Volcaniclastic Petroleum Systems – Concept and Examples from Indonesia[1]

by Bernhard W. Seubert[2]

ABSTRACT: Arc-related volcanism has been active in Java since the Eocene, producing primary volcanic rocks and thick volcaniclastic sequences that serve as reservoir for at least one commercial gas accumulation. Porosity prediction in volcaniclastic reservoirs remains problematic. However, volcaniclastic deposition can also promote hydrocarbon maturation in marine settings.

In restricted marine environments, volcaniclastics act as a fertilizer to stimulate organic growth, causing algal blooms and elevating the total organic carbon (TOC) of marine sediment (e.g., the Eagle Ford shale, Texas, USA). Furthermore, zeolites are common decay products in volcaniclastics that can act as catalysts to accelerate the maturation of source matter. The result is a self-sourced petroleum system that could exist in large, and as yet under-explored, areas in Java and elsewhere on Sundaland.

In this paper presents data from several tested or producing gas wells that support the concept of volcanic-enhanced petroleum systems. Despite indisputable problems with respect to the predictability of reservoir quality, the proximity to a growing energy market and available infrastructure makes Indonesian volcaniclastic gas plays worth further pursuit.

Keywords: volcaniclastic, andesite, zeolite, algal bloom, secondary porosity, maturation.

Introduction

Terminology: For the purpose of this paper everything, except solid volcanic lava flows will, be lumped together here under the generalizing term 'volcaniclastics'. This includes the whole range of volcanic-derived sediments such as pyroclastic of any kind, ashes, ash-flow deposits, lahar, ignimbrites, tuff (vitric and crystal), hyaloclastics, etc. Obviously, fractured basement and weathered granite is not part of this consideration. Figure 1 summarizes the sedimentary processes involved.

Sedimentary responses to volcanic eruptions depend on a complex interplay between the volume, nature and distribution of the pyroclastic material, the physiography and hydrology of the affected environment, its energetic conditions, the availability of accommodation space and temporal effects.

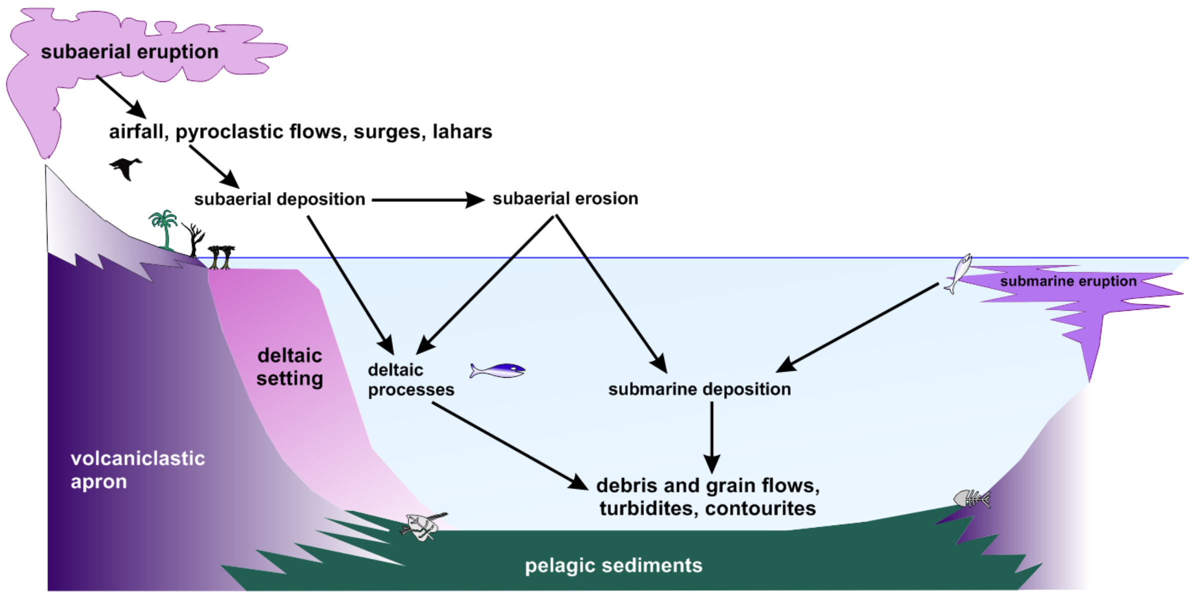

Figure 1: Sedimentary volcanic processes (redrawn and modified from Carey, 2000, quoted from Manville, 2009).

1 A similar version of this paper has been presented and published in the **Proceedings of the 39th Annual IPA Convention & Exhibition, Jakarta, May 2015** under with the title “Volcaniclastic Petroleum Systems – Theory and Examples from Indonesia” (digital paper IPA-15-G026). In addition to the published version, this PDF here includes the some of the figures which have been used to present this paper during the convention. Changes and edits have been made to the body text – and the title. Please note also the copyright note at the end of this document.

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2. Processes

2.1 Source Potential and Maturation

Volcaniclastic input into stagnant oceans increases the supply and preservation of organic matter (Zimmerle, 1985; Jin et al., 1999). The contribution of volcanic material to source potential has been underrated because of: (1) a paucity of exploration in volcanic basins; and (2) the lack of volcanic components in Cretaceous and older rocks, in which the metastable minerals and vitric material has long since decomposed.

Volcanic activity contributes to organic source potential in several ways.

- The input of volcanic ash and dust into a marine basin acts as a fertilizer to promote algal bloom (Magara, 2003). The lower Eagle Ford gas shale (Texas, USA) includes tuff layers that may have enhanced organic growth (Workman, 2013; Pierce et al., 2014).
- Volcanic input into the marine environment creates ephemeral anoxic conditions that lead to the mass extinction and preservation of plankton and benthos.
- Volcanic ash decays readily to clay minerals, which can act as catalysts for transformative reactions of kerogen, the source material into hydrocarbons (Horsfield and Douglas, 1980; Jin et al., 1999).
- *Source rock*: Volcanics input into proximal marine embayments and low-energy shallow waters. This would immediately kill most living organic material but also preserve organic matter from oxidation. The volcaniclastic input serves also as a nutrient to the marine biota.

2.2 Maturation

Surface active materials such as clays and zeolites can act as *catalysts* in reactions to transform organic matter to hydrocarbon. In the case of volcaniclastics, catalysts are zeolites, the weathering products of feldspar and/or volcanic glass (i.e., vitric tuff). Zeolites facilitate the decomposition of organic matter and the expulsion of mature hydrocarbon at a lower temperature than conventional source–temperature models predict (Jin et al., 1999; Liu et al., 2012). In downstream petrochemistry, the use of zeolites as a catalytic cracker has long been established and an analogous subsurface process is plausible.

The catalytic roles of metallic compounds such as pyrite have also been considered (Reuter and Perdue, 1977; Manggo, 1992; Liu et al, 2012). In the Monterey Formation (California, USA), early maturation and hydrocarbon generation associated with unusually low vitrinite reflectance was attributed to high concentrations of pyrite as a catalyst (Petersen and Hickey, 1987).

Thermal feedback is another potential impact of volcaniclastic diagenesis on the maturation of source rock. Hydration reactions during shallow diagenesis are strongly *exothermal* (Surdam and Boles, 1979). Theoretical calculations (*ibid.*) demonstrate that if all feldspar in a typical volcaniclastic sandstone is hydrated to zeolites, and if heat is conserved, the temperature of the rock will rise by approximately 45°C. However, this prediction has not been verified using field data.

Not all gas accumulations in volcaniclastic reservoirs are thermogenic or biogenic. Abiogenic methane from degassing of the mantle can occur (Liu et al., 2012), and can be distinguished from biogenic gas based on helium and the carbon isotope ratios.

Notably, the thermal contribution from hot volcanic material is practically negligible for the maturation of organic material for the Tertiary Sundaland volcaniclastic gas plays, although intrusives elsewhere have altered the maturity profiles of proximal source rock (see summary in Schutter, 2003).

2.3 Reservoir

Volcaniclastics have long been disregarded as economic hydrocarbon reservoirs. Low porosity in volcaniclastic rocks occurs when pore space is clogged by clay, a decay product of tuff, and/or filled by calcite, an alteration product of plagioclase. Nevertheless, commercial volcaniclastic hydrocarbon accumulations in Kamchatka and the Caucasus have brought attention to this play concept in recent decades. The Kamchatka reservoir is remarkably similar to that in Java: Oligocene to middle Miocene volcaniclastic rocks with 21% porosity, 5–11 mD permeability, and temperatures of 80°C at a depth of 1 km (Levin, 1995). Additional volcaniclastic reservoirs include the Songliao Basin in NE China (Feng, 2008), the Samgori Field in Georgia (Dan, 2012), Java (Willumsen and Schiller, 1994), Japan (Magara, 2003), Argentina (Sruoga et al., 2004; Sruoga and Rubinstein, 2007), and Venezuela (Landes et al., 1960).

Primary porosity in volcaniclastic reservoirs can be relatively high, depending on the volcanic processes at work (e.g., a non-welded ignimbrite with well-developed gas pipes; Sruoga and Rubinstein, 2007). Secondary alteration, such as the decomposition of tuff materials to clay, can decrease porosity. However, some dissolutive and/or fracturing processes common to volcaniclastic rocks can enhance porosity and permeability (Sruoga and Rubinstein, 2007).

2.4 Diagenesis and Porosity

2.4.1 Diagenesis

The various diagenetic processes that can affect the porosity of subsurface volcaniclastics (see reviews in Surdam and Boles, 1979 and Mathisen et al., 1991) are outlined below.

- The formation of clay rims by the devitrification of non-crystalline tuffaceous matter.
- Carbonate cementation, typically from the alteration of plagioclase. Calcite cementation can occlude the framework grains and inhibit further diagenesis.
- Albitization of plagioclase and subsequent alteration to zeolite. Also, the alteration of vitric tuff to zeolites. These hydration reactions are strongly exothermal.
- Dehydration of zeolites. (i.e., heulandite to laumontite, analcime, albite, or prehnite).

The alteration to zeolite minerals (e.g., stilbite, heulandite, laumontite, pumpellyite, and phillipsite) plays a key role in the diagenetic sequence of events, from the modification of framework grains to the generation and/or obliteration of secondary porosity. The production of zeolites during diagenesis, within a wide range of parameters, appears not so dependent on the chemistry of detrital framework minerals (Remy, 1994) as it is sensitive to pressure, temperature, pH, and ions in the formation water (Ratterman and Surdam, 1981).

2.4.2. Porosity

Many continental volcaniclastics, such as tuffs and ash deposits, have good primary porosity. However, this porosity is often reduced during early diagenesis when unstable volcanic components alter rapidly to pore-filling phases like clays and carbonate cements. Most minerals are metastable in the subsurface zone, and exist within stability fields defined by the chemistry of the formation waters and coexisting minerals, as well as pressure and temperature.

Successful exploration of volcaniclastic plays therefore depends on a full understanding of the processes affecting the development of secondary porosity (not including that derived from fractures). These processes are summarised below.

- Minor changes in pore-water chemistry can cause deviations from a diagenetic model and the generation of unexpected alteration products. Further uncertainty regarding paleo-heat flow, heat transfer, and pressure anomalies in the formation caused by tectonic events can affect diagenetic models.
- Porosity enhancement occurs also at greater depths if there are tectonic perturbations (i.e., regional stress; Mathisen et al., 1991). In particular, thermal convection can enhance mass transport through fractures, moving formation water into, or away from, the reservoir (Remy, 1994).
- Dissolution by organic compounds or CO_2. Surdam et al. (1984) determined that carboxylic acids, produced during kerogen maturation, facilitate the dissolution of aluminosilicate minerals (i.e., feldspars). Gautier and Claypool (1984) highlighted other aspects of diagenesis in the presence of CO_2 and organic material. [Please consider a more specific explanation of the Gautier and Claypool (1984) results here.] Hawlader (1990) described a volcaniclastic reservoir where the porosity was significantly enhanced by CO_2-leaching from migrant formation waters.

Although the experimental and theoretical frameworks are compelling, the problem of mass transport in dissolution models is more difficult. To generate a certain amount of secondary pore volume, a comparable volume of material must be dissolved and transported away, where a portion will re-precipitate (e.g., Surdam et al., 1984; Surdam et al., 1985, or Prochnow, et al., 2006). Thyne (2001) and Thyne et al. (2001) have partially addressed the combined problem of mass transfer and compositional controls on the development of porosity and pointed out the problem of volume and solution transport.

2.5 Additional Storage Potential by Means of Adsorption to Zeolites

By definition, unconventional gas resources are those contained in reservoirs in which the reservoir fluids do not follow the Boyle–Mariott pressure–volume relationship for ideal gases. Early theoretical work by Langmuir (1916) and Freundlich (1926) showed that unconventional reservoirs have such miniscule pores that near-molecular forces become an important consideration.

Additional hydrocarbon storage exists by means of adsorption to carbonaceous matter or zeolites (Figure 2) and should be included in gas reserves estimates. Zeolites are a common constituent of reservoir rock in Java (Willumsen and Schiller, 1993) and elsewhere (Ijima, 2001) and can store substantial volumes of methane by adsorption (Hayhurst, 1980). The adsorption capacity of zeolites is about 30% (by weight), depending on the specific zeolite mineral. One ton of zeolite could adsorb roughly 300 kg of methane, a significant volume that would not be included in conventional volumetric assessments.

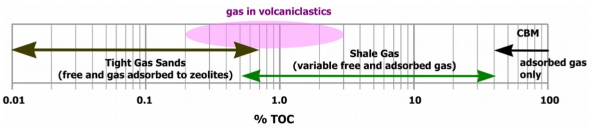

Figure 2: Relationship between total organic carbon (TOC) and amount of free versus adsorbed gas.(Redrawn and modified fromMiller, 2010). Then pink ellipse shows the approximate TOC range of the tight-gas play in the type of volcaniclastics discussed.

Carbonaceous matter and zeolites can also adsorb substantial volumes of CO_2 and may offer a viable mode of carbon sequestration in depleted volcaniclastic reservoirs.

3. Petrophysical Aspects

The petrophysical evaluation of volcaniclastics is similar to that for conventional reservoirs and is well documented (Khatchikian, 1983; Vernik, 1990; Schutter, 2003; Liu et al, 2012; Bust et al., 2014).

Departures from conventional workflows, also summarized in Figure 4, include the following:

- Estimation of the volume of shale (V_{sh} or V_{cl}). Typically, Vsh is calculated from the gamma ray (GR) response, which in turn depends upon the presence (in shales) or absence (in clean sands) of potassium. This approach does not work for volcanics because there is no significant variation in potassium content between plagioclase-rich sands and shales, which are largely the decay products of plagioclase. Therefore, the shale content of volcaniclastic deposits must be measured by methods that do not depend on variations in potassium.
- Porosity. Zeolites contain variable volumes of water, and petrophysical analysis over a zeolite-bearing interval will “see” a relatively high water saturation (S_W). However, this water is fixed in the zeolite phase; i.e., in petrophysical terms, it is “shale-bound water”. Therefore, despite high Sw, the hydrocarbon phase may be movable and allow production with a low water-cut.

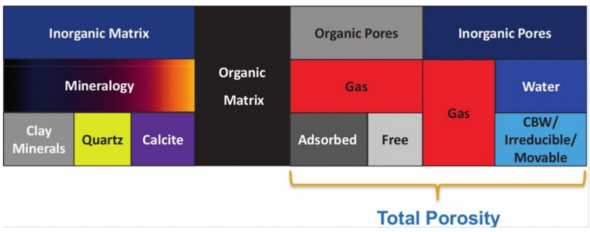

Figure 3: Various types of petrophysical porosity (from Bust et al., 2014).

In terms of evaluating an unconventional resource for source rock (i.e., presence, absence, richness), understanding these departures is germane. Early log-based approaches used to identify source intervals were overlay methods, such as source-log and Δ-R methods to identify TOC.

4. Commercial Aspects

The volcaniclastic play has geological and economic “sweet spots” that depend on the following aspects to reach the threshold of commerciality:

- Production constraints (i.e., depth, fracability): Many tight gas reservoirs require stimulation (“fraccing”) if they are to produce hydrocarbons at economic rates. Tight reservoir rocks typically are calcite- and/or quartz-rich shales, marls, or argillaceous limestones. Well stimulation is optimized when the tectonic regime of the field is understood. The tectonic study should not be limited to fieldwork, but should also include down-hole information; fracture analysis based on borehole imagery and breakout patterns; and oriented cores.
- Accessibility for seismic acquisition and drilling. For example, mountainous terrain and dense surface rocks on the slopes of Javanese volcanoes are problematic for seismic acquisition, causing a “ground-glass effect” that distorts the subsurface images.
- Reservoir. Several diagenetic processes in volcaniclastics enhance porosity. Unfortunately, porosity-limiting processes also exist. The unpredictability of these processes necessitates that the play must be onshore. Tight well-spacing, extensive fracking, wastewater treatment, and low-pressure gathering systems are prohibitively expensive offshore.
- Proximity to the energy market is equally important for economic reasons. Unconventional hydrocarbon accumulations are typically low-pressure systems, with some exceptions (e.g., well Jati-1). Distribution to a distal end-user requires gas compression that renders most projects non-economic.

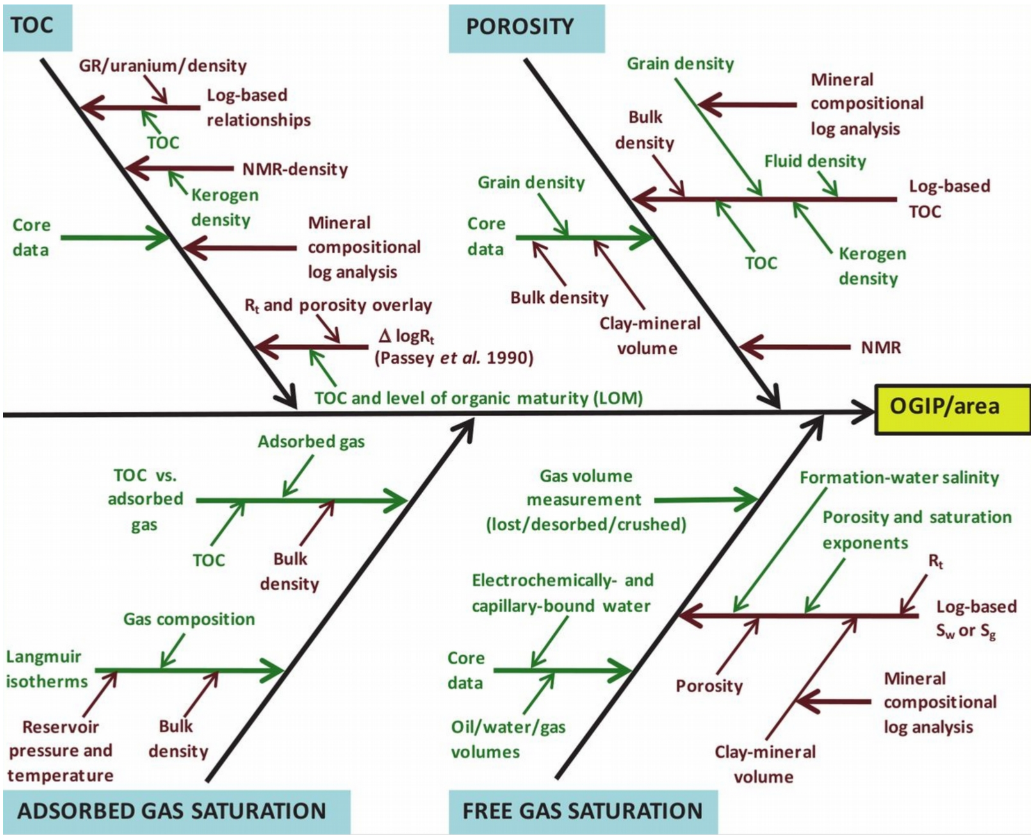

Figure 4: Extended workflow for the evaluation of tight gas reservoirs (from Bust et al., 2014)

5. Regional Occurrence of prospective Volcaniclastics in Indonesia

Worldwide, most volcaniclastics (by volume) occur along active plate margins, both divergent and convergent (Manville et al, 2009), but where in Indonesia should I explore for volcaniclastic plays? The volcaniclastic tight-sand play is regionally pervasive in Java, primarily along the Sundaland (sensu Hutchinson, 1989) margin. Other volcanic provinces in Indonesia, such as North Sulawesi, Gorontalo Bay, or Halmahera, could contain self-sourcing volcaniclastic plays, although exploration has yet to test the concept.

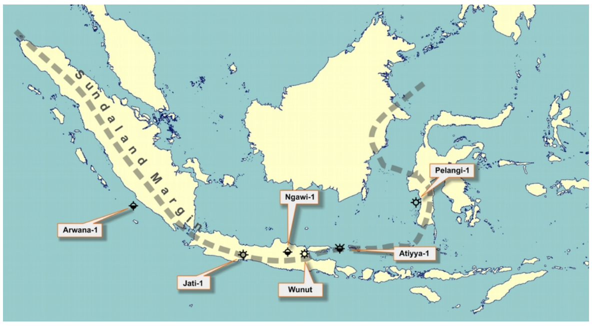

Figure 5: Location map of the wells discussed in the next chapters. The gray, dashed line follows approximately the margin of the Sundaland "craton".

During the Tertiary, volcanic activity on Java was variable. The bulk of volcanics and volcaniclastics in Java are Oligocene and early Miocene in age, although Eocene, middle Miocene, and younger volcanics also occur (Bellon et al., 1990; Soeria-Atmadja et al., 1991). However, the age and the stratigraphic position of many volcaniclastic sequences are poorly defined, because of a lack of scientific and economic interest. Here, I present a restricted set of wells and one outcrop as examples of the volcaniclastic play in Indonesia (Figure 5).

5.1 Well Arwana-1, South-West Sumatra

This well was drilled in 1992 in the offshore region of Bengkulu, Sumatra, it penetrated Tertiary sediments and reached its total depth (TD) in Eocene(?)–Oligocene marine volcaniclastic sedimentary rocks. The well is relevant because encountered liquid hydrocarbons and a mature source in the volcaniclastic sediments in the Palaeogene interval (Figure 6), and is remarkable in that it documented pervasive, fluorescent oil stains in a core of andesitic volcani-clastic rock. Porosities (as reported by Hall et al., 1993) were between 11% and 13%. It is also significant that—based on biomarkers—the oil in the core migrated into the Oligocene volcaniclastics from a deeper, more mature level (Hall et al., 1993).

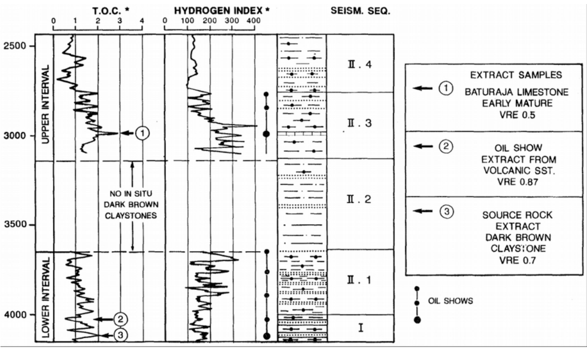

Figure 6: Illustration of the source-rich and prospective Palaeogene interval in well Arwana-1.

5.2 Well Jati-1, West Java

The Jati-1 well was drilled onshore in Java, about 30 km NNW from Cilacap, in 2005–2006 and to a TD of 14,747 ft. It penetrated a thick section of Miocene marine volcaniclastics. Image logs (Figure 10) and seismic data indicate that the extraordinary thickness was caused by a series of slumps and/or olistostromes. This points towards an aqueous sedimentary environment. High mud-weights (up to 18.2 ppg) were required from top-hole to TD to keep the hole open in this setting.

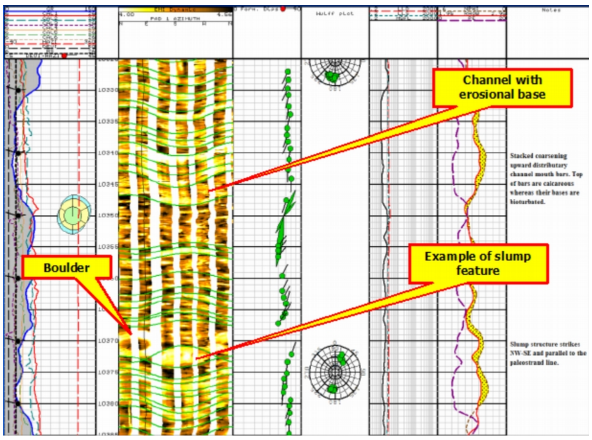

Figure 7: Image log showing several sedimentary features such as slumps, channels etc.

The well penetrated various gas bearing zones. A barefoot test (in a slotted liner) was run over a zone near TD that flowed gas to the surface (Figure 8), but the pressure did not stabilize and the well eventually killed itself, eventually. Circumstances seem to suggest that this test was mechanically flawed. However, the test indicated that movable hydrocarbons exist in the volcaniclastics and can be brought to the surface.

Figure 8: Well Jati-1 flowed gas to surface, albeit not in a stabilized test.

Geochemical analysis found that sediment TOC rarely exceeds 1 wt%. Biomarkers pointed towards a marine algal kerogen, but subordinate terrestrial markers were also present. These findings are consistent with the paleontological and sedimentological interpretation. Gas composition was >99% methane, and free of H_2S and CO_2.

5.3 Well Ngawi-1, Central Java

The Ngawi-1 well was drilled in 2002 and reached a TD of 8,007 ft in early Miocene marine sedimentary rocks, which were identified using foraminifera biostratigraphy. Most of the section penetrated in this well consists of various amounts of plagioclase-rich sandstone (arkose), tuff, and volcanic lithic fragments, typically classified as litharenite. Secondary cement and replacement mineral phases include calcite, zeolite, chlorite/smectite, and less common pyrite (Figure 9). Mean vitrinite reflectivity ranges from 0.31% at 2,450 ft to a maximum recorded value of 0.51%. This suggests that the sequence penetrated is immature to marginally mature for oil generation. The kerogen typing recorded non-fluorescing amorphinite, sporinite (exinite), and vitrinite as the main constituents, whereas inertinite and semifusinite were present in only trace amounts. Values for TOC were just over 1% (for comparison, Magara (2003) reports TOCs rarely exceeding 2%, but still sufficient to source a commercial accumulation in the Niigata district of Honshu, Japan). The solution gas was >94.5% methane and was free of H_2S and CO_2.

The Ngawi-1 well demonstrates that low-maturity hydrocarbon generation can occur in volcaniclastic sediments.

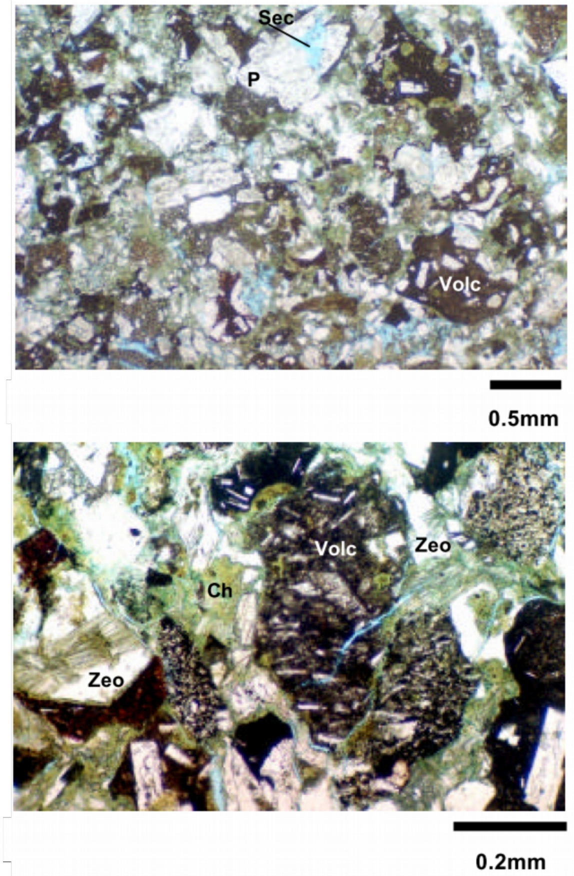

Figure 9: Ngawi-1; a medium to coarse-grained, poorly sorted, shaly tuffaceous sandstone composed mainly of altered basic volcanic fragments (Volc) along with minor plagioclase and pyroxene (Px, augite). Some volcanic fragments contain chlorite amygdales. The matrix is predominantly of detrital origin but includes secondary chlorite/smectite (Ch) that results from alteration of volcanic fragments. Secondary zeolite (Zeo) occurs as a replacement of feldspar and also possibly in veins. Zeolite is post-dated by minor amounts of calcite. Minor secondary porosity (Sec) results from late stage grain dissolution. Visible porosity is poor due primarily to the high clay content

5.4 The Wunut Gas Field, East Java

The Wunut field was discovered onshore in East Java in 1994. The Tanggulangin field (2001) is in a similar stratigraphic and lithological setting and illustrates that the Wunut field is not a unique occurrence in the basin. Despite the modest field size (<<100 BCF, no published reserves), the proximity to the market and a well-developed infrastructure allowed commercial production soon after discovery.

Wunut produces from Pleistocene marine volcaniclastics. The lowermost producing interval was deposited in an outer neritic, turbiditic environment, and the upper part was deposited in a deltaic setting. Overall shallowing and coarsening-upward sequences are well-defined. The source of the gas is believed to be re-migrated from deeper (?Kujung) reservoirs. Geochemical data show that the gas is thermogenic; its gravity and wetness both increase with depth, which is thought to be caused by a process of fractionation. At a shallow depth, the structure is partially filled and it becomes progressively more filled with depth. At the deepest pay levels, the structure is filled to the spill-point (after Kusumastuti et al., 2000).

This field is significant for two reasons. First, it demonstrates that volcaniclastics can have excellent porosities and permeabilities. Second, it is the first commercial gas field developed in the Pleistocene volcaniclastics of Indonesia.

5.5 Outcrop Samples from the ?Pucangan Formation, East Java

Surface samples were collected in East Java near Pasuruan (S 7° 37' 8", E 112° 50' 33") to illustrate some of the processes related to secondary porosity. The sampled formation relates closely to the Wunut gas field reservoir and exhibits very good visual porosity in outcrop.

Thin sections (Figure 10) show phenocrysts of plagioclase, pyroxene, and olivine. These minerals commonly form glomeroporphyritic clots. Plagioclase phenocrysts form mostly euhedral to subhedral crystals which are zoned. Inclusion of fine grained material in the early phases of plagioclase crystal growths are very common. The groundmass consists mainly of plagioclase and fine-crystalline pyroxene. Opaque components, probably magnetite, are common. The olivine commonly shows alteration in the form of chloritic rim reactions and alterations to iddingsite that encompass part or all of the crystal. The plagioclase is often–but not always and not consistently–saussuritizedshowing wide areas of alteration.

Large pores exist, presumably where olivine was present and later dissolved. I can exclude the possibility that these 'holes' are preparation artefacts, where a crystal has fallen out during the preparation of the thin section, because amygdaloidal lining (zeolites?) of the pore space can be observed. Although it is simplistic to assume that any olivine-bearing volcanic material provides a proxy for abnormal porosity development, this could be a suitable starting point for petrologic studies of porosity.

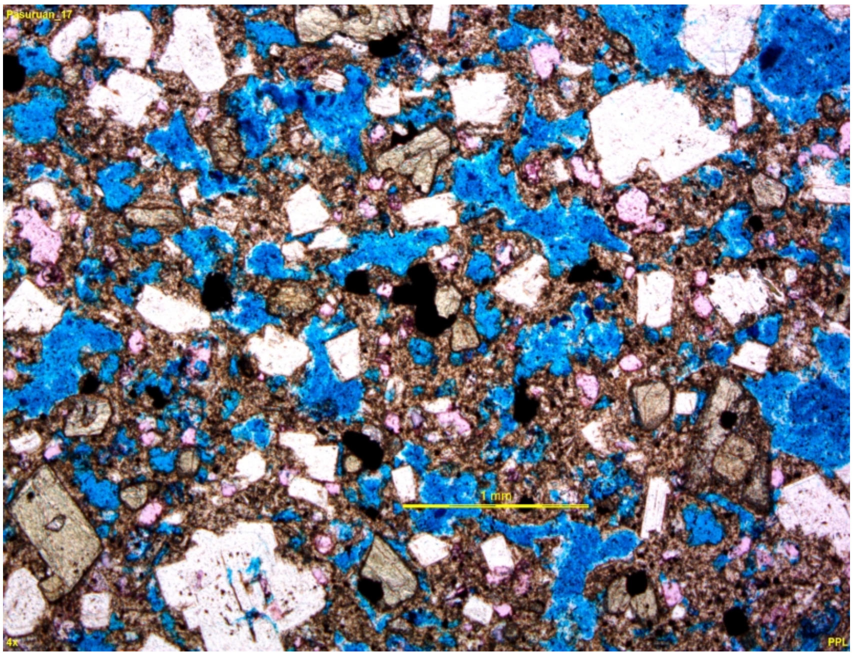

Figure 10: Microphotograph of an outcrop sample of the ?Pucangan Formation (in PPL), Pasuruan, East Java. Note the high visual porosity (blue areas). The pink phase is probably a mineral from the zeolite group.

5.6 Well Atiyya-1, East Java Sea

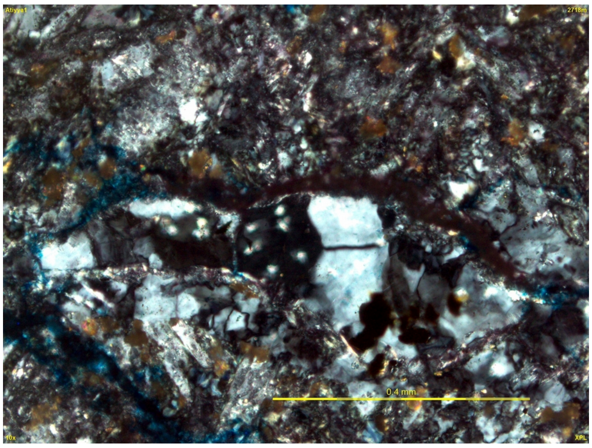

Figure 11: Microphotograph (XPL) from well Atiyya-1 at 2,718 m_rkb. The picture illustrates a complex diagenetic evolution where pyroxenes dissolved and were in part replaced by calcite. A late-stage quartz cement occludes some of the secondary porosity. Nevertheless, the volcanic section has an average (effective log-) porosity of 13%.

The Atiyya-1 well is located east of Madura Island and was drilled in 2006 to a TD of 9,245 ft in Eocene–Oligocene volcanics, after penetrating the Miocene and Kujung intervals. The petrography indicates a complex diagenetic evolution where pyroxenes dissolved and were in part replaced by calcite. A late-stage quartz cement occludes some of the secondary porosity. Nevertheless, the volcanic section has an average (effective log-) porosity of 13%.

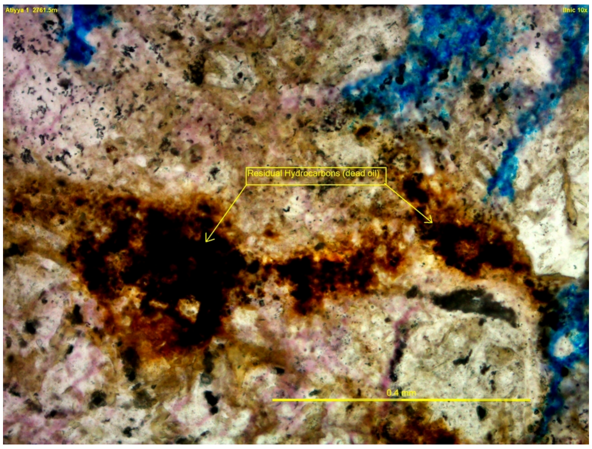

Figure 12: Atiyya-1, 2,761.5 m_rkb. Fracture fill with residual oil. The fracture runs approximately east-west through the center of the image, widening towards the right.

This well is relevant in that it had oil shows in the volcanic interval (Figure 12). Attempts to test the respective intervals were inconclusive. In contrast to the other wells, the oil seen in the volcanic interval is probably sourced from other sediments.

5.7 Well Pelangi-1, South Sulawesi

The Pelangi-1 well was drilled offshore South Sulawesi in 2000 to a TD of 13,200 ft, using oil-based mud (OBM). The well penetrated a thick middle Miocene to early Pliocene sequence of marine volcaniclastic sedimentary rocks. Geochemical analysis of the Miocene and Pliocene cuttings indicate fair to occasionally good gas and oil potential in several organic-rich units. The Ro values measured in this well are not considered relevant because the well was drilled with OBM, which usually gives falsely low vitrinite reflectance (Carr, 2000).

This well is remarkable because it proves the presence of volcaniclastic sediments with good to excellent porosity. The petrography of this tuffaceous sandstone is illustrated in Figure 13.

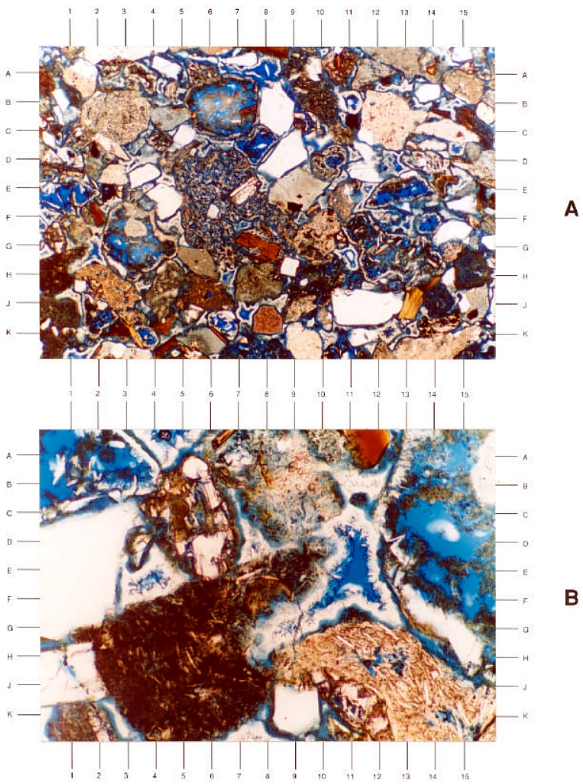

Figure 13: Well Pelangi-1,depth 9,775ft_rkb. Tuffaceous sandstone (feldspathic litharenite). A lower coarse-grained, poorly sorted feldspathic litharenite composed predominantly of volcanic rock fragments (Plate A: E6; Plate B: HS, J13) and plagioclase (Plate A: B8; Plate B: E1), with lesser biotite (Plate A: J13), hornblende, pyroxene, altered grains and very minor other grains. There are abundant secondary chlorite (Plate B: B14) and common zeolite cement that occurs as pore-linings (Plate A: J7; Plate B: F10), pore-fillings (Plate B: 811) and as a replacement of volcanic rock fragments. Matrix is illitic in composition. Secondary chlorite occurs as a replacement of volcanic rock fragments. Late stage grain dissolution has created secondary porosity (Plate A: G3; Plate B: C14). Visible porosity is poor due to the combined factors of secondary chlorite, zeolite, chloritic matrix and compaction. Photographed with plane polars, Heϕ 34.3%, Kair 1710md.

6. Discussion

I note that:

- hydrocarbon-bearing volcaniclastic reservoirs are typically marine;
- TOCs (up to 2 wt%) and source potential in marine volcaniclastics is higher than expected;
- volcaniclastic reservoirs in Indonesia occur across a range of stratigraphic levels (Figure 14) within the Cenozoic, from the middle Eocene to the Pleistocene;
- it appears plausible that other, as yet undrilled, volcanic basins, such as Gorontalo and offshore southern Halmahera, could contain hydrocarbons in volcaniclastic rocks;
- access to well data is limited and data from only a few wells were available for this study. It would be desirable to review all volcanic well penetrations and basins in a comprehensive study to assess the real potential of volcaniclastic deposits.

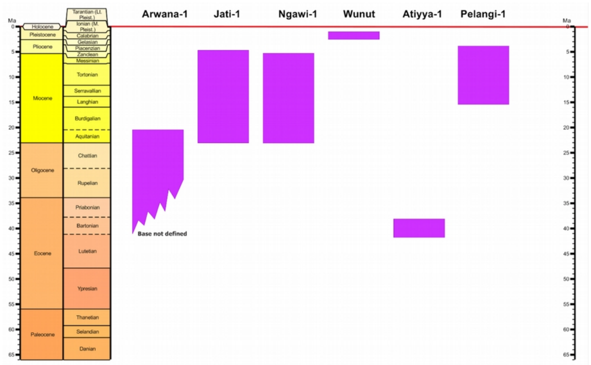

Figure 14: Stratigraphic position of the volcaniclastic intervals discussed in the previous section.

7. Summary and Conclusion

In this paper, I have proposed and argued the following points:

- Source *and* reservoir can and do exist in Tertiary volcaniclastics in Indonesia and are best known from onshore Java.
- Here and elsewhere in Indonesia, these deposits are under-explored and may add substantial (gas-) reserves to the country as proven by one producing field and one deep well.
- The predictability of porosity (either preserved primary or secondary), and tools to explore volcaniclastic reservoir properties, remain problematic. However, this could be addressed in collaboration with geoscience colleagues who study the petrology of volcanics.
- As a closing statement, I would like to use these two quotes:
- “Commercial oil deposits in basement rocks are not geological “accidents” but are oil accumulation which obey all the rules oil sourcing, migration, and entrapment; therefore in areas of not to deep basement oil deposits

should be explored with the same professional skill and zeal as accumulation in overlying sediments" (Landes et al., 1960).

and:

- "While some operators might stop drilling after encountering "basement", those with a better understanding of the potential of volcanic rocks may treat them like any other prospective reservoir rock" (Farooqui et al., 2009).

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