The Oldest Pillow Lavas, 3.8–3.7 Ga from the Isua Supracrustal Belt, SW Greenland:
Plate Tectonics Had Already Begun by 3.8 Ga

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Abstract

The presence of pillow basalts in the 3.8–3.7 Ga Isua supracrustal belt, Southern West Greenland indicates the presence of liquid water on early Earth around 3.8–3.7 Ga. The total thickness of pillow basalts is up to 1.0 km for the thickest unit, suggesting an ocean depth of at least 1.0 km. The rigidity of the Early Archean oceanic lithosphere can be calculated from the petrologically estimated mantle potential temperature of 1450°C and ocean surface temperature below 100°C. The results show that the oceanic lithosphere was sufficiently rigid to operate modern-style plate tectonics only 0.7–0.8 Ga after the formation of the Earth.

Key words : plate tectonics, oldest pillow lava, Early Archean, rigidity calculation, Isua belt

I. Interpretation of Outcrop

The Isua supra-crustal belt, approximately 150 km NE of Nuuk, Greenland (Fig. 1), occurs as an enclave with an ovoid shape 10 × 25 km in size in the Akulleq terrane of the oldest geologic units dating back to 3880–3660 Ma Amitsoq gneiss and 2820 Ma Ikkattoq gneiss (Friend et al., 1987; Nutman et al., 1989; Komiya et al., 1999). With two coworkers, we made the geologic map of the Isua supracrustal belt over two months in 1991 and 1992; the details were reported first by Maruyama et al. (1991) with more details from Komiya et al. (1999).

The best photograph of pillow lava is shown in Fig. 2. Five pillows captured in the image are fringed by dark-colored chilled parts on each pillow. The approximate size of pillows in this region is 30 cm × 50 cm with the cross-section vertical to the elongated axis of a pillow tube. The matrices among pillows and outermost margin are both characterized in white, indicating fine-grained fragments of basaltic glass in origin including small amounts of carbonate. The outcrop is underlain by epidote-amphibolite facies grade of
regional metamorphism presumably at 2.6–2.8 Ga or much earlier, although this is debated (Nutman et al., 1989; Komiya et al., 1999).

Enormous amounts of pillow basalts occur in the entire region of the Isua belt, and are metamorphosed and tectonically deformed and flattened under greenschist and epidote-amphibolite, to the upper amphibolite facies of the regional metamorphism. The metamorphic grade increases southward (Komiya et al., 2002).

II. Significance 1: Pacific-type orogeny began at least 3.8 Ga ago in the intra-oceanic environment

The associated rocks of pillow lavas are massive sheet flows, basaltic dikes, and sills, all of which are related to thick piles of pillow, komatiitic lava flows, bedded cherts, mafic, and pelitic sediments with minor conglomerate. These rocks are not randomly distributed, but form a unit called horse shown by ocean plate stratigraphy (OPS) and occur as duplex-type tectonic duplication. For example, the southern Unit of the Isua region is underlain by eight units of horse (fault-bounded slice) with a particular OPS (Fig. 3).

The duplex-type structure with OPS indicates the presence of the oldest accretionary complex formed in an intra-oceanic consuming plate boundary at 3.8–3.7 Ga. The strong lateral shortening underthrusts the oceanic lithosphere from north to south and structural top to the bottom over time (Fig. 4). The process is almost identical to the on-going subduction front around the circum-Pacific subduction zone, as well as the circum-Pacific orogenic belts in the Phanerozoic. The subducted and underplated materials are composed of fragments of oceanic materials capped by trench-fill turbidites dominated by mafic sediments in Isua. The horse II contains komatiitic rocks as fragments within bedded chert sequences not directly above MORB (Fig. 4). Komatiite is not formed at the mid-oceanic ridge but by an off-ridge process presumably by a hotspot OIB.

These accretionary complexes were penetrated by TTG magma a few tens of millions year or 100 m.y. subsequently, and are related to the advancement of the volcanic front oceanward over time. Thus, the Pacific-type orogeny had been operating dating back to 3.8–3.7 Ga in an oceanic environment similar to the recent Western Pacific domain (Miyashiro et al., 1982; Maruyama, 1997).

III. Significance 2: Mantle temperature and composition at 3.8 Ga

Discrimination diagrams of volcanic rocks on modern Earth are not appropriate to estimate the composition and temperature of the mantle because they differ between the Archean and modern Earth. To overcome this difficulty, identifying the OPS is a unique key to resolving the issue. The stratigraphic bottom of the OPS must be mid-oceanic ridge basalt, whereas the
Fig. 3a
igneous rocks inserted within the pelagic bedded cherts conforming as slices, sills, or lava flows must be OIB in origin as shown in Fig 4. TTG volcano-plutonic sequences overly or intrude the accretionary complex at the latest stage of orogeny.

Systematic chemical analyses of major elements and trace elements, including REE, were performed by Komiya et al. (2004). The results are summarized below. Archean MORB is low-K tholeiite 2–3 wt% more FeO-enriched. The Archean OIB is not alkaline, komatiite and related rocks with high-Mg andesite or REE-flat basalts made by a higher degree of partial melting of FeO- and H2O-enriched source mantle. Early Archean MORB-source mantle was 150–200 K higher in temperature (Komiya, 2004).

**IV. Significance 3: Rigidity of 3.8 Ga oceanic lithosphere**

Evidence of the accretion of oceanic materials by the strong lateral shortening mentioned above indicates successive underthrusting of the oceanic crust and overlying sediments. It, however, does not necessarily prove that modern plate tectonics were actually at work, in a strict sense. The rigidity of the oceanic lithosphere must be considered. Some workers considered that a hybrid of plate and plume tectonics operated in Early Archean (Head and Crumpler, 1990, also see a recent review by Condie and Kröner (2008)).

The oceanic geotherm of the Early Archean lithosphere can be calculated with a model of
Fig. 4  Travel history of Early Archean oceanic lithosphere reconstructed from Fig. 3. This figure shows the paleogeographic reconstruction of the accretionary complex documented in Fig. 3b (bottom left), which was followed by successive underthrusting of the oceanic crust to form a series of duplex VIII to I over time. Numbers of horses correspond to Fig. 3b (bottom left) (Komiya et al., 1999).
transient half-space cooling as a function of age (Turcotte and Schubert, 1982). Source mantle temperature and surface temperature were 1450°C and 100°C, respectively. The corresponding temperatures of modern Earth are 1330°C and 0°C, and for Venus are 1450°C and 470°C. In addition, the transition temperatures of brittle-ductile for peridotite and metabasite are calculated as a function of pressure for a given steady-state strain rate of $10^{-14}$ s$^{-1}$ (Hoffman and Ranalli, 1988). Details are given in Komiya et al. (1999). The results are reproduced in Fig. 5.

Fig. 5 Rigidity of surface boundary layers (plate thickness) at 3.7–3.8 Ga (after Komiya et al., 1999). (a) Geothermal gradients of oceanic lithosphere for Early Archean Earth and present-day Venus. Also shown are brittle-ductile transition temperatures for metabasite and peridotite in a P-T space. Numbers on the line mean time in millions of years after the birth of the lithosphere. (b) Strength profile of oceanic lithosphere on modern Earth with 7 km MORB crust, (c) same profile of the Early Archean Earth with 15 km thick MORB crust, and (d) same profile as present-day Venus. For more detailed information, see Komiya et al. (1999).
The estimated structure of the oceanic lithosphere in Early Archean Earth indicates that the lithosphere older than 20 million years behaves rigidly, while the younger one has a ductile basaltic zone between brittle basaltic crust and ductile mantle peridotite (Fig. 5). It should be noted that the young oceanic crust is cooled efficiently by active hydrothermal fluid circulation at the mid-oceanic ridge. This suggests that the Early Archean oceanic lithosphere had hardened enough to operate plate tectonics, because of efficient freezing at mid-oceanic ridges, analogous to the modern ridge-hydrothermal system.

The thickness of the lithosphere is calculated to be about 80% thinner at a given age than today (Fig. 5).

References


38-37億年前のグリーンランド・イスア表成岩帯にみられる
世界最古の枕状溶岩

—プレートテクトニクスは38億年前にはすでに始まっていた—

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グリーンランド・イスア地域は緑色片岩・角閃岩相程度の広域変成作用を受けてはいるが、見事な枕状溶岩の構造を普遍的に残している。枕の形、急冷縁、マトリックスの構造などが明瞭に残存している。枕状溶岩の存在は38億年前に海洋がすでに存在していたことを示すが、さらに付随する岩石との関係から、典型的な付加体の存在が認められる。海洋プレート層序は付加体が現在の西太平洋地域のような海洋内島弧の一部として形成されたことを示す。付加体の形成は北から南側にプレートが沈み込んだことを示す。さらにCA系列の花崗岩帯が付加体を貫く。これらは太平洋型造山運動が38-37億年前に機能していた証拠である。玄武岩の化学組成から、起源マントルの組成と温度が推定される。海洋の温度を100℃以下とみなすと、38-37億年前の海洋プレートの剛性度とプレートの厚さが求められ、プレートテクトニクスが38億年前にすでに機能していたことがわかる。

キーワード：プレートテクトニクス、世界最古の枕状溶岩、太古代前期、剛体度の計算、イスア表成岩帯

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