

## Potential of impact-structure hydrocarbon plays in continental Southeast Asia

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**Abstract:** The pre-Tertiary of continental SE Asia, the Indosinia and Sundaland tectonic blocks, most probably hosts a number of brecciated impact structures with good reservoir properties. Hydrocarbons that migrated or re-migrated during the Tertiary may have accumulated in such structures where top seal is present and these structures therefore constitute a potential hydrocarbon play. In the known sedimentary basins of Sundaland, the pre-Tertiary lies too deep or too shallow to be of commercial interest to the petroleum industry. The shallow basement has been considered to possess less proven trap styles of the stratigraphic and “buried hills” categories. Very recently, three areas onshore Peninsular Malaysia were proven products of meteorite impacts. Their definitive features of shock metamorphism comprise multi-directional cleavage in quartz crystals, mosaicism in their optical extinction, and suevite breccia in association with circular topography. About several dozen of circular features have been identified in the peninsula and study is in progress to ascertain their nature. The peninsular area constitutes less than 15 per cent of the pre-Tertiary expanse of Sundaland. The presence of more impact structures in pre-Tertiary Sundaland is undeniable. In addition, the wide offshore areas of shallow basement (> 1 km deep) bordering the petroleum basins are worth exploring for this new play.

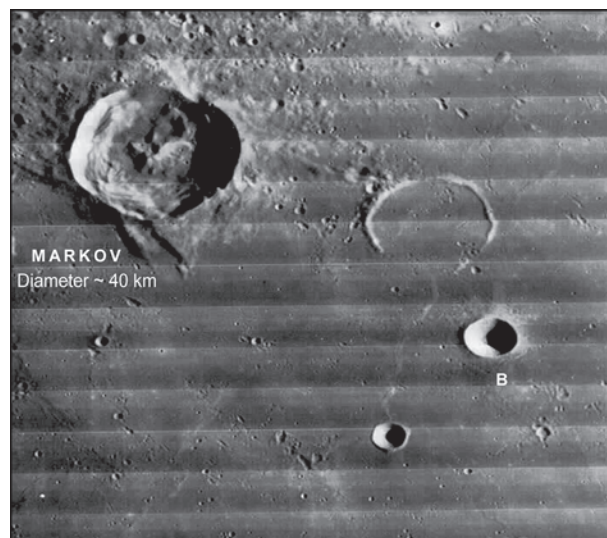
### BACKGROUND

Craters abound on the surfaces of the Moon, the solid planets and their satellites. Prior to the manned Apollo missions, views that the craters of the Moon were products of volcanism or of meteorite impacts were about equally strong. The collected Moon rocks show definitive features of high pressure but relatively low-temperature metamorphism that overwhelmingly favour impact origin. On Earth, the suspected impact depression in the Southwestern United States known as Meteor Crater was found associated with high-pressure quartz, or coesite (Chao *et al.*, 1960). Currently some 300 terrestrial structures are considered products of impacts by extraterrestrial objects. Almost two hundred of these have been proven as such by the presence of arcuate to circular surface morphology, circular gravity anomaly patterns, shatter cones, mega poly-breccias containing cleaved quartz, quartz and feldspars with mosaicism (patchy optical extinction), the high-pressure quartz polymorphs of coesite and stishovite, anomalously high Iridium, diaplectic glass, and sometimes micro-diamonds (McKinnon, 1982; Melosh, 1989). The comparatively low density of terrestrial impact craters on the Earth's surface is attributable to reworking by exogenous processes of weathering, erosion, organic activity, burial by younger deposits, tectonics (subduction, overthrusting) and to the fact that 70 per cent of the surface is covered by water.

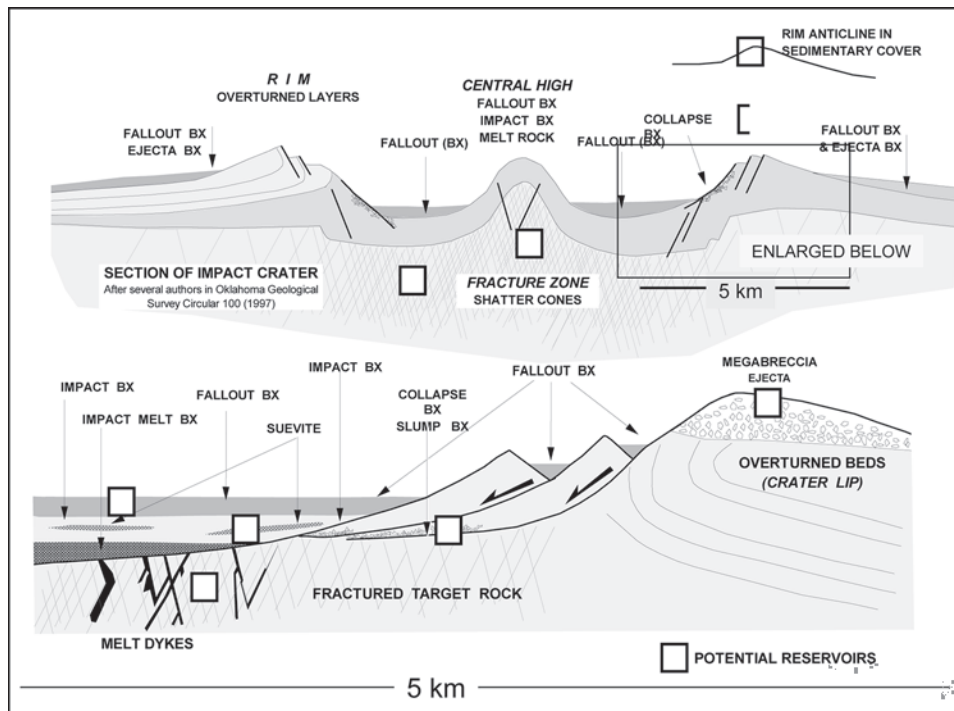
In other words, impact craters should be as common on Earth as on the solid extraterrestrial bodies (Fig. 1). Calculations suggest a mean probability that in excess of 15,000 significant impacts occurred on land. The average depth to diameter ratio of an impact crater is 0.2 to 1.0, while rim height is about 4 per cent of the total diameter (Buthman, 1997). Also on land, the dimensions of simple, bowl-shaped impact craters probably do not exceed 4 km

in igneous rocks and about 2 km in sedimentary rock. Beyond these limits, complex crater morphologies develop as a result of flattening through gravity. Impact craters with diameters 10 km or more are characterised by a central peak surrounded by several concentric rims (Figs. 1 & 2).

Renewed attention to impact structure plays is relatively recent and was fueled by the 1991 single-strike discovery (25 MMBO, 15 BCFG recoverable reserves) in the vicinity of Ames, Oklahoma, U.S.A. About twenty years earlier, other significant discoveries were made at Red Wing Creek, North Dakota (20 MMBO, 25 BCFG), and at the world-famous Chicxulub, Yucatan Peninsula,



**Figure 1.** Impact craters are common on the solid bodies of the solar system. On the Moon these structures are preserved due to the absence of weathering. The smaller impact structures are bowl-shaped; those of diameters 10 km and more are characteristically multi-ringed and have central peaks. Lunar Orbiter V. Photographs by courtesy of U.S. National Aeronautics and Space Administration (NASA).



**Figure 2.** Diagrammatic sections of impact structures > 10 km across. Loci of rocks with good poroperm properties, i.e. potential reservoirs, are indicated. Rim anticlines in overlying strata are known traps. Diagrams are based on descriptions in a number of the listed references.

Mexico (30 BBO, 15 TCFG). However, the structures of these earlier finds were not identified as astroblems and at the time of their discoveries the respective reservoirs were considered ordinary fractured carbonates and fractured granite-and-carbonates.

[Note: MMBO = million barrels of oil; BBO = billion barrels of oil; BCFG = billion cubic feet of gas; TCFG = trillion cubic feet of gas]

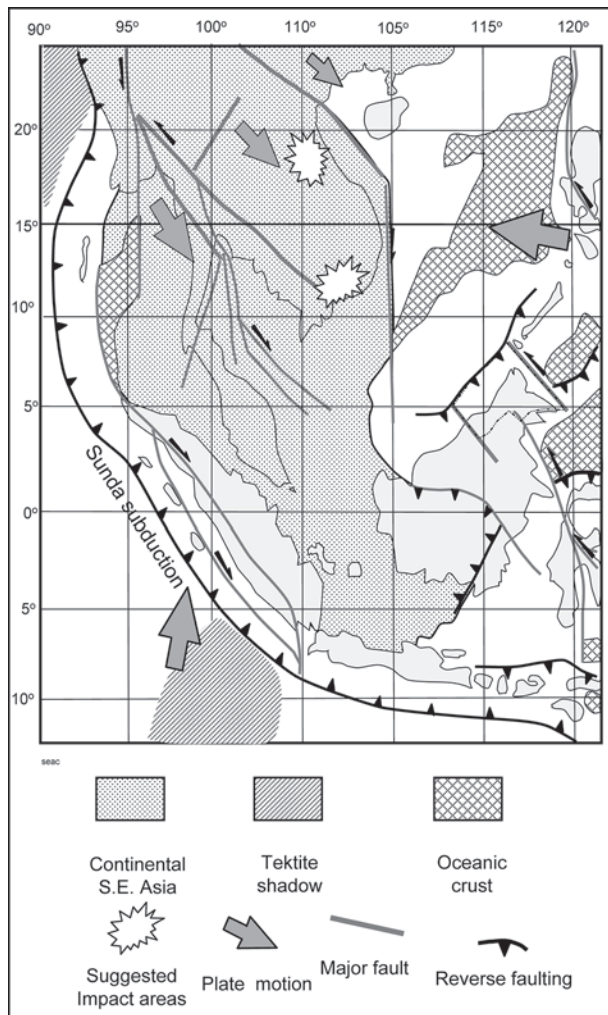
The extensively described impact structure play is centred about Ames, a small town in Oklahoma, U.S.A. Its reservoir rocks are lithified “basement” granodiorite and Cambro-Ordovician Arbuckle dolomite breccia exposed in the crater rim; 2D seismic indicates erratic, pocket-like distribution of porosity and permeability. Trapping is by subsurface closures with one known structural closure. A dolomite cap rock and overlying Middle Ordovician Simpson Shale provide the cap and seal. The source consists of the Arbuckle sediments or rocks that were exposed to the “cracking” environment of the meteor impact, and the shales that were deposited in the crater (Castano *et al.*, 1997; Donofrio, 1997; Koeberl, 1997; Sandridge & Ainsworth, 1997). As of 1995, flow was 250 to 500 BOPD; some of the wells produced in excess of 250,000 bbl oil, while one particular well has yielded 3 BCFG. Recovery has been in the 10% to 60% range (Johnson & Campbell, 1995). Carbonate breccia in the Campeche marine platform of southeastern Mexico was interpreted by Grajales-Nishimura *et al.* (2000) as a product of the Chicxulub impact whose centre is between ~350 and 600 km away. The Cantarell oil field in platform daily produced 1.3 MBO.

An impact structure creates a closed lacustrine or marine depression for source rock to develop. Large-scale brecciation forms fractured rock reservoirs. The shock

metamorphism may cause partial fluidisation whose products invade some of the fractures and thus adversely influence poroperm conditions. Reservoirs are sandstones, carbonates and crystalline rocks whose porosity generally became enhanced by the impact event. Oil and gas are typically entrapped in and above the encircling rim anticline and in the central rebound peak (Fig. 2).

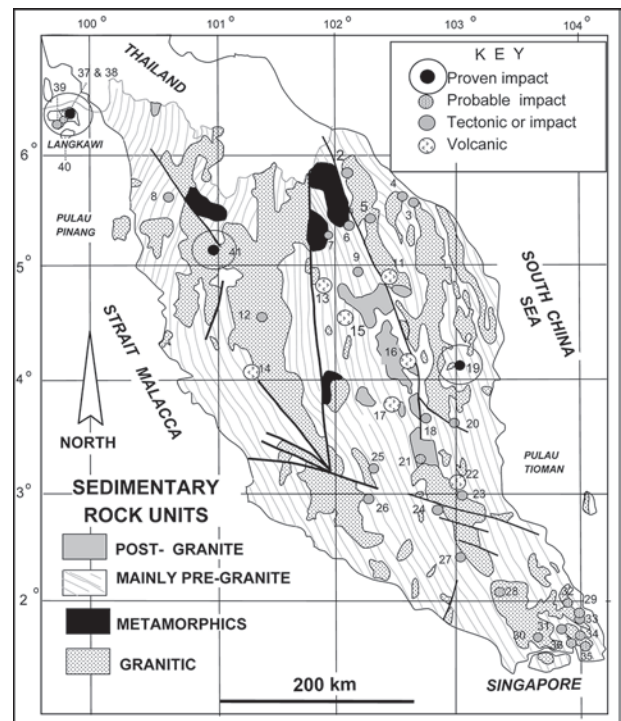
## THE CASE OF SUNDALAND

The land areas of continental Southeast Asia largely consist of outcropping pre-Tertiary “basement” (Fig. 3) which by virtue of its longer exposure can be expected to host more impact structures than Cenozoic regions. The reach of a large impact is probably regional. A case in point is the early Pleistocene Australasian tektite distribution that is generally considered as a product of a large impact in eastern Indosinia. In pre-Tertiary Peninsular Malaysia several impact structures have been recently discovered (Fig. 4). In the Langkawi islands three of four sets of arcuate ridges are associated with cleaved quartz that crops out as sills and sill-dyke complexes (Tjia, 2002; Fig. 6). Other shock-metamorphic features include ribbon quartz and mosaicism, that is, patchy extinction of certain minerals viewed under polarised light. The two major craters, named Mahsuri Rings, partially overlap and each is about 2.4 km across. Their centres are 600 metres apart in the 280° - 100° direction (Fig. 5). Bouguer gravity cross sections prove their crater form (Abdul Rahim Samsudin *et al.*, 2001). One crater is 45 m deep, the other attains 107 m depth into the target rocks of Carboniferous-Permian Singa Formation. Both depressions are filled, the top surface consisting of Quaternary alluvium that forms an inland plain in central Langkawi island. The partially encircling hills of Singa Formation crest at less than 150



**Figure 3.** Outcropping pre-Tertiary rock assemblages of continental Southeast Asia. The extensive reach of a large impact is demonstrated by the early Quaternary Australasian tektite strewn field, covering the entire map area of this figure and regions well beyond it (Stauffer, 1978). On the figure are only two patches of “tektite shadows”. The tektites become progressively smaller away from the suspected impact sites in Indosinia.

m above the plain and are open to the west. Towards southwest are two other circular/arcuate topographic features: Malut Ring (called Temoyong Rings in earlier articles) and the horseshoe-shaped Tepor Island. The diameters decrease in the same direction: approximately 800 m and 500 m (Fig. 5). These four arcuate structures have been interpreted as products of serial impacts by a flight of extraterrestrial projectiles arriving from the Southwest. [In a brief on photographic observations and successful recovery of “Neuschwanstein” meteorites that streaked in onto central Europe on 6 April 2002, Oberst et al. 2003 wrote that ....”The smaller fragments, which are typically subjected to greater atmospheric drag, were expected to have landed uptrack of the meteor’s path”]. The impact age of the Langkawi structures is not yet determined and field relations only indicate a post-granite (Triassic-Jurassic) event. The Singa strata in the eastern

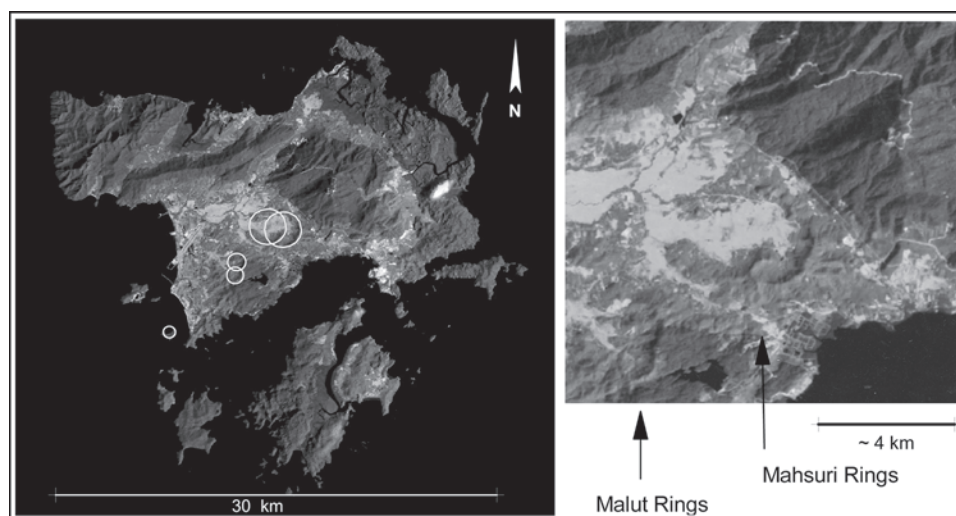


**Figure 4.** Distribution of medium and large ring-like and oval topography in the pre-Tertiary of Peninsular Malaysia. Site numbers are tabulated in Tjia & Mazlan Md Zain (2002). Shock metamorphic features prove the impact origin of sites # 37, 38, 39 & 40 in the Langkawi islands; of site # 41 in the Kota Tampan area; and of site # 19 at Bukit Paloh. Probable impact sites are # 28, 29, 32, 34, 35 and 36.

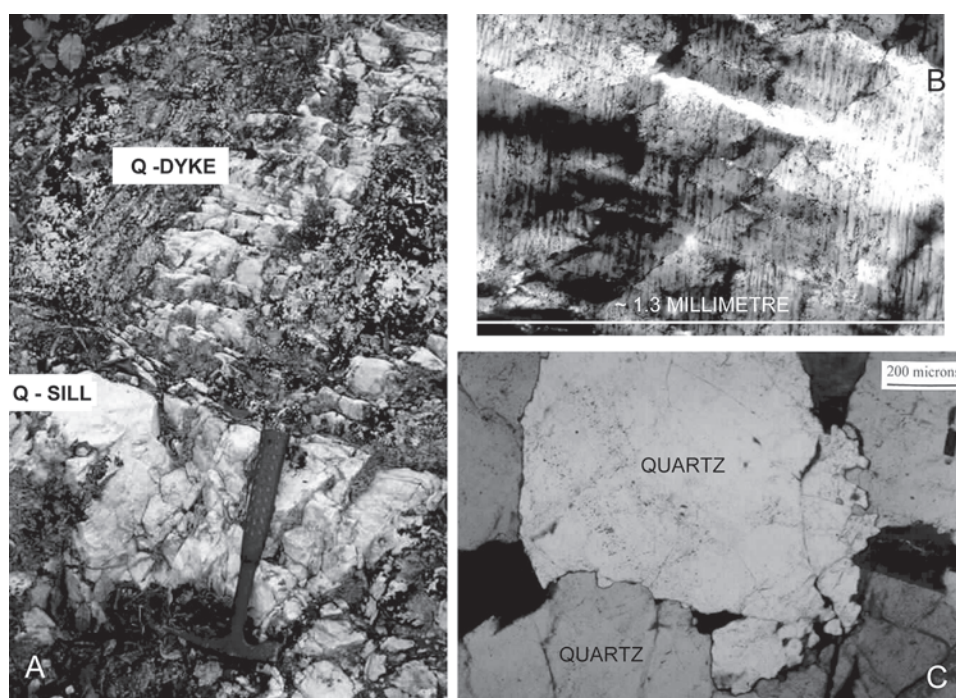
side of the easternmost Mahsuri Ring dip towards the Gunung Raya granite pluton. In the case that the morphologically young Mahsuri Rings are not exhumed features, impact could have occurred within the last 10 million years. A longer exposure to weathering and erosion should have obliterated the topographic evidence.

Another proven impact structure is the Paloh Ring (No. 19 on fig. 4) that straddles the state boundary between Terengganu and Pahang. The proof consists of planar deformation features (PDFs) and mosaicism in vein quartz intruded into undivided Carboniferous metasedimentary strata that compose the lower eastern slope of the 623 m high Paloh peak. PDFs are also seen in thin sections of quartz phenoclasts of polymict-breccia boulders in Sungai Mengkuang that drains the east side of the hill. Bukit Paloh is the peak on the high, circular topography surrounding a deep depression, now referred to as Paloh Ring-1. This ring-like topography is 3.5 km across and has local relief of the order of 150 to 200 metres. A small - about 0.5 km across - circular depression is located on the Paloh Ring-1. The south half of the larger ring consists of felsic igneous rock whose K/Ar age is 243 Ma, while the north half is composed of Carboniferous metasedimentary rocks. The youthful morphology of Paloh Ring-1 points to a geologically young impact event, estimated to be not later than Late Miocene (Tjia & Mazlan Mohd Zain, 2002).





**Figure 5.** Serial impact craters in the Langkawi islands, of which the two Mahsuri rings and the Malut rings are associated with shock features in the quartz populating veins, dykes and sills. Each of the Mahsuri rings is 2.4 km across. A closer look at the Mahsuri and Malut rings is on the right satellite image.



**Figure 6.** A. Quartz sill and dyke intruded in Singa Formation at Sungai Batu Asah, main island of Langkawi. B. Microphotograph of a thin section of quartz taken from the sill (A) seen under plane polarized light. Planar deformation features (PDFs) consist of cleavage in 2 or more directions and imperfect parallel lamellae of optical extinction. These are shock metamorphic products. Plane polarized light. C. As comparison is a thin section of non-shocked quartz in a granite from Ca Na, southern Vietnam.

Figure 7 comprises microphotographs of cleaved quartz retrieved from veins intruded in rocks forming the foot of Bukit Paloh. More than a decade earlier, PDFs in quartz were discovered in partly weathered granite underlying the Quaternary basalt at Gebeng, some 40 km SE of Bukit Paloh. The granite at Bukit Ubi quarry, located in the same area but nearer to Kuantan town, also contains quartz with PDFs. These two findings were the initial proofs for impact products in the whole of Malaysia (Anizan Isahak, 1990). It is unresolved if the Gebeng-Bukit Ubi impact products and those at Bukit Paloh originated from the same event.

The third proven impact products are at Bukit Bunuh (No. 41 on fig. 4) near the world-famous palaeolithic site of Kota Tampan along the Perak River (Fig. 8). Recently Mokhtar Saidin, geo-archaeologist of Universiti Sains Malaysia, verbally reported a 1.74 Ma fission-track age for a “volcanic agglomerate” composed of unsorted small to huge fragments of quartz, quartzite, schist, felsic igneous

rocks, and other as yet unspecified rock types. Parts of the rock assemblage show effects of fluidisation, or “schlieren”-like features. The megabreccia is set in light-coloured groundmass, superficially resembling volcanic tuff. Thin-section examination of the quartz turned up parallel planar fractures, mosaicism extinction and also several cleavage sets. (Fig. 7). However, satellite images do not show a topographic crater form. Detailed studies are in progress, but there is little doubt that this “agglomerate” is in fact suevite, an impact breccia containing “schlieren”. In spite of alteration by oxidation, hydrolysis and local secondary mineralisation of fractures and other voids, porosity estimates by visual inspection are of the order of 10 per cent.

Satellite and side-looking radar images complemented by topographic maps and aerial photographs indicate over 60 prominent arcuate and circular features throughout Malaysia. Crater form, geological and geophysical field

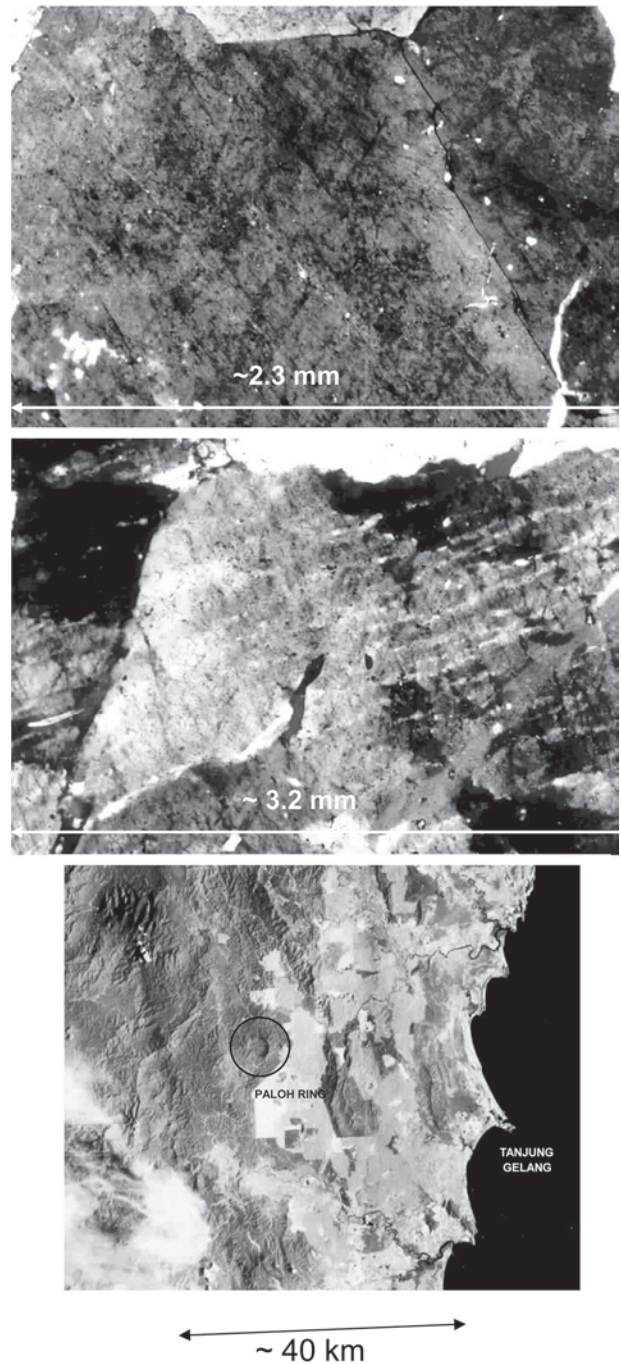
studies, presence of suevite, and PDFs in quartz prove the impact origin for the Mahsuri Rings in Langkawi, the Paloh Ring-1 on the Terengganu-Pahang border, and the megabreccia at Bukit Bunuh (Kota Tampan) in central Perak. At least seven other arcuate/circular features could be impact products and will need confirmatory studies; eight other structures appear to represent domal intrusions or exhumed volcanic complexes, while the remaining sixteen are structural basins. Contributing factors of extraterrestrial impacts to petroleum systems comprise depressions favouring source-rock development, enhancement of reservoir quality in most of the target rocks through brecciation and fracturing, providing a trapping environment for fluids, and perhaps accelerating maturation. Given that prominent impact structures are not rare in Malaysia and that during the transition from the Mesozoic into the Cenozoic vast regions of continental Southeast Asia were sub-aerially exposed, impact-structure plays should be significant. Their occurrence was most probably overlooked as, to my knowledge, impact features are not included in the industry's exploration strategies. Several years ago Buthman (1999) attempted to draw attention to the role impact structures might have in this region. He suggested that the Tertiary hydrocarbon fields occurred in concentric bands around the South China Sea. He believed that this oceanic depression was formed by a gigantic meteorite impact.

### NEXT STEP

The initial step in exploring for impact-structure plays should include expansion of the regional database of impact structures and re-examination of seemingly anomalous subsurface structures that are already known.

During the transition from the Mesozoic to the Cenozoic an extensive peneplain existed in continental Southeast Asia (Phan *et al.*, 1991; van Bemmelen, 1949). The area was sufficiently vast to have been impacted by several medium and larger extraterrestrial bodies (compare with Bunopas *et al.*, 1999). Older pre-Mesozoic impact structures may have also been present on this peneplain. On the Sunda Shelf such structures should be preserved under a cover of younger sediments. Large areas of the shelf have pre-Tertiary basement at depths of a kilometre or less (CCOP, 1991). Since petroleum in this region is almost exclusively produced from Tertiary sediments, these thinner sedimentary packets have not been considered to present commercial interest. Moreover, any plays associated with the crystalline basement are considered problematic or "high risk" and may be volumetrically non-commercial. These plays include stratigraphic pinch-outs, buried hills, and fractured crystalline basement.

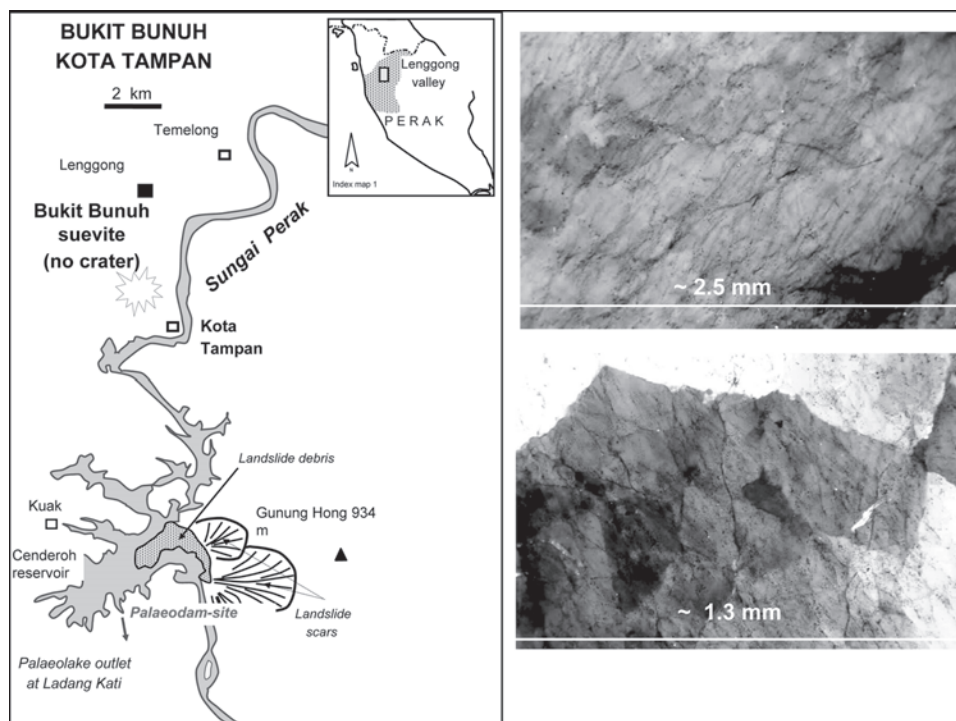
To my knowledge, impact structure plays are not part of current exploration strategies for the region. However, we may assume that because of their extended exposure time and geographic expanse, the pre-Tertiary basement and Palaeogene sediments of the Sunda Shelf were



**Figure 7.** Critical indicators of shock metamorphism in vein quartz intruded into the base of Bukit Paloh: several directions of cleavage and lamellar to patchy optical extinction or mosaicism. Plane polarized light; vein quartz is from the headwaters of Sungai Mengkuang, Terengganu.

bombarded by medium to large meteorites to form several medium to large structures of diameters amounting to several kilometers each. Their areas may range from 50 to over 300 square kilometers. The poroperm properties of impact structures are usually good, while medium and larger structures provide large reservoir volumes. The structures that could be exploration targets are in crystalline basement, pre-Tertiary metasedimentary rocks, or in





**Figure 8.** Microphotographs of thin sections of large quartz crystals with shock metamorphic effects: Multidirectional sets of cleavages and fractures (PDFs), and mosaicism. Plane polarised light of thin sections of quartz collected from large breccia clasts at Bukit Bunuh (index map), near Kota Tampan, the quartz blocks are large to small fragments forming suevite, a typical impact breccia with fluidal structures and chaotic distribution of clasts.

Palaeogene sediments located in the large areas of the Sunda Shelf where covering sediments are as thin as a kilometer. Most promising are the shallow margins of the known petroleum basins, whence hydrocarbons could have originated and migration paths were relatively short. Gravity and magnetic anomalies could delineate targets. Careful study of regional, subregional and closer spaced seismic lines that cross these areas may turn up circular to oval structures. Another impact-related reservoir could be intervals of breccia or chaotic deposits within the Tertiary sequences. These breccias are not necessarily restricted to the vicinity of the impact proper, as the oil fields of southeastern Mexico seem to suggest (Grajales-Nishimura *et al.*, 2000).

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