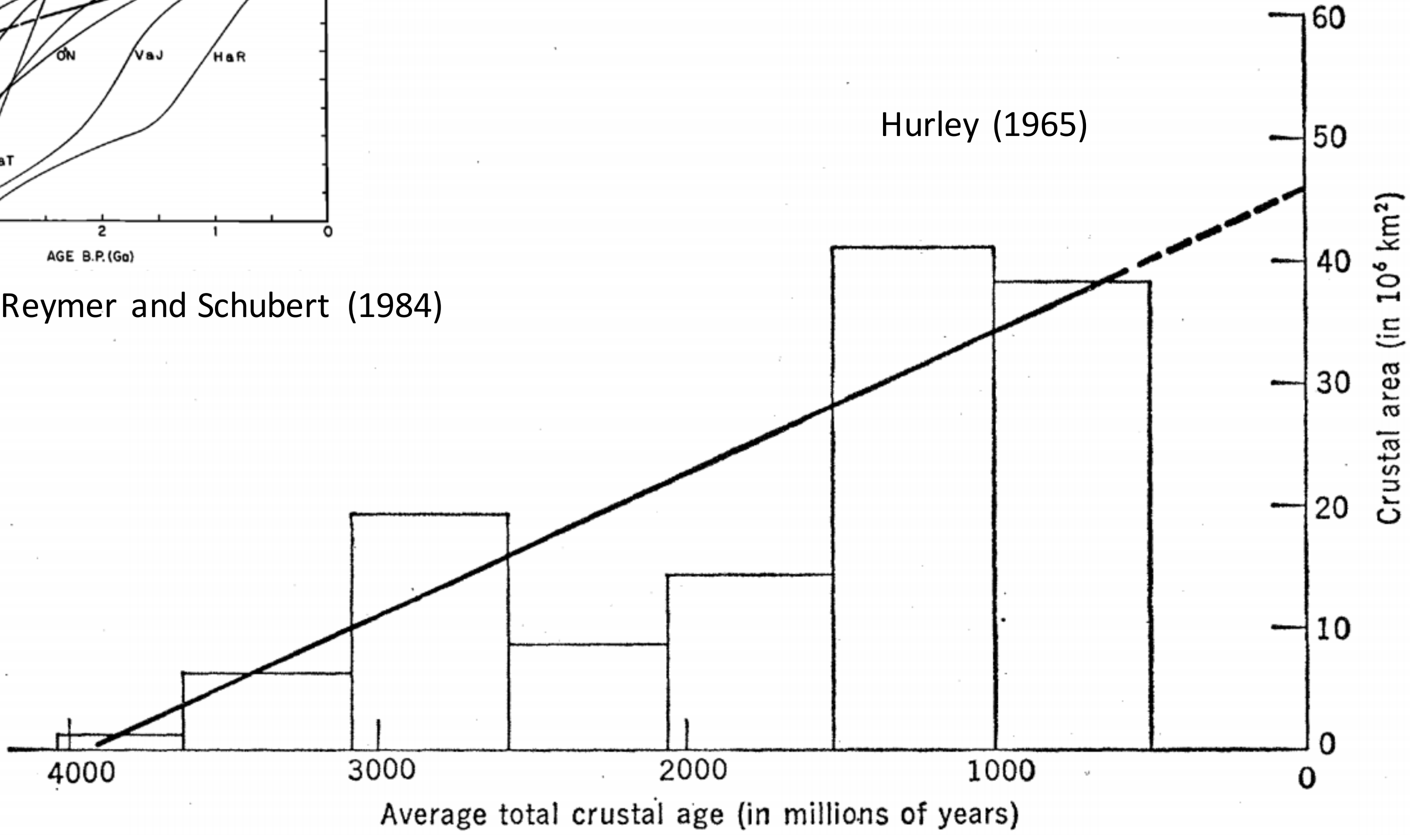


Fig. 8. Continents reassembled in a pre-drift reconstruction. (Lighter hatching) Regions underlain by rocks having apparent ages in the range 800 to 1700 million years; (heavier hatching) regions having apparent ages > 1700 million years. It appears that there are two (or one) central regions of older rocks, transected and totally surrounded by belts of younger rocks. This suggests that there was no significant fragmentation or scattering of the continental nuclei prior to the last great drift episode.

The rate of crustal growth



20 years later: Reymer and Schubert (1984)



Hurley (1965)

Fig. 13. Histogram showing the area of continent underlain by rocks within successive intervals of total crustal age. The total-crustal-age values are the sum of the whole-rock rubidium-strontium isochron age and a crustal prehistory. The differences in the Sr^{87}/Sr^{86} ratios and in the rubidium-strontium ratios for average crust and average earth are used to determine the duration of the crustal prehistory in the block of crust represented in each age interval.

The stubbornly episodic nature of crustal growth: the 'magic' tectonic ages

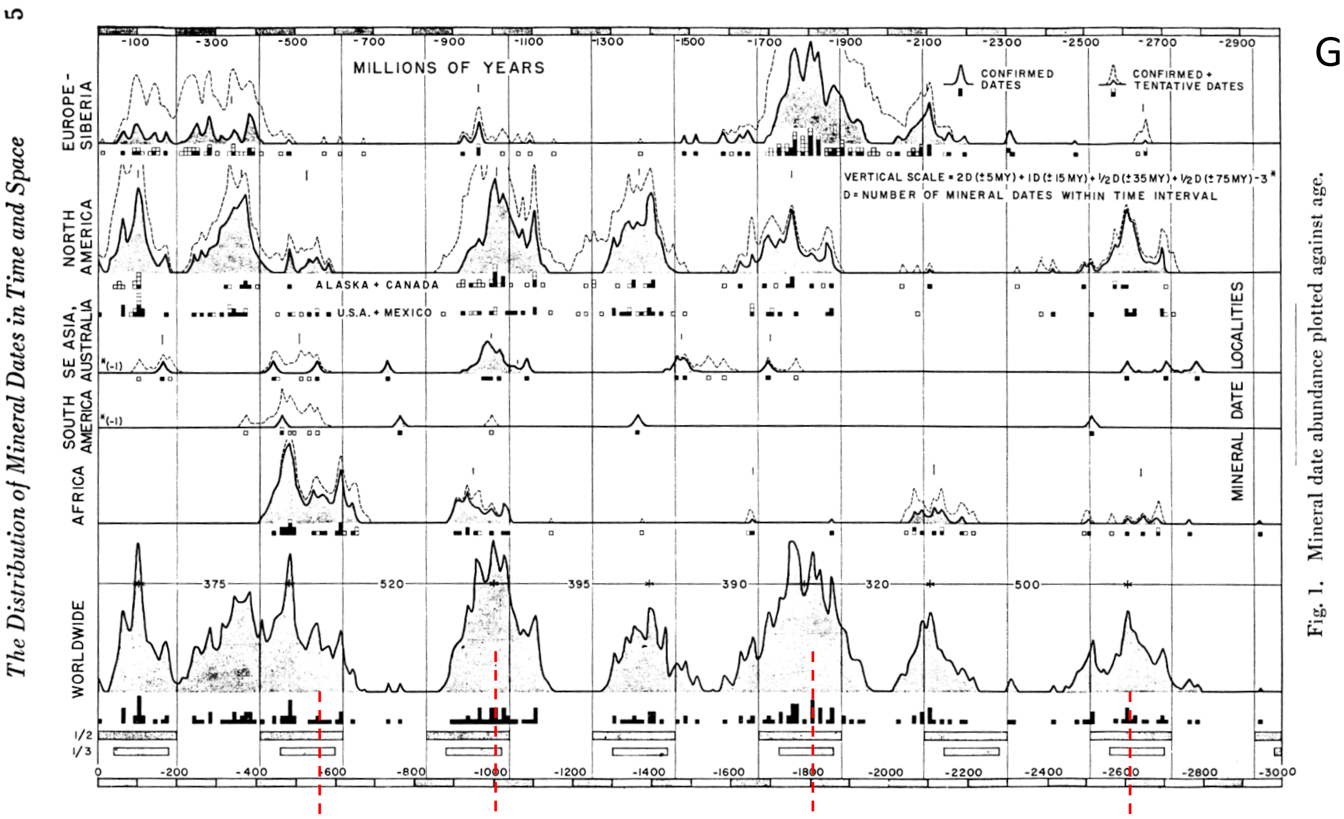
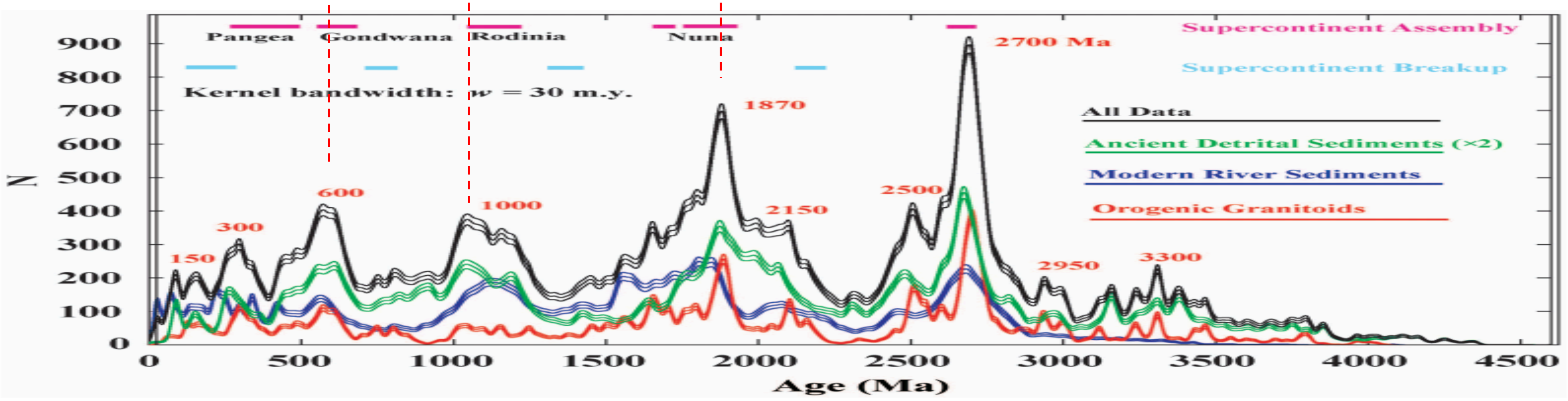


Fig. 1. Mineral date abundance plotted against age.

Gastil (1960)

Selective preservation is clearly not an issue. The overall continuous character of Plate Tectonics is therefore not consistent with episodicity of crustal growth: **deep mantle plumes are the continent makers**.

Condie and Aster (2010)



After dust settled

- Geochemistry is process-oriented (ridges, the basalt dichotomy).
- Radiogenic isotopes add the dimension of time. Geochemistry can look back!
- Radiogenic tracers (Sr, Nd, Hf, Pb) are most powerful at the billion year time-scale, whereas the mean age of the ocean is 65 million years.
- Geochemistry helped resolve some conundrums created by Petrology and Seismology: the Moho is more than a phase change, and so is the 660 km transition zone. The continental crust, the upper mantle, and the lower mantle are geochemically distinct geodynamic entities and have remained so for most of the Earth's history.
- Geochemistry is plumes' best friend.

July 20, 1969: Apollo 11

And yet, most geochemists had their head in the stars!

And many men wound in and out,
And dodged, and turned, and bent about,
And uttered words of righteous wrath,
Because ‘twas such a crooked path;
But still they followed—do not laugh—
The first migrations of that calf,
And through this winding wood-way stalked
Because he wobbled when he walked.

Sam Foss: the Calf-Path