Archean Subduction or Not? Evidence from Volcanic Geochemistry

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including collaboration with Hugh Smithies and David Peate
Plan

Part 1: Theory: Fingerprinting Subduction Volcanism
Part 2: Life Cycles of Volcanic Arcs
Part 3: Identification of Subduction Volcanism in the Palaeoproterozoic
Part 4: Identification of Subduction Volcanism in the Middle to Late Archean
Part 5: Identification of Subduction Volcanism in the Early Archean
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Arc-aeology: Fingerprinting Arc Lavas in the Geological Record

1. Selective element enrichment in the mantle wedge.

2. Distinctive mantle flow pattern constrained by the subducting slab.

3. Effects of high water content on melting of the mantle wedge

3. Effects of high water content in magmas on crystallization history and vesicularity/explosivity
Arc-aeology: Fingerprinting Arc Lavas in the Geological Record

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The best-known and individually most effective subduction indicator is the Nb anomaly. All arc magmas have negative Nb anomalies.

On the Th/Yb-Nb/Yb projection, rocks with negative Nb anomalies plot above an array formed by MORB (mid-ocean ridge basalts) and OIB (ocean island basalts) basalts.
Arc-aeology: Fingerprinting Arc Lavas in the Geological Record

Lavas with no negative Nb anomalies plot in the MORB-OIB array: depleted (MORB) compositions at bottom right, enriched (OIB) compositions at top left.

Arc lavas are displaced from this array to higher Th/Nb

Continental tholeiites often follow diagonal (contamination) trends extending off the MORB-OIB array
Cold subduction vectors are subvertical (Th released but Nb retained in rutile)
Hot subduction vectors are diagonal (Th released but also some Nb because rutile solubility increases with temperature
Th and Nb exhibit similar behaviour during mantle melting. Mantle melting and melt extraction trends are therefore diagonal.
Interaction with continental crust causes arc compositions to move within the volcanic arc array, from the oceanic arc field towards the continental arc field.
Caution: False Subduction Anomalies

Negative anomalies can also be created by **crustal assimilation**, **high-temperature metamorphism**, and by **inheritence** from lithosphere with an old subduction history.
The Th/Yb v Nb/Yb plot provides a representation of the two principal components in the geochemical patterns of altered arc volcanics and provides a good starting point for fingerprinting past arc volcanism.
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Life Cycles of Volcanic Arcs

Birth

Youth

Mid-Life Crises

Maturity

Inheritance

Resurrection

Death
Birth of Arcs

First arc

Protoarc

Ophiolite

From Ishizuka, pers. comm.
Birth of Arcs

First arc

Protoarc

Ophiolite

Western Pacific: c. 8 m.y. from subduction initiation to a stable subduction regime

Developed from Stern and Bloomer (1992)

BRE-Mikazukiyama - Hahajima volcanism

Ind Islands

Fore arc
Birth of Arcs

Increase in subduction contribution relative to mantle contribution with time

Developed from Stern and Bloomer (1992)
Young Arcs

This young arc (Izu: 50 m.y. since initiation) comprises volcanic rocks underlain by a tonalitic layer and then a mafic layer.
Mature Arcs

Andes: 170 m.y. since subduction initiation
Mature Arcs

Yuan et al. (2000) 
Teleseismic study

Thick crust with dehydration and crustal melting at mid-levels, possibly underlain by eclogite

MASH and AFC are key processes
Mid-life Crises

*Flat Subduction*

*Arc-rifting*

*Ridge Subduction/Edge effects*

*Collisions*

*Plume-arc interactions*
Each event has a distinctive effect on arc composition
Mid-life Crises: Slab Windows

Ridge subduction and subduction of young lithosphere (<20Ma) allows melting of the upper part of the subducting crust. This gives an ‘adakitic’ slab melt component (distinctive high Sr/Y due to eclogite fusion). Slab edges, where hot mantle can access the mantle wedge can also lead to slab melting.
Mid-life Crises: Slab Windows

Adakites have especially low HREE (very steep REE patterns), the adakite component has higher Th/Yb and Nb/Yb than a sediment melt component. This, together with side ways mantle flow gives compositions displaced from the normal arcs.
Mid-life Crises: Flat Subduction

Flat subduction leads to a volcanic gap or volcanism distal from the trench. Limited mantle flow and high subduction flux
Mid-life Crises: Seamount and Microcontinent Collisions

Most seamounts get subducted. Collisions typically increase subduction flux and give rise to more potassic lavas. Plateaus are accreted and can lead to reversal of subduction polarity.
Death of an Arc

Banda Arc (Indonesia)
Death of an Arc

Large subduction signal: isotopes indicate fused terrigenous sediments
Arc Resurrection

Delamination model
(Pearce et al., 1990)

Slab Rollback Model
(Keskin, 2005)
Most active volcanoes across Asia are post-collisional, the result of resurrection of earlier subduction zone components.
Post-collision magmas erupted at the site of the ‘dead’ arc have subduction signatures.

Post-collision magmas erupted where there was no arc have intraplate signatures (with or without crustal assimilation).
Inheritance

Many of the world’s LIPs have inherited subduction signatures that can be traced back to older subduction events that have led to lithosphere enrichment.
Inheritance

The oldest basalt unit (Pitanga) was derived from the greatest depth in the lithosphere (90-120 km), melting relatively fertile, anhydrous peridotite. The magma source became gradually shallower with time, with the Gramado basalt unit reflecting shallow-level magma generation (< 60 km), melting relatively refractory and hydrous peridotite. Asthenospheric material only becomes clearly recognisable in the youngest unit (Esmeralda), once extension has proceeded to the extent that decompression of the asthenosphere can take place.

Paraná) are virtually aphyric (<5% phenocrysts) with low incompatible element contents (e.g., Zr <400 ppm), high δ18O (~+10‰ in pyroxene) and high 87Sr/86Sr of 0.714–0.727. Analyses of selected Paraná rhyolites are listed in Table 2. Calculated eruption temperatures for both types are unusually high for silicic magmas (950–1100°C [Bellieni et al., 1986; Garland et al., 1995]).

Low-Ti lavas from the Parana flood basalt terrane have arc-like signatures, the result of remobilizing sub-continenental lithospheric mantle of probable Proterozoic age (Fig from David Peate)
Key Point

Present-day arcs are highly variable in space and time with expected stratigraphic variations. This needs to be factored in to any attempt to interpret past volcanic arcs.
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The Palaeoproterozoic is possibly the earliest record of ‘modern-day’ subduction processes in which complete life cycles of arcs can be recognised.
Trans-Hudson Belt

Short-lived oceanic arc in the Trans-Hudson Suture. Flin Flon (northern Manitoba): similar sequence to Bonin arc, but at 1.9Ga.
Trans-Hudson Belt
Trans-Hudson Belt

Trans-Hudson Belt (c. 1.9 Ga)
Flin Flon

Calc alkaline (c. 1890-1865 Ma)
Calc alkaline (c. 1905-1890 Ma)
Tholeiite-boninite (c. 1905-1900 Ma)
MORB/OIB (c. 1905 Ma)

Th/Yb vs. Nb/Yb plot

Hanson L. (1905 Ma)
W. Amisk (1905 Ma)
Flin Flon (1905 Ma)
Snow Lake (1905 Ma)
Trans-Hudson Belt

[Graph showing Th/Yb vs Nb/Yb ratios with various data points and labels indicating different geological features and time periods such as Calc alkaline (c. 1890-1865 Ma), Tholeiite-boninite (c. 1905-1900 Ma), MORB/OIB (c. 1905 Ma), etc.]

Izu-Bonin

[Graph showing Th/Yb vs Nb/Yb ratios with various data points and labels indicating different geological features and time periods such as First Arc, Protoarc, Spreading, etc.]
Trans-Hudson Belt
Early Basin and Range samples have arc-like chemistry and model ages of 1.9Ga Inherited from the Trans-Hudson Belt
Present-day style subduction and volcanic arc growth extends back to at least 1.9 Ga. A key question is whether or not there was a dramatic change in global tectonics between that time and the Archaean.
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Archean Subduction or Not?

Four types of model:

1. **Archean Subduction, Uniformitarian, model**: subduction as we know it throughout geological time

2. **Archean Subduction, non-Uniformitarian, model**: some form of subduction, but different from that at the present day (though there may be present-day analogues)

3. **No Archean Subduction**. Heat-loss dominated by plume activity; other methods of crustal recycling (e.g. delamination) give any apparent subduction characteristics.

4. **Intermittent (Stop-start) Subduction**. Subduction interspersed with episodes with no subduction
The Smoking Guns

**Igneous:** Arc volcanic and plutonic rocks

**Metamorphic:** Blueschist and eclogite facies

**Sedimentary:** Accretionary complexes

**Structural:** Horizontal tectonics

**Mineralogical:** Diamonds with low $\delta^{13}C$ signatures; inclusions in zircon of minerals requiring subduction (high P/T) conditions

The volcanic record is potentially the most significant because:

1. The volcanism can give the age and location of the subduction zone;
2. The stratigraphy provides information on the geological setting and evolution of the subduction zone;
3. The geochemistry provides information on the thermal and tectonic characteristics of the subduction zone
Pilbara Terrane
Pilbara Terrane

Made up of the East Pilbara Terrane, the West Pilbara Terrane and the Mallina Basin, overall giving a 500 m.y. volcanic stratigraphic record from c. 3.5 to 3.0Ga. See papers by Hugh Smithies for full details.
East Pilbara Terrane: Pilbara Supergroup

Yellow = felsic
Green = basic
Purple = komatiitic
Pilbara Supergroup

Typical continental tholeiites (crustally-contaminated)
Pilbara Supergroup

Evolved volcanics extend the crustal assimilation trend.
Pilbara Supergroup

Most likely model. Note the remarkably small mantle variation for 300Ma of volcanic activity.

A separate subduction-related origin for basic and evolved lavas still needs disproving though.
West Pilbara Terrane; Whundo Group

- Siliceous high-Mg basalt and other LREE-enriched basalts (3.0-2.95 Ga)
- High-Mg diorites (sanukitoids) (~2.95 Ga)
- 3.12 Ga Whundo Group

Western zone where Nd model ages are typically similar to the magmatic age of the Whundo Group (western limit of old ‘east Pilbara’ crust)

Scale: 100 km
West Pilbara Terrane; Whundo Group

Identified by Smithies et al. as a potential Archean arc sequence.

Wide range of magma types:

- Tholeiites (T)
- Boninites
- Calc-alkaline rocks (CA)
- Rhyolites
- Nb-enriched basalts (NEB)

3115-3135Ma
Pilbara Whundo Group

Identified by Smithies et al. as a potential Archean arc sequence. But is it? There are two options on this projection.
Pilbara Whundo Group

**Explanation 1:** Similar to the Pilbara Supergroup – interaction between magma and crust with no subduction Influence.
Pilbara Whundo Group

**Explanation 2:** The boninitic and calc-alkaline rocks (at least) are derived from a subduction-modified mantle.

The tholeiites may be continental tholeiites (as in the E. Pilbara) or have a small subduction component.
Pilbara Whundo Group

To discriminate between the two explanations, we need to consider fractionation as well as Nb anomaly
Evolved arc lavas should extrapolate back into the arc basalt field
Pilbara Supergroup Revisited

East Pilbara BADR sequence are best explained the result of interaction between basic magmas and crustal melts.
Pilbara Whundo Group Revisited

The trend formed by the boninitic and calc-alkaline lavas extrapolates back into the arc field, confirming the Smithies et al. hypothesis for an arc origin.
Pilbara: Subduction v Non-subduction

Is subduction the only option? No, but it is much the most likely. Alternatives are:

* Extreme contamination at the base of the crust  
  (expect less than in the Pilbara Supergroup when magma was komatiitic)
* Mantle-delaminated crust interaction  
  (not obviously consistent with the subduction vector on the Th-Nb plot)
* Archean-specific process not yet considered
Pilbara: Nature of the Possible Subduction Component

Numerical modelling assuming a dominantly sediment source of any ‘SZ’ component does not require a particularly high temperature for derivation of the component. Here a MORB mantle source gives c. 800°C, but the more likely undepleted mantle gives c. 650°C.
Pilbara: Nature of the Possible Subduction Component

Zegers & van Keken (2001)

Subduction component too low temperature and insufficiently basalt-derived for a delamination model. Much more like conventional subduction.
Pilbara: Mallina Basin

- Siliceous high-Mg basalt and other LREE-enriched basalts (3.0-2.95 Ga)
- High-Mg diorites (sanukitoids) (~2.95 Ga)
- 3.12 Ga Whundo Group

Western zone where Nd model ages are typically similar to the magmatic age of the Whundo Group (western limit of old 'east Pilbara' crust)

Scale: 100 km
Sedimentary basin setting but with a clear subduction signature.

Interpret as an inherited signature, confirming that the mantle beneath Western Pilbara was modified by the earlier subduction event.
Superior Province
The Superior Belt also has extensive non-subduction volcanism predating a short episode of arc volcanism.
Younger Lamprophyres of the Superior Province also require modification of the lithosphere by an earlier subduction episode to explain their geochemistry.
There are two types of BADR (basalt-andesite-dacite-rhyolite) sequences in the Middle-Late Archean: one plume-related, the other subduction-related. The subduction events may be short-lived and mark the ends of long periods of plume activity.
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Early Archean Terranes: Two Locations

Isua, Greenland

Nuvvuagittuk, N. Canada
Early Archean Subduction?

Implications of the Nuvvuagittuq Greenstone Belt for the Formation of Earth’s Early Crust

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Heading down early on? Start of subduction on Earth

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Geochemical Fingerprinting of the Earth’s Oldest Rocks

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Nuvvuagittuq

Low-Ti Enriched
Low-Ti Depleted
BIF
High-Ti

O’Neil et al (2011) lava stratigraphy

Note: 9Km² total exposure
Nuvvuagituq: Turner et al. Interpretation

- **Nuvvuagittuq (4400-3800 Ma)**
  - **low-Ti enriched (calc-alkaline)**
  - **low-Ti depleted (boninites)**
  - **BIF**
  - **high-Ti (tholeiites)**

- **Trace element patterns**
  - Enriched LILE negative HFSE anomalies
  - Strongly depleted HFSE-REE patterns
  - Flat HFSE-REE patterns

- **IBM forearc (52-44 Ma)**
  - **arc andesites**
  - **hydrothermal boninites**
  - **forearc basalts**

- **Interpretation**
  - Mature subduction produces typical calc-alkaline volcanics
  - Onset of subduction and fluid release remelts shallow refractory residue in asthenosphere
  - Hydrothermal fluid - seawater interaction (black smokers)
  - Fracturing of oceanic plate leads to decompression melting of asthenosphere
Nuvvuagituq: O’Neil et al. (2011) Plot
Misinterpretation of Subduction Zones: Amphibolite-facies Metamorphism

HT fluids/melts from sediments impregnated and metamorphosed the lavas.

The result is that some normally-immobile LIL elements (e.g. Th) are enriched.

Broken Hill
Nuvvuagituq: My Interpretation

The two lowest units are dominated by HT alteration; but the uppermost unit could be subduction-related.
Key Point

The oldest volcanic exposures have been extensively modified by HT fluids carrying Th and some other ‘immobile’ elements. Nonetheless the uppermost unit from Nuvvuagutuq may be subduction-related
**Archean Subduction or Not?**

1. No problem in identifying modern subduction processes back to c. 2Ga

1. There is good evidence for subduction at c. 3.2Ga (Pilbara) and 2.7Ga (Superior). These appear to be short lived events, though, following a long period of plume activity. Inherited subduction signatures in later lavas strongly support this model.

2. The earliest volcanic sequences in Isua and Nuvvuagituq have compositions masked by element mobility during high-grade metamorphism. The upper lava unit at Nuvvuagituq has a significant probability of having a subduction origin.
Venus Analogue?

Hamilton's view of the Archean: unimodal topography rather than bimodal (oceans and continents)