Chapter 1

Introduction to the geology of Myanmar

KHIN ZAW1*, WIN SWE2, A. J. BARBER3, M. J. CROW4 & YIN YIN NWE5

1 CODES ARC Centre of Excellence in Ore Deposits, University of Tasmania, Private Bag 126, Hobart, Tasmania 7001, Australia
2 Myanmar Geosciences Society, 303 MES Building, Hlaing University Campus, Yangon, Myanmar
3 Department of Earth Sciences, Southeast Asian Research Group, Royal Holloway, Egham TW20 0EX, UK
4 28a Lenton Road, The Park, Nottingham NG7 1DT, UK
5 Myanmar Applied Earth Sciences Association (MAESA), 15 (C) Pyidaungsu Lane, Bahan, Yangon, Myanmar

*Correspondence: khin.zaw@utas.edu.au

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The Republic of the Union of Myanmar (Pyidaungsu Thamnada Myanmar NaingNganDaw), formerly Burma, occupies the northwestern part of the Southeast Asian peninsula. It is bounded to the west by India, Bangladesh, the Bay of Bengal and the Andaman Sea, and to the east by China, Laos and Thailand. It comprises seven administrative regions (Ayeyarwaddy (Irrawaddy), Bago, Magway, Mandalay, Sagaing, Tanintharyi (Tenasserim) and Yangon) and seven states (Chin, Kachin, Kayah, Kayin, Mon, Rakhine (Arakan) and Shan). From north to south Myanmar extends for some 2000 km from 28° N to 10° N, with the Tropic of Cancer (23°30′ N) dividing the country into a temperate to subtropical north and a tropical south (Fig. 1.1). Although Myanmar is located within the Monsoon Belt of Asia, the climate is influenced locally by geographical position and topography. During the winter the northern mountains are influenced by cold air masses from Central Asia and are covered in snow for two months of the year. The mountains prevent cold air from spreading further south, so that most of Myanmar lies under the influence of the NE and SW monsoons. However, the north–south alignment of mountains and valleys results in a pattern of alternating zones of high and low precipitation during both the NE and SW monsoons. Most precipitation comes from the SW Monsoon. Myanmar has three seasons, including: a dry summer from March to mid-May; a monsoonal rainy season from mid-May to September; and a cool winter season from October to February. The western coast of Myanmar is subject to occasional tropical cyclones such as Cyclone Nargis (2008) which, together with a storm surge, inundated the Ayeyarwaddy (Irrawaddy) Delta, killing an estimated 140 000 people, and Cyclone Giri (2010), which made landfall south of Sittway on the Rakhine coast, rendering tens of thousands of people homeless.

Topographically, Myanmar is composed of central lowlands surrounded by steep, rugged highlands (Fig. 1.2). The highest point is Mount Hkakabo Razi (5881 m) in the far north of Kachin State. From here mountain ranges generally trend north–south, with the Patkai Range, the Naga Hills, the Chin Hills and the Rakhine Yoma to the west along the borders with India and Bangladesh. Mountain ranges also form the eastern border with China, passing southwards into the highly dissected Shan Plateau at an average elevation of 900 m in Shan State. Four main rivers draining the mountains, the Chindwin, Ayeyarwaddy (2170 m long), Thanlwin and the Sittaung, flow southwards through the central lowlands to form an extensive delta in the northern part of the Andaman Sea and the Gulf of Mottama (Martaban). The central lowlands are divided into two unequal parts by the Bago Yoma Ranges, the larger Ayeyarwaddy Valley and the smaller Sittaung Valley. The Bago Yoma Ranges pass northwards into a line of extinct volcanoes with small crater lakes and eroded cones; the largest of these is Mount Popa (1518 m). Coastal lowlands and offshore islands margin the Bay of Bengal to the west of the Rakhine Yoma and the Andaman Sea in Tanintharyi (Tenasserim) (Hadden 2008).

Tectonic setting of Myanmar

Myanmar lies at the junction of the Alpine–Himalayan Orogenic Belt and the Indonesian Island Arc System. In northern Myanmar, the orogenic belt is bent around the Eastern Himalayan Syntaxis into a north–south direction and passes southwards through the resource-rich Indo-Myanmar Ranges (Kyi Khin et al. 2017a, b; Hla Huy et al. 2017; Barber et al. 2017) into the Andaman and Nicobar islands, Sumatra and the Sunda and Banda arcs of Indonesia. The Himalayas and the mountain ranges of northern Myanmar mark the collision between the Indian subcontinent and the southern margin of the Eurasian continent. Detritus from the Himalayas, transported by the rivers Ganges and Brahmaputra, has built an extensive delta into the Bay of Bengal on Indian Ocean crust. At the present day the Indian Tectonic Plate, carrying India and the Indian Ocean Crust, is moving north-eastwards at 5 cm a−1, and is moving past Myanmar on transcurrent faults. The collision between Indian continental crust and Eurasia continues at the Eastern Himalayan Syntaxis; to the south in Myanmar collision occurred earlier in the Indo-Myanmar Ranges, resulting in the Patkai Range and the Naga and Chin hills. Further south, the overlying sediments of the Bengal Fan have been affected by transcurrent faulting and transpression to form a fold-and-thrust belt in the Rakhine Yoma. Curray et al. (1979) defined a Burma (Myanmar) Microplate, delimited to the west by the active Andaman subduction zone and a major strike-slip fault between the Indian Plate and Myanmar, and to the east by the north–south-aligned strike-slip Sagaing Fault. The Burma (Myanmar) Microplate is presently moving northwards at a rate of 18 mm a−1 relative to Southeast Asia along the Sagaing Fault (Maurin et al. 2010).

To the east of the Indo-Myanmar Ranges in Myanmar the Central Lowlands (Naing Maw Than et al. 2017; Myint...
Fig. 1.1. Map showing states and regions of Myanmar (Div., divisions).

Thein & Maung Maung 2017), with a crystalline continental basement, are intruded by the Mesozoic–Cenozoic Wuntho-Salingyi-Popa Volcanic Arc (Myint Soe et al. 2017). The basement is overlain by Cenozoic sediments, divided between forearc and back-arc basins by a line of volcanic crater lakes and eroded cinder cones with Mount Popa in the south and Taungthonlon in the north, representing part of a Quaternary volcanic arc which can be traced southwards through the Andaman Sea to the Sunda volcanic arc which can be traced southwards through the Anda-Taungthonlon in the north, representing part of a Quaternary and eroded cinder cones with Mount Popa in the south and forearc and back-arc basins by a line of volcanic crater lakes.

Although the basement beneath the Central Basin of Myanmar is not exposed, the basin is underlain by continental crust, indicated by fragments of high-grade metamorphic rocks brought up in the Mount Popa calc-alkaline volcano. The basement extends eastwards to include the Mogok Metamorphic Belt and the Slate Belt in the Shan Scarp area. This continental basement is considered to have been a separate crustal block during the Mesozoic, called Mount Victoria Land (Mitchell 1989) or the West Burma (Myanmar) Block (Metcalf 1996). Mitchell (1993) suggested that a zone of ophiolites at the foot of the Indo-Myanmar Ranges, together with associated metamorphic rocks occurring further east in the Jade Mines Belt of Kachin State, have been displaced dextrally by c. 300 m along the Sagaing Fault.

The West Myanmar Block is considered to have formed part of the northern margin of the megacrust of Gondwana, comprising all the southern continents during the Proterozoic and Early Palaeozoic (Metcalf 1996). The subsequent history of the West Myanmar Block is contentious. Audley-Charles (1988) suggested that this block, together with other crustal blocks, separated from the northern margin of Gondwana in the region of north Australia during the Jurassic, and collided with eastern Australia.

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fossils from the Naga ophiolite, northwestern extension of Indo-Myanmar Ranges of Myanmar. Ridd (2017) suggests that a branch of the Tethys Ocean to the north passes southwards in Myanmar and Thailand into a major transcurrent fault. In Mitchell et al.'s (2012) interpretation, the Shan Plateau was thrust westwards over the eastern margin of the West Myanmar Block in the Early Cretaceous.

The Shan Plateau, or the Eastern Highlands Province, is composed of a crystalline basement and a weakly metamorphosed turbidite sequence of probable Late Precambrian–Early Cambrian age, overlain by a thick sequence of Palaeozoic–Mesozoic continental shelf (Aye Ko Aung & Cocks 2017; Zaw Win et al. 2017) and Cenozoic terrestrial sediments.

The Sibumasu Block is considered to have formed part of the megacontinent of Gondwana until the Early Permian. The break-up of Gondwana began in the Devonian, with the separation of Indochina and the formation of the Palaeotethys. Sibumasu is thought to have lain on the northern margin of Gondwana, offshore Western Australia, until the Early Permian when it separated by rifting with the opening of the Mesotethys (Metcalfe 1996). During the Late Permian, Sibumasu moved northwards, due to the expansion of Mesotethys to the south.
and the subduction of Palaeoethys to the north, until it collided with Indochina and the outlying Sukhothai Volcanic Arc in the Triassic, resulting in the Indosinian Orogeny (Sone & Metcalfe 2008). In northern Thailand the site of the collision between Sibumasu and the Sukhothai Arc and Indochina is recognized as the Inthanon Zone (Barr & MacDonald 1991; Ueno 1999), where the intervening Palaeoethyan oceanic crust and associated sedimentary units were thrust over sediments of the Sibumasu continental margin (Barber et al. 2011). Presumably the collision zone and the Sukhothai Volcanic Arc continued further north in the eastern Shan States of Myanmar, but they have not yet been convincingly described from this region (Gardiner et al. 2015). Tectonic developments in the Myanmar Region occurred throughout the Phanerozoic as a result of the long history of Gondwana break-up, rifting, subduction and postcollision processes. These tectonic processes associated with semi-continuous sedimentation, magmatic and metamorphic events have made the Myanmar Region highly prospective for metallic ores and gem deposits (Khin Zaw 2017).

Molnar & Tapponnier (1975) proposed that the collision of the Indian continental crust with the southern margin of Eurasia since Cretaceous (Baxter et al. 2016; references therein) resulted in the eastwards extrusion of continental blocks along major strike-slip transcurrent faults, together with the clockwise rotation of the whole of Southeast Asia. Two of the major strike-slip faults, the Papun (Mae Ping) Fault Zone and the Three Pagodas Fault Zone in Mon and Kayin states, extend from the Sagaing Fault southeastwards into Thailand. The Sagaing Fault is a major continental-scale right-lateral transcurrent fault, which has a potential for geohazards and fatal earthquakes in Myanmar, and played an important role in the Cenozoic tectonic evolution of the whole of Southeast Asia (Myint Thein 2017; Soe Thura Tun & Watkinson 2017).

**Commencement of geological studies in Myanmar**

Scientific observation concerning the geology of Myanmar commenced only after the First Anglo-Burmese War in 1824–26, when the British annexed the coastal provinces of Rakhine (Arakan) and Tanintharyi (Tenasserim) (Win Swe 2009). The earliest records contain information about mineral and petroleum occurrences in these two provinces of Myanmar, which were already being exploited by the inhabitants. Most of the papers are published in journals of the Asiatic Society of Bengal and the Royal Society of Edinburgh. In 1826, shortly after the First Anglo-Burmese War, John Crawford was sent by Lord Amherst, Governor General of India, as an envoy on a mission to the Court of Ava in Upper Burma. Crawford travelled up the Irrawaddy by paddle steamer. On the return journey Crawford (1829a, b) collected fossils north of Magway on the left bank of the river, including the jaw of *Stegolophodon latidens* (Clift 1829). Also included in Crawford’s report is an account of the finds of fossil bones and wood examined by Dr William Buckland (Oxford). In 1826 after the First Anglo-Burmese War, Lower Burma (Pegu) was also annexed to the British Raj. Subsequently D’Amato (1833) published an account of the ruby mines of Burma and Captain Low (1829) compiled a list of the tin mines of the Tanintharyi (Tannasserim) region.

When the Geological Survey of India (GSI) was established in 1851, just before the commencement of the Second Anglo-Burmese War in 1852, Thomas Oldham was appointed as Superintendent. The remit of GSI also included British-controlled territories in Burma. Oldham accompanied Arthur Phayre, the British Commissioner for the annexed territories, as part of the Yule Mission to the Court of Ava in 1855. In an appendix to Yule’s report of this mission, Oldham (1858) contributed a comprehensive account of the geology of Central Burma. After the Third Anglo-Burmese War in 1885, Upper Burma was incorporated into the Indian Raj; the whole of Myanmar territory was then under British control and the province of Burma became a part of British India.

At this time, by compiling scattered geological data and using evidence from mining and other activities, the mineral and hydrocarbon potential of the entire country could be visualized. For example, it was appreciated that there was excellent oil and natural gas potential in the Tertiary basins of Central Myanmar and in the coastal areas along the Bay of Bengal, the Andaman Sea and the offshore islands. There were good mineral prospects for tin and tungsten in Kayah and Tanintharyi, for gems in the Mogok area, for lead, zinc and silver in the Shan Plateau, for gold in the Wintho Massif in the Central Belt and in Kachin State, as well as other different metals and minerals in other parts of the country.

In the early part of the twentieth century, prior to the Second World War, GSI geologists carried out a comprehensive programme of regional surveys and mineral exploration throughout the country. Particularly noteworthy are reports on the Northern Shan States by La Touche (1913), the Mergui District by Rau (1930), the Southern Shan State by Brown & Sondhi (1933), the Kayah State by Hobson (1941), parts of the Minbu, Myingyan, Pakokku and Lower Chindwin districts by Cotter (1938), the Cretaceous and associated rocks of Myanmar by Clegg (1941) and the Mogok Stone Tract by Iyer (1953). Articles on the mineral resources of Myanmar were published by Penzer (1922) and Clegg (1944). All the available geological information on India and Myanmar up to the outbreak of the Second World War was included in the three volumes of Pascoe’s (1950, 1959, 1964) *A Manual of the Geology of India and Burma*.

**Development of geosciences education in Myanmar**

The University of Rangoon (Yangon) was founded in 1920; shortly afterwards, in 1923, the Department of Geology and Geography was established with the appointment of Dr Laurence Dudley Stamp, who had worked previously as an oil geologist in Burma, as Professor and Head of the department. An Indian geologist, Dr H.L. Chhibber, joined the department in the following year. Chhibber (1934a, b) published two volumes on *The Geology of Burma* and *The Mineral Resources of Burma*, exhaustive compilations of the geology and resources of Myanmar as far as they were known up to 1933.

During the Japanese occupation in the Second World War the University of Rangoon was closed; it reopened in 1946 with the appointment of Dr Tha Hla as Professor and Head of the Department of Geography and Geology. Dr Tha Hla had graduated in Chemistry (Honours) from Rangoon University before the war and was granted a government scholarship to study for a BSc (Honours) degree in geology at King’s College, London; he further studied for a PhD degree in geology at the Imperial College of Science and Technology, London (Tha Hla 1945, 1946).

Up until that time there had been no qualified professional Myanmar geologists, although the subject of geology had been offered in the Department of Geology and Geography since 1923. In those days, Myanmar students were more interested in the prestigious and lucrative legal and administrative professions. The study of geology also required extensive periods of physically demanding work in the field, not an attractive prospect for educated people in Myanmar. Greater numbers of students were attracted to geography rather than to geology, to the point that the name of the department was changed to the Department of Geography and Geology. A separate Department of Geology was established in Rangoon University only in 1948, with the aim of producing professional geologists to guide exploration and exploitation of natural resources for the newly independent nation.
Dr Tha Hla was the first fully qualified Myanmar geologist and became the founder of the geological profession in the country. Initially, he was assisted by Indian geologists on short-term contracts. One of them was Bhimal Prasad Dey, who first identified the Sagaing Fault in Central Myanmar which he named the ‘Hninzee Fault’. In 1956 and 1957 Dr Tha Hla was joined by his first batch of students, notably Dr Nyi Nyi and U Ba Than Haq on their return from further studies in Britain, and U Saw Clarence Thacpaw on his return from studies in the USA. At that time, several geology graduates were selected for the university and other geological organizations in Myanmar, and were sent overseas for further studies in the various branches of geology.

In order to further expand training in the geological profession, a Department of Geology was established at Mandalay University College, Upper Myanmar in 1953. In the first year, the department was guided by U Ko Lay, the College Principal, assisted by U Thein Maung, the Head of the Geography Department and by Professor Dr Tha Hla of Rangoon University. In the following years, Indian geologists were engaged on short-term contracts. They were led by Mr D. Sarin, who remained as Head of Department for about ten years. Sarin was assisted occasionally by visiting expatriate professors, Professor Edward (Florida), Dr Anderson (UK) and Mr T.O. Morris (UK), supported by the Colombo Plan and Fulbright Scholar Program. Mandalay University College became the separate Mandalay University in 1958. Dr Tin Aye, a former graduate of the Mandalay Agricultural College who had later obtained a degree and a MSc in geology at the University of Iowa and a PhD at the University of Illinois in the USA (Tin Aye 1958), returned to Burma (Myanmar) to join the Geology Department. In 1961 he was appointed the first Professor of Geology at Mandalay University.

The departments of geology at Yangon and Mandalay universities are now well able to conduct teaching and research in the various specialized fields of the geosciences led by Myanmar geologists, many of whom have advanced degrees from overseas universities. Masters degrees in the various disciplines of the geosciences have been offered by both universities since the late 1960s; in the 1990s, the universities of Yangon and Mandalay offered doctorates. Like other major subject fields, the teaching of the geological sciences leading to Bachelor degrees has been extended to newly established colleges at Moulmein (Mawlamyine), Magway, Bassein (Pathein), Mohnyin and Taunggyi, all of which became universities in the 1990s.

Over the early years, notable contributions to the geology of Myanmar were made by geologists from the universities of Yangon and Mandalay. These included: ‘A note on the petrology and provenance of the Webu and Marble (Alabaster) Inscription Stones of the Kyaukse area’ by Tha Hla (1959); ‘The Mogok Belt of Burma and its relationship to the Himalayan Orogeny’ by Searle & Ba Than Haq (1964); ‘The Pre-Paleozoic and Paleozoic stratigraphy of Burma’ by Maung Thein & Ba Than Haq (1970); and ‘A preliminary synthesis of the geological evolution of Burma with reference to the tectonic development of Southeast Asia’ by Maung Thein (1973). More recently, the work of young Myanmar geologists has significantly improved our knowledge of the Palaeozoic and Mesozoic stratigraphy and palaeontology of the Shan Plateau, and our knowledge of the strike-slip activity, earthquake hazard and disaster potential of the Sagaing Fault from the Hukawng valley to the Andaman Sea. In addition, since the 1990s international attention has been focused on the primate fossils of the Eocene Pondaung Formation, known to be among the earliest in the world, due to the collaboration of Myanmar and international scientists with the support of the Government of Myanmar. These studies date back to Cotter (1914) in the pre-WWII period, in the 1970s by Myanmar and American geologists, in the 1980–90s by Myanmar and French geologists/primatologists and in the 1990–2000s by Myanmar and Japanese geologists/primatologists (e.g. Zin Maung Maung Thein et al. 2017). Recent LA-ICP-MS geochronology and U-Pb dating demonstrates that the earliest anthropoids originated in Asia rather than in Africa (Khin Zaw et al. 2014). In 1967 the most significant development for teaching and research on gem and jade deposits in Myanmar was implemented with the support of UNESCO. The project was led by Mr E.A. Jobbins, Keeper of Minerals and Gemstones in the Geological Museum, South Kensington, London on secondment from the Institute of Geological Sciences. The objective was to provide training and research for gemmological studies at university level and to generate a new breed of gemmologists/geologists of international standard capable of exploration, exploitation and marketing, thereby contributing to the development of Myanmar’s rich gemstone potential (Jobbins 1968). This project had a great impact and, in 1968, produced the first batch of 15 graduate diplomas of the Gemmological Society of London (FGA Lons.). These students included Dr Yin Yin Nwe (UNICEF) and Professor Khin Zaw (CODES ARC Centre of Excellence in Ore Deposits, University of Tasmania, Australia). The project had laid the foundation for the currently flourishing training and gemstone testing by private companies and universities in Myanmar, including research on gem materials (e.g. Kyaw Thu 2007; Khin Mar Phyu 2009; Yin Yin Myint 2009; Nwe Nwe Oo 2010; Win Win Htay 2010; Khin Zaw et al. 2015; Kyaw Thu & Khin Zaw 2017; Thet Tin Nyunt et al. 2017).

At the request of the Myanmar Government, the UNESCO project was followed by a major UNDP/Funded project to upgrade the technical ability of Myanmar geologists and to develop modern analytical facilities. In 1972 the ‘Post Graduate Training Programme in Mineral Exploration’ was established at the Arts and Science University, Yangon. This project employed several overseas mineral geologists from Canada, UK, USA and Belgium as counterpart experts for teaching courses in Mineral Exploration and Applied Geology. Notable overseas geoscientists included Professor E. Hale from Canada and Dr P.J. Goossens from Belgium. Young Myanmar geologists were sent to overseas universities for training in mineral exploration, later replacing the expert expatriates. This project made a profound contribution by producing Myanmar geologists with diplomas in applied geology, exploration geochemistry, and geophysics and mining. Most are now employed in government ministries. A fluid-inclusion laboratory was established under the UNDP scheme, and ore geneses and mineral parageneses of a variety of ore deposits in Myanmar were studied (e.g. Khin Zaw 1978, 1984; Khin Zaw & Khin Myo Thet 1983; Goossens 1978). However, due to international sanctions and political isolation Myanmar geoscience has stagnated since 1988. It will require a huge injection of funds for the up-skilling of the current work force and the training of the younger generation of geoscientists. Some progress has been made: there are now 29 universities in Myanmar offering bachelor’s degrees in geology, and several other colleges teaching geology as a subsidiary subject.

**Myanmar Geological Survey Department**

British Burma was administered separately from British India in 1937 and, in 1938, the Burma Geological Department (BDG) was established on the same lines as the Geological Survey of India (GSI) with the transfer of several GSI geologists, led by E.L.G. Clegg. However, the Second World War soon intervened and all geological work was suspended. In 1946 the BDG was re-established with E.J. Bradshaw as Director. Surprisingly, although a few students had graduated with
degrees in geology from the University of Rangoon before the war, there were no Myanmar geologists in Yangon University, GSI, BGD, the Burmah Oil Company (BOC) or any of the oil or mining companies at that time. The only qualified geology graduate was Dr U. Lwin. He had reputedly obtained a MSc degree in Mining and Geology from Stanford University, California, USA and worked with BOC for a while. He was a leader of the General Council of the Burmese Association (GCBA) in the 1920s, and then became immersed in national politics (Maung Maung 1969; Khin Maung Gyi 1973). Dr Ba Thi, a chemistry graduate from the University of Rangoon before the war, returned from studies in petroleum chemistry overseas to join BGD in 1946. When Myanmar became independent in 1948 he was appointed as the first Director, initially supported by several Indian geologists employed on short-term contracts.

Mineral Resources Development Corporation (MRDC)

The Mineral Resources Development Corporation (MRDC) was founded in 1952 with the aim of exploration and development of the mineral resources in the newly independent Myanmar. MRDC was administered by a Board of Directors chaired by the Minister of Mines. U Ba Tun, formerly of the Burma Civil Service, was appointed as Secretary to the Board and became the first Director General. Technical management of the MRDC was by U Minn Din (micropalaeontologist) and U Saw Aleric (mining geologist). The MRDC offered scholarships to outstanding students of geology at the University of Rangoon, with the possibility of employment in the Corporation on graduation. Subsequently, many geology graduates were employed by the Corporation in the Mines Department. Between 1959 and 1977 the Burma Geological Survey Department and the Mineral Development Corporation were assisted by the Colombo Plan, the United Nations Development Programme (UNDP), the Japan International Cooperation Agency (JICA) and Yugoslavia, supporting expatriate geologists working in Myanmar.

Colombo Plan geosciences projects (1968–76) were financed by the Ministry of Overseas Development of the UK, and provided scientists from the Institute of Geological Sciences who were seconded to or worked with counterparts in the Department of Geological Survey and Mineral Exploration. Geochemical exploration and geological mapping in the Nayyaungga and Ye-nan areas were reported by Garson et al. (1972, 1976). The latter included the subdivision of the Plateau Limestone in the Southern Shan State into three lithological units, which is still recognized today. Similar integrated surveys were conducted in the Seikphudaeng–Padatgyaung area (Bateson et al. 1972), Yadanatheingi and Kyaukmye–Longtawkno area (Mitchell et al. 1977), and Mount Popa area (Amos et al. 1981; Marshall et al. 1983; Stephenson et al. 1983). Geochronological age dates of samples provided by these projects were reported by Brook & Snelling (1976), and the samples collected in 1977 by Dr R.D. Beckinsale were analysed later by Darbyshire & Swainbank (1988). A geophysical survey by Greenwood & Thomas (1973) located what later became known as the Lepadaung copper ore body at the Monya Mine, currently the largest exploited copper deposit in Southeast Asia.

Gradually a national geological organization was developed in Myanmar, similar to the Geological Survey of India and other national geological organizations throughout the world. This organization is known as the Department of Geological Survey and Mineral Exploration (DGSE), and employs the largest number of geologists in Myanmar. Many of these geologists have received specialist training overseas in the various branches of the geosciences, for example: geophysics, geochemistry, micropalaeontology, photogeology, remote sensing, hydrogeology, engineering geology, petroleum geology, mining geology and laboratory techniques, etc. The DGSE, now under the Ministry of Natural Resources and Environmental Conservation, provides Myanmar with a service in the geosciences equal to that of other geological survey organizations elsewhere in the world.

The Geological Survey Division of DGSE is the successor of the BGD and has carried out integrated geological surveys and mineral exploration programmes over extensive areas of Myanmar, for example: the Geological Survey and Exploration Programme (GSEP) from 1974 to 1978 under the auspices of joint DGSE-UNDP projects in the Wuntho-Bamauk area, parts of the Western (Indo-Myanmar) Ranges in Chin and Rakhine (Arakan) States and the western part of the Shan Plateau; and departmental projects from 1974 to 1983 in Tanntharyi (Tenasserim), Myeik (Mergui) Archipelago, western Shan Plateau, Bago Yoma and the southern part of the Western Ranges in the Ayeyarwaddy (Irawaddy) Division and the adjoining parts of Rakhine State. It is intended that the Geological Survey Division should extend this programme throughout Myanmar. At the same time the Mineral Exploration Division of DGSE, the successor of MRDC, has carried out exploration of specific mineral occurrences in various parts of Myanmar. Integrated geological surveys have been conducted by DGSE in Kachin State since the year 2000, as well as continuing exploration for specific minerals in different part of Myanmar. The results of these DGSE surveys were published in annual progress reports for 1974–76 (DGSE 1975, 1976) and several UNDP-DGSE reports (United Nations 1978a, b, 1979a, b, c, d, e, f). Mitchell (e.g. 1981, 1989, 1992, 1993) has published several accounts of the regional geology of Myanmar, based on his work with Myanmar geologists on several projects funded by the Colombo Plan, UNDP and Ivahoe-Myanmar Holdings.

Other geological organizations in Myanmar

By the 1960s several government ministries had established geological departments, including the Mineral Development Corporation (MDC) or Myanmar Mineral Development Corporation (MMDC) under the Ministry of Mines. These organizations employed most of the geologists in Myanmar, collecting basic geological information and engaged in mineral exploration. Mining Corporation 1 (lead-zinc–silver and copper), Mining Corporation 2 (tin–tungsten and gold) and Mining Corporation 3 (industrial raw materials) were established under the Ministry of Mines. The Myanmar Oil Corporation (MOC), the successor of the Burmah Oil Company (BOC), was purchased by the Myanmar Government for 63.5 million Kyats in 1963. Since 1963 the petroleum industry has been managed by Myanmar nationals, U San Maung (General Manager) and Dr Aung Khin (Exploration Manager), who were instrumental in developing the Myanmar petroleum industry. The MOC, now known as Myanmar Oil and Gas Enterprise (MOGE), was administered under the Ministry of Mines until 1976 when it was placed under the Ministry of Industry; a separate Ministry of Energy was later established. The universities of Yangon and Mandalay, previously semi-government institutes, were brought under the Ministry of Education in 1964. In 1973 the Irrigation Department, which was under the Ministry of Agriculture and Forests, established a badly needed Engineering Geology Section headed by U Sann Lwin, a post-Independence graduate of Rangoon University and formerly a geologist with DGSE. This section developed into the Engineering Geology Division of the Department of Irrigation in the Ministry of Agriculture and Irrigation, and now employs a large number of geologists. In addition several geologists are employed in the Engineering Geology Section of the Ministry of Electric Power No.1, which is developing hydroelectric...
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power projects in Myanmar. Recently 16 engineering geologists became members of the Southeast Asian Geotechnical Society (SEAGS).

Another major contribution to the geology of Myanmar was made by the Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR), also known as the Federal Institute for Geosciences and Natural Resources, from the 1970s to the 1980s in a technical cooperation programme involving geological mapping, hydrocarbon exploration and seismic surveys in Kachin Sate and the Gulf of Martaban (e.g. Bannert 1980). The programme also included mineral exploration of nickel laterite at Tagaung Taung, gold exploration at Kawlin, lead–zinc at Bawdwin and Quaternary alluvial gold–platinum in the Chin-dwin area (e.g. Unger et al. 1996) in a project named the Eastern Chin and Arakan Mineral Survey (ECAMS) under Technical Service Corporation (TSC), then Ministry of Industry No. 2. ECAMS produced several interim and final reports (e.g. ECAMS 1982, 1985) and also culminating in The Geology of Burma by ‘the German team’ of Bender (1983) and his associates, with the co-operation of Myanmar geologists headed by U Than Htay and U Soe Win.

In 1967 a national committee was set up to co-ordinate the various geological organizations in Myanmar through the UNESCO International Geological Correlation Programme (IGCP). Field excursions have been organized annually to areas of geological interest under the auspices of the IGCP National Committee, led by geologists of MOGE, DGSE, Mining Corporations 1, 2 and 3, and Yangon and Mandalay universities. In 1977 the Earth Sciences Research Division prepared and published the first edition of the 1:1 000 000-scale Geological Map of the whole of Myanmar.

Major contributions to our knowledge of the geology of Myanmar and adjacent territories have been made by the Geo-dynamics of India/Asia Collision (GIAC) project funded by international oil companies working in Myanmar, led by TOTAL. This regional project was established to conduct fundamental research on geodynamics between the Indian and Asian plates. Other Southeast Asian countries have participated in this collaborative effort, led by French geologists and co-ordinated by Claude Rangin (CRNS, Nice University). In Myanmar, this project was joined by Myanmar geologists from MOGE and the universities (GIAC 1999). Many valuable scientific papers have been published as the result of this project in recent years (e.g. Bertrand et al. 2001; Bertrand & Rangin 2003; Maurin & Rangin 2009; Maurin et al. 2010), and this project is still ongoing.

Petroleum geology

Natural oil from seepages and shallow pits at Beme and Twigon in the Yenangyuan (=oil creek) in central Myanmar has been utilized by local people for medicine and preservatives from the earliest times. From the eleventh century, in the time of the Myanmar kings, oil was traded from the royal capital of Bagan. The right to extract oil in the area was granted by the king to 24 heads of families, known as Twinzoyos: Large quantities of crude oil were extracted by local people from hand-dug wells, some reaching depths of 130 m. Oil was also produced from shallow pits or wells from Yanbye (Ramree), Man-angun (Cheduba) and Phayongar (Baronga) islands along the Rakhine Coast. Crude oil was found to be useful in the preservation of wood, bamboo and cane in buildings, carts, furniture and domestic utensils, protecting them from fungal and insect damage. It was also used for protecting Buddhist texts inscribed on palm leaves.

The occurrence of petroleum in Myanmar was first reported in 1759 by Captain G. Baker, and later in 1800 by Major M. Symes, in 1825 by Captain H. Cox and in 1929 by John Crawford (Chhibber 1934b; Nyi Nyi 1964; Khin Maung Gyi 1973). The first account of the geological setting of the petroleum occurrences in the Yenangyau area was published by Thomas Oldham (1858), who noticed the relationship between anticlinal structures and petroleum accumulations. In 1857 crude oil from Myanmar was exported to England for the extraction of wax for candles, for use as a lubricant and in oil lamps for lighting. Reportedly, some oil was shipped to New York in 1859 (Anon 1946), the same year in which ‘Colonel’ Edwin Drake demonstrated that oil could be extracted by drilling at Titusville, Pennsylvania, regarded as marking the beginning of the modern petroleum industry. In 1871 much of Myanmar’s crude oil was sold to the Rangoon Oil Company (ROC), which established an oil refinery at Danidaw near Yangon for the production of wax for candles, the separation of kerosene for lamps and of heavier fractions for use as lubricants and fuel oil.

In 1866, immediately after the British annexation of Upper Burma, the Burmah Oil Company (BOC) was founded to be followed by many other smaller, short-lived oil companies. The BOC introduced cable tool and rotary drilling for extensive exploration in Central Myanmar in areas where local people had previously extracted oil from surface pools. Drilling was then extended to other areas in Central Myanmar. BOC bought up the ROC refinery at Danidaw, and subsequently established modern refineries in other parts of Myanmar.

Noëtling (1889, 1897), Pascoe (1912), Stamp (1927), Lepper (1933) and Tainsh (1950) provided accounts of the geology of the areas of petroleum occurrences. Later comprehensive accounts of the petroleum geology of Myanmar were provided by Aung Khin & Kyaw Win (1969), Bender (1983), most recently by Racey & Ridd (2015) in the Geological Society of London’s memoir on the Post-war Geology of Myanmar, and Win Maw (2017) and Than Htut (2017) in this volume.

Within a few decades the petroleum industry in Myanmar flourished and became one of the foremost industries in the British Empire. In 1941, at the outbreak of war in the Pacific, one of the main aims of the Japanese Government was to gain access to this petroleum resource. However, to deny access to the Japanese the British Government ordered the destruction of the oil wells and refineries in Burma.

After the war and after independence the oil industry was gradually re-established by the Burma Oil Company (1954) Ltd, a joint venture of the Myanmar Government and the oil companies which had been operating in the country. However, oil production never recovered to pre-war levels. Eventually in 1963 the Myanmar Government purchased the shares of the British partners in BOC (1954) Ltd and renamed the company the People’s Oil Industry (POI). Initially the POI was headed by U Sann Maung and later by Dr Aung Khin, a geologist and former student of Professor Dr Tha Hla at Rangoon University, assisted by post-war graduates of the universities of Rangoon and Mandalay. The POI gradually expanded its activities, and is now represented by the MOGE and the Energy Planning Department as well as other enterprises under the Ministry of Energy. In joint ventures with international oil companies, MOGE has recently identified extensive gas reserves in the Myanmar offshore areas (e.g. Zawtika, Yetagun, Shwe, Mya and Shwe Phyu).

Since the new democratic government took power in 2011, and with the partial lifting of sanctions, Myanmar has emerged as a leading exploration target for global and regional oil and gas explorers. Myanmar offered 30 offshore and onshore blocks for oil and gas exploration under Production Sharing Contract (PSC) agreements in 2016 (Figs 1.3 & 1.4). Interest with bidding has been shown by several major international companies such as Woodside, Daewoo, PTTE, Petronas, Total, Ophir, Unocal, Shell, PetroVietnam Chevron and BG with the collaboration of local partners. Most of these companies undertook extensive offshore seismic surveys during 2015–16. The Woodside Company of Australia recently
announced the discovery of a gas play in the Shwe Yee Htun-1 exploration well in Block A-6 in the Rakhine Basin in the western offshore area of Myanmar. The well intersected a gross gas column of approximately 129 m. Approximately 15 m of net gas pay is interpreted within the primary target interval (ASX listing, 4 January 2016).

Myanmar has a total of 19 sedimentary basins including 15 onshore (e.g., Central Myanmar, Chindwin and Salin basins) and 4 offshore basins (e.g., Moattama, Mergui and Rakhine). Although Myanmar has a long history of oil production since 1886, only one-third of the hydrocarbon-bearing areas has been explored using modern techniques; the actual potential for oil and gas reserves of Myanmar is unknown. Currently, hydrocarbon exploration is focused only on the Tertiary system; the pre-Tertiary systems are virtually untested (Lynn Myint 2015a).

Gem and jade industry

The gem and jade industries, involving both the government and the private sector, were previously controlled by the Ministry of Mines, now the Ministry of Natural Resources and Environmental Conservation, through the Myanmar Gems Enterprise. At the time of the Myanmar kings, it was decreed that gemstones of any size belonged rightfully to the king. Traditionally, nine different varieties of gems (Nawarat Koe Pa) were reputed to have mystical value in Myanmar: ruby, diamond, sapphire, emerald, zircon, pearl, coral, cat’s eye (usually Chrysoberyl cat’s eye) and topaz (although coral and pearl are not strictly minerals). In addition to these mystical nine gems, tradition also recognized other gemstones such as jade, tourmaline, spinel, garnet and peridot, all of which have indigenous Myanmar names. The largest Myanmar pearl (104.39 carats) came from the Mergui (Myeik) Peninsula. Among the beads found from the ancient Pyu people of Central Myanmar are amber and jade. Myanmar amber, known as Burmite, of Albian–Cenomanian age from Mongkweng, Kachin State contains some of the world’s oldest insects, including bees. Ruby and sapphire have been the best-known Myanmar gems for their quality since the earliest times. The extreme value of a Myanmar ruby is recorded in an inscription on stone at the Manuhar Pagoda in Bagan, erected during the reign of King Anawrahta (AD 1044–77). Western merchants, such as the Genoese Hieronimo de Santa Stefano who travelled in Myanmar and visited Pegu (Bago) and Ava (Inn-wa) in 1496, commented on the abundance of rubies and other precious stones. The Bolognese Ludovico di Varthema visited Tenasserim and Pegu around 1505–06. He described the king in Pegu as wearing rubies to the value of a large city (Myo Min 1947). Caesar Fredericke, who visited Pegu in 1569, reported that there was a brisk trade in rubies and that the King of Burma at Hanthawaddy was ‘The Lord of Mines of Rubies, Saffres and Spinels’. He added that the king was so rich that the ‘idols’ in the court were decorated with the ‘rarest rubies and safires’ (Chhibber 1934b). Ralph Fitch, who was the first Englishman to visit the Kingdom of Pegu in 1586, reported

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*Fig. 1.3. Map showing petrolierous basins and petroleum and gas tenders for Production Sharing Contract (PSC) agreements in Myanmar (map courtesy of Lynn Myint 2016).*

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Fig. 1.4. Map showing offshore and onshore blocks for oil and gas exploration concessions and pipelines in Myanmar (map courtesy of Lynn Myint 2016).
that the ruby mines were in the district of ‘Caplan’ (Kyatpyin), six days journey from Ava in the Kingdom of Pegu (Nyi Nyi 1964). None of these foreign visitors to Pegu were permitted to visit the mining areas.

At the present time, rubies, sapphires and other less valuable gemstones such as spinel, garnet, peridot, apatite, feldspar and felspathoids are mined mainly in the Mogok area where the gems are found in marble and syenite, and as placer deposits (Hughes 1997; Kyaw Thu & Khin Zaw 2017). More recently, previously unknown or little-known areas such as Pyenglong, Mong Hsu, Namsa-hka and Nanyazeik have been actively mined and have produced considerable quantities of inferior-quality gemstones.

Burma Ruby Mines Ltd was established in 1887 by a British jeweller, Edwin Streeter, under exclusive license with the Indian Government. The company intended to develop both underground and open-cast mechanized mining and the washing of placer deposits throughout the Mogok Stone Tract. A hydroelectric generating plant, the first in Asia, was built in 1898 to power some of the machinery. Flooding of the workings during the rainy season was a major problem until a tunnel was drilled 30 m below the workings to carry away the water. The business was highly lucrative until 1908, when gem prices began to fall due to the arrival of synthetic gemstones on the market. Ruby prices were further depressed during the First World War; after the war the company was badly managed and made unwise decisions. Eventually it was decided that mechanized mining was too expensive; the company went into voluntary liquidation in 1925 and was declared bankrupt the following year. By this time output had declined so much that the company merged with the Burma Mines Development and Agency, obtaining a lease in the area which covered four square miles. The enterprise changed hands several times before being taken over by the Burma Corporation Ltd (Chhibber 1934b). Initially the company smelted slag left by the old miners at Mandalay, but also conducted intensive exploration in the Bawdwin area. Ore was discovered at deeper levels and the company developed a successful modern mine at Bawdwin, with an ore dressing plant and smelter in the Namtu area. Before the Second World War the mine became the most important in Myanmar and in the whole of the British Indian Empire. Production ceased during the earlier part of the war, but the Japanese reopened the mine until the concentrator plant was severely damaged by allied bombing. After the war the mine was rehabilitated by the Burma Corporation (1951) Ltd. However, production never reached pre-war levels, due to the lack of an adequate concentrator plant. The Bawdwin Mine was nationalized in 1965. Oxidized near-surface ore is now being mined because the rich underground ore at Bawdwin has declined gradually in reserve and grade.

In addition to lead and silver, the Bawdwin ores contain zinc, copper, antimony and nickel. Old slag containing zinc still remains at the smelter site and the original copper-rich portion of the ore body remains in place at depth in the mine. The administration of the mine and extraction of lead, zinc, silver and copper is the responsibility of the No. 1 Mining Enterprise of the previous Ministry of Mines. The geological setting, exploration and mining of the Bawdwin Mine is described by Gardiner et al. (2017) and the history and origins of the other lead–zinc–silver deposits in Myanmar are discussed by Than Htun et al. (2017a).

**Copper**

Several copper occurrences are known in Myanmar (Khin Zaw et al. 2017); the most important is the high-sulphidation copper deposit known as the Monywa deposit on the left bank of the Chindwin River, opposite Monywa City (Myint Soe et al. 2017). Attempts had been made to mine this deposit from the time of the Myanmar kings but this low-grade, large-tonnage high-sulphidation copper type of mineralization requires the use of heavy mining equipment and modern metal extraction techniques, requiring substantial investment for the development of a successful mining operation. This type of deposit occurs in magmatic arcs all around the Pacific Rim and along the Alpine–Himalayan Tethyan Orogenic Belt. Successful methods for the exploitation of these deposits, in contrast to the rich ores of lode type, were only developed at the beginning of the twentieth century. It has taken some time for mining of the Monywa deposit to be developed successfully.

Since 1952 when the MRDC was formed, the huge Monywa deposit has been explored by drilling and studied for resource assessment. These studies have been carried out by MRDC and DGSE geologists with the support of the Colombo Plan, UNDP, JICA and Yugoslavia, and the assistance of expatriate geologists. Mining became fully operational in 1986 and pure metallic copper has been extracted since 2000. The ore deposit fortunately contains the minerals chalcocite and covellite, which are soluble in acid and amenable to solution with the electrolytic extraction (SX-EW) of pure copper. The Ivanhoe Mining Company reported that this deposit is of world class, and forms the
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second-largest source of copper in Southeast Asia. The deposit was sold recently by the Ivanhoe Mining Company and is currently operated by the Wabao Company of China.

Chromite–nickel ± platinum

Myanmar has sizeable nickel-chromite ± PGE deposits associated with three north–south-trending ophiolitic belts of Jurassic to Cretaceous–Eocene age: the Western Ophiolitic belt (WOB); the Central Ophiolitic belt (COB); and the Eastern Ophiolitic belt (EOB) (Hla Htay et al. 2017; Khin Zaw et al. 2017). Chromite mineralization occurs as pods and disseminations in serpentinitized dunite and peridotite. The most significant lateritic nickel deposits occur at Tagaung Taung and Mwetaung. The Tagaung Taung nickel deposit is in the Tigyaing township (Htiyagya township), Katha district, Sagaing division in the EOB of northern Myanmar and the mine is currently operated by the China Nonferrous Metal Mining (CNMC) Group. The Mwetaung lateritic nickel deposit is in weathered peridotite and serpentinite of WOB in the Chin State. The feasibility studies was completed in 2014 by a joint venture of Jinshang (Hong Kong) International Mining Company (100% subsidiary of Zijin Mining Group), China North Industries Corporation and Myanmar Government. Secondary PGE–Au mineral occurrences are also found in Quaternary placers in the Upper Chindwin and Uyu rivers and in the area around Lake Indawgyi.

Tin and tungsten

Tin and tungsten minerals occur in pegmatite and quartz veins along the margins of granitic bodies and in sedimentary rocks close to intrusive granitic contacts (Mi Palk 2017; Than Htun et al. 2017b). Primary tin and tungsten, and associated detrital and placer deposits, have long been known to occur in a linear belt extending northwards from Tanaungtharyi (Tenasserim) along the western margin of the Shan Plateau to the Yamethin area, forming the northern branch of the Southeast Asian Tin belt, which continues southwards through Peninsular Thailand and Malaysia to the Indonesian islands of Bangka and Billiton. Mining and smelting of tin was carried out by local people in Myanmar long before the arrival of the British. In 1599 an English traveller, Ralph Fitch, reported that there were great stores of tin in Tenasserim, which supplied the whole of India. In the 1930s the Mawchi Mine in Kayah State (Aung Zaw Myint et al. 2017) was the most important source of tungsten in the world; during the First World War, and again in the Korean War, the Mawchi Mine and other tungsten-rich mines made huge profits when tungsten prices were unusually high.

Placer tin is being mined north and east of Dawei (Tavoy) in the Tanintharyi (Tenasserim) areas. toddlers and placers, calc-silicates and gneisses (e.g. Thabeikkyin-Kwinthonze). Tin and tungsten minerals are stibnite, antimony, arsenic and rare native antimony. The Palaeozoic stratabound antimony ores in Myanmar are formed as shallow, low-temperature hydrothermal deposits filling fissures, joints, shear zones and selectively replacing rocks, showing preference for massive carbonates. The antimony minerals in Myanmar are stibnite, arsenic, valentinite, cervantite, kermesite and rarely native antimony. The Palaeozoic stratabound antimony deposits are the most important style of mineralization in Myanmar (e.g. Tha Buyu and Natsan). At Lebyin, the stibnite veins are hosted in greywacke, quartzite and shales of possible Carboniferous age and closely associated with Mesozoic granite intrusion; antimony may be accompanied by arsenic and gold. The geological settings, classification, distribution and origins of the antimony ores in Myanmar are described by Toe Aung Kyaw (2017).

Antimony

Antimony is currently a 'critical metal' in the world economy and in 2014 Myanmar became the second largest producer of antimony ores in the world, after China (Toe Aung Kyaw 2017). Antimony deposits are widely distributed in Kayah, Kayin and Mandalay Region of Myanmar. The majority of antimony deposits in Myanmar are formed as shallow, low-temperature hydrothermal deposits filling fissures, joints, shear zones and selectively replacing rocks, showing preference for massive carbonates. The antimony minerals in Myanmar are stibnite, arsenic, valentinite, cervantite, kermesite and rarely native antimony. The Palaeozoic stratabound antimony deposits are the most important style of mineralization in Myanmar (e.g. Tha Buyu and Natsan). At Lebyin, the stibnite veins are hosted in greywacke, quartzite and shales of possible Carboniferous age and closely associated with Mesozoic granite intrusion; antimony may be accompanied by arsenic and gold. The geological settings, classification, distribution and origins of the antimony ores in Myanmar are described by Toe Aung Kyaw (2017).

Gold

Gold occurs in placer deposits and in unconsolidated or poorly consolidated Quaternary–Recent detrital sediments and as primary deposits in quartz veins in igneous and metamorphic rocks in many parts of Myanmar (Ye Myint Swe et al. 2017). Placer deposits are well known in the Central Myanmar Belt in the Chindwin, Upper Ayeyarwaddy (Irrawaddy) and Sittang valleys, the Wuntho volcanic-plutonic region and in Quaternary gravels of the Momeik-Bamaw tract. Indigenous mining has been conducted in several areas since the time of the Myanmar kings, when the local people paid an annual tribute to the king in gold. As placer gold is so widespread, primary gold deposits can be expected in the upper reaches of the river drainage basins.

Quartz veins with gold mineralization are widespread in the Wuntho volcanic-plutonic region and on the western margins of the Shan Plateau in the Slate Belt and the Mogok Metamorphic Belt (MMB). Mining of primary gold deposits has been conducted at Kyaukpazat to the north of Wuntho since before the First World War, and continues at a small scale today by a local company. Private companies are also working presently in the Wuntho-Bamauk area and in several areas along the western margin of the Shan Plateau, including Modi Taung, east of Tatkong and Phayaung Taung, NE of Mandalay. Most of the primary gold deposits are mesothermal orogenic mineralization, but the Kyaukpahto gold ores in the Kayin area are Carlin-like sediment-hosted deposits in Eocene turbiditic sandstones and are found to be highly refractory (Khin Zaw 2008; Ye Myint Swe & Cho Cho Aye 2009). Gold mineralization in the MMB occurs as skarn-type or as orogenic gold-quartz veins in marbles, calc-silicates and gneisses (e.g. Thabeikkyin-Kwinthonze area). Gold mining, together with tin and tungsten mining, was previously administered by the Ministry of Mines but now by No. 2 Mining Enterprise of the Ministry of Natural Resources and Environmental Conservation.

Geological hazards

Myanmar, situated in a tectonically active zone of continental collision, oceanic subduction and strike-slip faulting, is a highly seismic zone and is extremely earthquake prone with many recorded earthquakes (Oldham 1833; Brown & Leicester 1933; Chhibber 1934a; Thawbita 1976; Win Swe & Win Naing 2008; Than Tin Aung et al. 2008; Wang Yu et al. 2011, 2014; Rangin 2017; Sloan et al. 2017). A total of 44 earthquakes with $M_w \geq 1.5$ were recorded in 2014. Notable historical earthquakes occurred in 1839 at Inn-wa, in 1930 at Bago, in 1975 at Bagan and in 2003 at Taungdwingyi. However, not all instrumentally recorded earthquakes produce...
significant effects such as the destruction of buildings or other infrastructure or deaths in the population. These effects depend on the magnitude of the earthquake, its depth, the amount of movement, the nature of the substrate (with the effects being less on solid rock and greatest on soft alluvial sediments) and on the density of the population in the affected area.

It is estimated that 3 cm of the average 5 cm annual movement between the Indian Plate and Southeast Asia is taken up by strike-slip and thrust motions, distributed among numerous faults in the Indo-Myanmar Ranges of Myanmar. The remaining 2 cm is taken up along the Sagaing and associated strike-slip faults further east (Vigny et al. 2003). Earthquakes of Richter magnitude 4.3–4.5 are extremely frequent in the India–Myanmar border region and along the Rakhine Coast, with 12 events in the first 5 months of 2012. The depth of earthquake hypocentres related to the eastwards subduction of the Indian Plate beneath Myanmar increases from >50 km along the Rakhine Coast to c. 250 km beneath the Central Lowlands (Satyabala 2003). Further east, a concentration of shallow hypocentres is related to strike-slip movements along the Sagaing Fault and related faults, extending northwards from the Ayeyarwaddy Delta into the Central Lowlands. In 1975 the magnitude 6.5 earthquake on the Richter scale occurred near Bagan, the ancient capital of Myanmar. Fortunately, the earthquake occurred in a sparsely populated area and only one person was killed; several ancient monuments were, however, damaged, in particular near the Ayeyarwaddy River, and three production rigs in the Chauk oilfield were toppled. The cost of the damage was estimated at $500 000. According to the Myanmar Director of Archaeology, this was the worst earthquake recorded in Bagan over the last 1000 years.

Hurukawa & Maung Maung (2011) relocated six historical earthquakes of $M_s \geq 7.0$ which had occurred since 1918 along the Sagaing Fault. They identified two seismic gaps along which earthquakes of up to $M_s 7.9$ may be expected in the near future. This is significant since the trace of the fault passes through Nay Pyi Taw, the recently established capital of Myanmar. The Myanmar Earthquake Committee (MEC) in collaboration with the Earth Observatory of Singapore (EOS), Nanyang Technological University commenced a research programme along the Sagaing Fault in 2010, establishing Geographical Positioning Systems (GPS) adjacent to the fault to monitor present-day movements. The group is excavating historical trenches along the trace of the fault to determine the timing and slip rate of past phases of movement along the fault, in collaboration with Japanese universities, EOS and Royal Holloway University of London (e.g. Than Tin Aung et al. 2006; Tsutsumi & Sato 2009; Wang et al. 2011, 2014; Soe Thura Tun & Watkinson 2017; Soe Min et al. 2017).

Earthquakes with scattered hypocentres occur in eastern Shan State near the borders with China, Laos and Thailand related to strike-slip movements in the central part of Southeast Asia, extending into China. In 2011 an earthquake of magnitude $M_s 6.8$ occurred in eastern Shan State near Tachileik, adjacent to the borders with Thailand and Laos. A total of 73 people were killed and houses, government buildings, Buddhist monasteries, roads and bridges were damaged.

Myanmar is also exposed to other natural hazards, especially storms, cyclones, floods and landslides, often leading to disasters that affect many more people than earthquakes. For example, earthquake-related disasters have led to 812 reported deaths since 1930, while floods and landslides resulted in 145 598 deaths over the same period (Centre for Research on the Epidemiology of Disasters 2017). Floods in 2015 affected 12 out of 14 states and regions, displaced over 1.6 million people, and directly affected more than 5 million people in terms of damage to livelihoods, public and private infrastructure and extensive impacts on the agriculture sector. Losses to the economy due to these floods and landslides were estimated at about 1.7% of 2014 gross domestic product (Government of the Republic of the Union of Myanmar 2015). The worst-hit areas were in the central and western part of the country, based on rainfall and river discharge data provided by the Department of Meteorology and Hydrology. The department conducted hydrological simulations over the period 1979–2015 using satellite-derived data, and performed extreme-value analysis (Gumbel). These analyses characterized the 2015 floods as a rare event, one with an estimated return period of 20–50 years depending on the location within the Ayeyarwady subcatchments (Government of the Republic of the Union of Myanmar 2015).

The floods also caused morphological changes leading to river bank erosion, newly eroded river channels and landslides in mountainous areas. In Hakha Township in the Chin State, unprecedented rainfall caused devastating landslides. During the last week of July 2015, over 30% more rain fell on Hakha than in any other month over the past 25 years. The monthly rainfall of July 2015 measured at the weather station in Hakha would be equal to a 1-in-1000-years rainfall. This, combined with the nature of mudstone, shale and colluvial deposits around Hakha, explains the widespread and devastating landslides and, in particular, the reactivation of a large, old and deep-seated landslide on which parts of Hakha had been built, as revealed by a detailed geological and geo-engineering study (Win Myint et al. 2015). The massive landslide affecting Hakha was known locally as the Rung Taung Landslide and has elsewhere been called the Tonzang Landslide, the largest non-seismic landslide for a decade. Satellite and seismic data showed that the landslide measured 5.9 km from the crown to the toe of the deposit, with a mass of 395 million tonnes (Ekstrom & Stark 2013). The Rung Taung and other landslides caused extensive destruction to roads and homes; in Hakha, hundreds of houses were relocated to a safer area.

The huge tsunami generated by the December 2004 earthquake, with an epicentre off the coast of Sumatra, caused considerable destruction and loss of life in eight countries around the Indian Ocean. In Myanmar, with 71 fatalities (Satake et al. 2006), the tsunami was much less destructive than in Sumatra, Thailand and Sri Lanka, but life in low-lying coastal communities in Rakhine State and parts of Ayeyarwaddy and Tanintharyi regions suffered major disruption, with the loss of livelihoods due to the destruction of fishing boats and fishing nets. Unfortunately these same areas were more severely affected a few years later by cyclone Nargis in 2008; the 4 m high wall of water left at least 140 000 dead and hundreds of thousands homeless, with rice fields inundated and rendered unproductive by the influx of salt water.

Environment and sustainability of resources

Myanmar is endowed with abundant natural and mineral resources. However, as in many other developing countries, Myanmar is suffering from environmental degradation as a result of deforestation with concomitant soil erosion and the release into the environment of waste materials containing deleterious chemicals from mining, industrial processes and modern agricultural practices.

Environmental degradation and social impacts have increased in recent years due to the application of unregulated methods in mining and processing to increase productivity. The growing trend towards new mining methods, particularly the shift from underground to open-cut methods and to mining and processing of low-grade ores, will contribute to the generation of large volumes of waste rock and tailings; these present a major challenge for disposal, particularly in the Jade mining area of Phakant, northern Myanmar (Kyi Htun 2014). The
absence of an efficient legal framework for artisanal and small-scale mining (ASM) for gold and gemstones, together with the application of mechanized mining, contribute to the adverse environmental and social impact of mining operations. Myanmar’s newly promulgated environmental law (2012) provides for training, community engagement and corporate social responsibility (CSR) are critically important for the sustainability of the industry. Strict environmental guidelines need to be established and implemented for mineral and energy exploration and mining and processing to avoid pollution, acid mine drainage and cyanide, mercury and arsenic contamination. By doing so, revenues from the mining and extractive industries can be utilized, there will be nothing left for future generations to enjoy. The participation of communities in the conservation of the environment. Efficient guidelines are needed, and continuous monitoring and life-cycle assessment (LCA) are essential for the greening of Myanmar’s mining sector.

Despite the fact that Myanmar is endowed with world-class resources, the mineral industry is still in its infancy due to several decades of isolation. As the extractive industry in Myanmar (including the energy and mineral sectors) is now in a renaissance stage, transparent management plans/programmes for training, community engagement and corporate social responsibility (CSR) are critically important for the sustainability of the industry. Strict environmental guidelines need to be established and implemented for mineral and energy exploration and mining and processing to avoid pollution, acid mine drainage and cyanide, mercury and arsenic contamination. By doing so, revenues from the mining and extractive industries can benefit future generations and the development of the country without the ‘curse’ of polluting resources in the future (Khin Zaw 2015a, b, 2016).

In order to achieve sustainable development, all the PSC operators have to conduct Environmental, Social and Health Impact Assessments related to petroleum operations, and submit specific environmental management plans before the start of work programmes. PSC operators should also be required to submit a CSR programme throughout the period of exploration and production, with huge untapped oil and gas reserves and a strategic location adjacent to the giant energy consumers of China, India and Thailand. Myanmar has recently become a ‘hot spot’ in the Southeast Asia region for international petroleum players (Lynn Myint 2015b).

Sustainable growth and development is an essential requirement, not only for the extraction of the mineral and energy resources of Myanmar, but also for the protection and preservation of the country’s geohistory with the establishment of well-regulated geoparks, geo-ecotourism and agrotourism. Within the framework of the UNESCO GeoPark program (http://www.unesco.org/new/en/natural-sciences/environment/earthsiences/unesco-global-geoparks/), Myanmar is on the verge of joining the UNESCO Global Geoparks network (U Than Htun, pers. comm. 2017). Myanmar has internationally significant monumental geosites suitable for the establishment of geoparks, such as Mt Popa Volcano near the cultural city of Pagan, which has a geological as well as a national/historical heritage, and the Hukawng Valley in Kachin State. Other potential sites include the Padaukpin Coral Reef in Northern Shan State, which is world-renowned as a site with a diverse Palaeozoic fossil assemblage. This site contains a marine biota that flourished in the Palaeoetethys Ocean, similar to the present-day diverse faunal and floral community around the Galapagos Islands. In addition, there are many caves throughout the country and also gem and jade mining areas in northern Myanmar. All these sites are currently being badly exploited and maintained; they are rapidly disappearing and the environment is becoming hugely degraded. If these assets are not properly managed and regulated, there will be nothing left for future generations to enjoy.

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