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Developments in the geological exploration of Nepal

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ABSTRACT

Prior to 1950, only sporadic geological observations by a few visitors were made in Nepal. With the opening of the country to foreigners in 1950, Nepal soon came into the focus of interest in Himalayan geology. It was the time of the classical "descriptive geology" with mapping as the primary objective. Several excellent monographs and the first geological maps of different parts of the Nepal Himalaya were produced. The best results were obtained in the richly fossiliferous "Tibetan" sedimentary zone in the north, whereas descriptions of the Central Crystalline zone and of the thick, unfossiliferous metasediments of the Lesser Himalaya reflected mainly the widely differing interpretations and conflicting views of the investigators; nappe structure vs. block tectonics was the main issue.

With the advent of plate tectonics in the late 1960s, the Himalaya became the "collided range". Microstructural, mineralogical and geochemical studies in the search for stress and heat effects of subduction and collision on structure, metamorphism and magmatism became dominant and in Nepal concentrated on the Main Central Thrust, which was treated in terms of post-collisional continental subduction. With it went a shift of emphasis from field to laboratory work, from observation to interpretation, from mapping to modelling, from fact to theory.

The last thirty years were characterised by the strengthening and diversification of geological institutions in Nepal with the creation of a National Seismological Centre, the beginning of petroleum exploration in the southern foreland of the Himalaya, an intensification and modernisation of classical geological surveying and a strong engagement in the application of geology for engineering and natural hazard assessment purposes.

Keywords: Nepal, geological mapping, petroleum exploration, mineral exploration, seismic hazard assessment

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EARLIEST INVESTIGATIONS

Prior to 1950, geological investigations in Nepal were limited to sporadic observations by a few occasional visitors. Nevertheless, those first observations revealed already some characteristic aspects of Himalayan geology.

The first references to geology are found in the voluminous "Himalayan Journals" of Hooker (1854), who styled himself "a naturalist" and dedicated his work to Charles Darwin. He described his trip to the middle and upper Tambur Valley in eastern Nepal, which he ascended up to the Tibetan border, noting down everything that aroused his interest: flowers, trees, birds, wild animals, insects, the villagers and their agricultural activities, and also the rocks. He identified mainly mica-schists, gneisses and granites. He mentioned the frequent occurrence of tourmaline in the granites and the fact that the granites often appear as veins in the schists, parallel to the lamination of the latter. In the Valley of the Pemmi, an eastern affluent of the middle Tambur, Hooker noticed that mica-schists make up the slopes below about 1500 m altitude, whereas gneisses predominate at higher levels – the first recognition of the widespread Himalayan phenomenon of reversed metamorphism.

Twenty years later, Medlicott (1875) walked up the old footpath leading from the Indian border via Hetauda, Chisapani, Kulikhani and Thankot to Kathmandu, the only access to the capital of Nepal at that time. On the Chandragiri Pass he discovered what has remained till today one of the extremely rare fossil localities known in the Lesser Himalaya. He also studied the hills north of Kathmandu and the Trishuli Valley.

It then took 60 years for the next geologist to visit Nepal. This was Auden (1935) from the Geological Survey of India, who in the wake of the Bihar earthquake of 1934 made several traverses in eastern and central Nepal. He, too, saw the fossils of Chandragiri, which he attributed to the Early Palaeozoic (later specified as Cambro-Silurian). Moreover, he recognised the fossiliferous beds as forming the core of a large synformal structure (later to become known as "Mahabharat Syncline") and as underlain with apparently normal stratigraphic contact by the thick metasediments that build up the flanks of the syncline. In eastern Nepal, Auden compared the extensive gneiss masses of the Arun and Tambur Valleys with his "Darjeeling Gneisses" of neighbouring Sikkim, which he believed to form one or several large nappes rooted in the Central Crystalline and thrust south over his "Daling Schists" – Auden's explanation for the reversed metamorphism.

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In 1939, Heim and Gansser published their classical memoir "Central Himalaya", in which they described and illustrated in great detail their observations of 1936 at the Darjeeling Mountain front and, mainly, on numerous traverses in the Kumaon Himalaya in the immediate western neighbourhood of Nepal. They confirmed the important role of thrust tectonics, which Auden had already recognised in the nearby Garhwal Himalaya, identifying particularly two major thrust faults, the Main Central Thrust and the Main Boundary Thrust. Included in their studies was the Nepal side of the upper Kali Ganga Valley, the border valley between Kumaon and Nepal, as well as the Tinkar Valley in northwestern most Nepal and the adjoining border region of Tibet to the north. Near the Tinkar Pass in the Tibetan zone ("Tethys Himalaya"), they found a nearly complete Palaeozoic-Mesozoic sedimentary section, in which the discovery of a rich Triassic ammonite fauna was specially noteworthy.

Apart from the above-mentioned few, widely scattered observations on Nepalese territory, however, all geological research in the Himalayas prior to 1950 was made outside Nepal.

PERIOD OF CLASSICAL "DESCRIPTIVE GEOLOGY"

The situation changed radically in 1950, when Nepal opened its borders. Among the first foreign advisors to be invited to the country was the Swiss geologist Toni Hagen. He still had to use the old footpath over the Chandragiri Pass to reach Kathmandu. During a 10-year arduous, systematic geological survey under the patronage of the United Nations he investigated virtually the whole country, accumulating an enormous amount of data. In the geological exploration of the Himalayas, Hagen's pioneer work is unparalleled. Although a great part of his material, unfortunately also most of his geological maps, remained unpublished, his essential results appeared in several preliminary papers and in two of the intended six final volumes, both richly illustrated. Vol. 1, entitled "Preliminary Reconnaissance" (Hagen 1969), is a kind of anticipated summary of the geology of Nepal with emphasis on the structural aspects. Vol. 2 (Hagen 1968) represents a geological monograph (including a coloured map) of the Thakkhola, a key area for the understanding of the structure of the High Himalaya.

Hagen developed his elaborate nappe concept right at the start of his investigations in the Kathmandu Region of Central Nepal, where Auden had recognised the synclinal structure of the Mahabharat Range. Here, Hagen introduced the fundamental distinction between a "Kathmandu Series" and a "Nawakot Series". With the former name he designated the high-grade metamorphic and crystalline rocks which form the bulk of the Mahabharat syncline, opposing them to the underlying "Nawakot Series", the weakly metamorphosed sediments constituting much of the broad Midlands to the north and the narrow Suparitar Zone to the south. Of the two rock complexes, Hagen considered the Kathmandu Series as the older one and its position on the Nawakot Series therefore as due to tectonic emplacement, interpreting it as an erosional relict of a once extensive crystalline nappe rooted in the Central Crystalline and thrust south onto the Midland sediments. Moreover, based on what he thought to be repetitions within the lithological ,, sequence of each of the two series, Hagen subdivided each into further thrust sheets, arriving thus at a whole pile of several "Nawakot nappes" followed by several "Kathmandu nappes". He then extended this nappe scheme to the whole of Nepal, distinguishing additional nappes in the western and eastern parts of the country.

After Hagen, other geologists soon came to Nepal, many with a strong Alpine background and attracted primarily to the high range in the north with its lure of the "roof of the World". Some were attached to the mountaineering expeditions of the 1950s, like Lombard (Mt. Everest)) or Bordet (Makalu). Many outstanding geological memoirs and maps of different sectors of the High Himalaya were produced by these investigators. Examples are the Everest-Makalu Region (Bordet 1961), the Thakkhola Region (Bordet et al.. 1968), the Dolpo Region and Dhaula Himal (Frank and Fuchs, 1970) or the Annapurna, Manaslu and Ganesh Himal (Colchen et al., 1986). Among the most important results of these studies in the high range were detailed descriptions of the stratigraphy and structure of the "Tibetan Zone" in the north, composed essentially of a conformable, richly fossiliferous Palaeozoic-Mesozoic sedimentary sequence normally overlying the "Central Crystalline", the very "backbone" of the High Himalaya.

Quite a different picture emerged in the less spectacular but economically more important Lesser Himalaya (Midlands and Mahabharat Range) with its great thickness of unfossiliferous metasediments. Here, Hagen's structural concept with its multitude of nappes became highly disputed. Although he had recorded carefully the rocks observed along his numerous traverses, we miss a clear, consistent stratigraphic scheme that would allow to characterise and distinguish his many nappes or, at least, to clearly define his Kathmandu and Nawakot Series, whose distinction formed the basis for his whole nappe scheme. Also, the Main Central Thrust (MCT), the postulated tectonic separation between the two series, did not show up in outcrop as a distinct thrust-line, but as a transitional zone of reversed metamorphism. Moreover, this "thrust zone" showed frequently a very steep to almost vertical attitude in both flanks of the Mahabharat syncline; this and abundant normal faults of various orientation threw doubts upon Hagen's concept of nappes with long horizontal transportation.

Hagen's successors in the Lesser Himalaya thus generally rejected his profusion of nappes, although many accepted nappe structure in principle, attributing the enormous cumulative thickness of metasediments to stacking of thrust sheets. They tried to define their thrust planes as demonstrable tectonic breaks in the normal rock sequence. This required the clarification of the Lesser Himalayan stratigraphy, which in the absence of palaeontological support had to rely entirely on lithology and remained accordingly subjective and controversial. In western Nepal, such attempts were made, e.g., by Frank and Fuchs (1970) and by Remy (1975), in eastern Nepal by Bordet (1961) and by Maruo and Pradhan (1977). Efforts were also made to find discontinuities in mineral content, in metamorphic grade or in structural style as indicators of thrust planes, in particular the MCT (e.g. Colchen et al. 1986).

Other geologists, among them many Indian and Japanese investigators, were reluctant to accept nappe tectonics for the Lesser Himalaya altogether. In their view, the present structure could be explained by normal faulting and block tectonics. Nadgir et al. (1968-73) saw in the Kathmandu Series the normal stratigraphic continuation of the Nawakot Series, the two forming a single, continuous sequence, with the higher metamorphism in the Kathmandu Series induced by the granite intrusions and by migmatisation (banded gneisses). For Arita et al. (1973), the Mahabharat Range represented an uplifted autochthonous block, bounded and dissected by numerous vertical faults; they considered the Nawakot and Kathmandu Series as stratigraphically in part overlapping, with local migmatisation and granite intrusions solely responsible for the differences in metamorphism.

Stöcklin and Bhattarai (1980), while mapping the Mahabharat Range in its central sector, worked out the stratigraphic details necessary to define and distinguish the Kathmandu and Nawakot Series. A number of distinctive lithologic marker horizons, which they traced persistently on the ground over great distances, allowed the shape and internal structure of the Mahabharat syncline to be lined out in considerable detail. Complications appeared in the northern flank and the eastern wing of the syncline, where a strong, but localised, selective migmatisation obliterates what elsewhere was found to be the normal stratigraphic sequence and the normal, upward decreasing regional metamorphism of the Kathmandu Series. The study showed that in the Lesser Himalaya a sufficiently detailed stratigraphy is not only an aim in itself, but also a precondition for obtaining a clear structural picture. Moreover, it showed stratigraphy to have its part in the control of certain mineralisations, copper in particular.

The studies of the different investigators mentioned so far were characteristic of what we may call the classical "descriptive geology". Field observation, geological mapping and the description of the observed facts in terms of lithology, stratigraphy and structure were the main objective. The author's interpretations and hypotheses were of secondary importance.

PLATE TECTONICS

Heim and Gansser (1939) had designated the Tibetan zone north of the Central Crystalline as *"Tethys Himalaya"*, describing it as *"made essentially of marine deposits... squeezed and pushed up out of an old sea"*. With this they referred to the "Tethys Sea", which had been conceived in the late 19th century by Eduard Suess as a long-stretched, narrow seaway separating the old Eurasian and Gondwanian Continents, and out of which the Alpine-Himalayan chains were born. Suess' Tethys became a classical example of a geosyncline. The history of the Alpine–Himalayan chains became the history of subsidence, compression and inversion of the Tethys.

This widely accepted view was profoundly revolutionised after the mid-1960s by the new theory of plate tectonics:

- As a geosyncline, the Tethys had been a narrow seaway; in the plate tectonic view it became a gigantic ocean, some 6000 km wide between India and Tibet.
- Previously, the Tethys had been imagined as resulting from down-buckling of the crust; now, it was thought to have originated from upwelling and spreading of mantle material.
- Previously, deep (eugeosynclinal) and shallow (miogeosynclinal) marine deposits overlying unspecified crust were distinguished in the Tethys; now, the Tethys became a specific "oceanic" feature, complete with oceanic sediments and oceanic crust.
- In the geosynclinal concept, the Alpine-Himalayan orogenic belt was a unity since the birth of the Tethys; in the plate-tectonic view it became a strange composite of two continental margins, which prior to collision were thousands of kilometres apart and had nothing to do with each other in their structural development.

The enormous width of the Tethys Ocean and its disposal by subduction were not concluded from any new geological discoveries in Tethyan rocks, but solely from new geophysical data obtained outside the Tethyan realm, viz. palaeomagnetic data on polar wander paths and on spreading of Indian oceanic crust. These and other premises of plate tectonics have not remained uncontested (e.g., Lavecchia and Scalera 2003). However, this is not the place to discuss the validity of plate-tectonics; let us only keep in mind that plate tectonics is still a theory, not a solidly established fact as many geologists got used to treat it.

Here, we deal with the consequences which plate tectonics had for geological investigations in Nepal. The Himalaya now became a sort of test case of a "collided range" (Le Fort 1975). The theory required that all orogenic events – deformation, metamorphism, magmatism – were the consequence of subduction and/or collision. Palaeomagnetic data from the Indian Ocean and stratigraphic data from sediments in the Indus Suture zone (Gansser 1964) suggested that collision along the suture, terminating Tethyan oceanic subduction, occurred in Early Tertiary time. However, isotopic work on crystalline rocks in Nepal indicated far predominantly Miocene ages for metamorphism and granite intrusions. This could be explained by arguing that north drift of India continued after Early Tertiary collision, causing ruptures in the Indian plate and a resumption of subduction along the Main Central Thrust and the Main Boundary Thrust in Late Tertiary time. The MCT movements in particular came now to be treated in terms of post- collisional, continental subduction.

Great emphasis was now placed on microstructural studies (e.g., Pêcher 1978; Brunel 1986) in order to disentangle the polyphase deformation and metamorphic imprints on Himalayan rocks and to correlate them with the corresponding collision and subduction events. The second of three or four major deformation and metamorphic phases recognised, the one believed to be associated with the shear movements along the MCT, appeared to be by far the most important one, absorbing a great deal of the exploratory efforts. As the MCT could not be identified as a clear-cut thrust plane by any sharp structural or metamorphic discontinuity, it came to be treated as a thick *zone* of shearing and gradual metamorphic change, affected in a ductile way by a characteristic set of deformations such as isoclinal folds, foliations, lineations and rotated minerals. To explain the intriguing reversed metamorphism, various shear-strain and thermodynamic models such as rapid overthrust of a hot upper plate over a cold lower plate were proposed (Le Fort 1975). However, all this only complicated the problem of identifying more precisely the location of the MCT, the proper thrust plane, which remained largely a matter of personal choice. In the established zonation of metamorphic grades, a certain isograd, e.g. the base of the kyanite zone, was often arbitrarily chosen as the preferred MCT plane.

The formation of Miocene leucogranites in the high part of the Central Crystalline was equally seen as a phenomenon related to the MCT (e.g., Le Fort 1981). From field and analytical data it was concluded that the granites may have an anatectic origin and may be rooted in the widespread migmatites in the lower part of the upper plate. Shear-stress heating during the MCT movement may have increased the temperature of the hot upper plate and caused the magma generation.

Another serious problem, bearing on the presence or absence of Indian Shield elements in the Himalayas, was the distinction of Precambrian structures from the overprinted polyphase Tertiary deformations. Based on field observations and microstructural studies, Johnson and Rogers (1997) found evidence for at least one deformation and metamorphic episode anteceding the intrusion of certain Lesser Himalayan granites dated radiometrically as Cambro-Ordovician.

The few examples given above show clearly that in Nepal, as elsewhere, plate tectonic reasoning has given great impetus to new scientific approaches such as microstructural analyses and related petrographical, mineralogical and geochemical investigations to solve the problems of mountain building. There is no doubt that these studies, together with similar ones (including geopohysical work) carried out in other Himalayan countries, have opened important new insight into the nature and behaviour of the deeper layers of the crust and the kinematic processes involved in the Himalayan orogeny.

However, these investigations were primarily of theoretical interest and had only a limited impact on the practical concerns of geology. Plate tectonics had diverted much of the attention of geologists from the surface to the subsurface, to deeper parts of the crust, to the mantle, to the interior of the Earth. This necessarily brought about a shift of balance from description to interpretation, from observation to speculation, from fact to theory. The classical, "descriptive", field geology was to a large extent replaced by analytical laboratory work, the cross-section by the diagram, the map by the model. Gansser (1991) has brought it to the point when he wrote: *"During the classical exploration in the 19th and early 20th centuries the ratio between facts and theories was 1:0.5. Plate tectonics changed it to 1:3, and with geophysics, geochemistry and structural analysis the ratio became 1:5".*

RECENT DEVELOPMENTS

The last three decades were characterised by a marked strengthening and diversification of geological institutions in Nepal and a remarkable increase in the application of geology for industrial, environmental and natural hazard assessment purposes. Particularly significant in the early part of this period were the creation of a National Seismological Centre, the beginning of petroleum exploration, and the foundation of the Nepal Geological Society. Nepali geologists now came into the forefront in the geological exploration of their country.

Microseismic monitoring started in 1978 by the Department of Mines and Geology (DMG) in collaboration with the Laboratoire de Géophysique Appliquée of Paris University with the installation of a first seismic station on Phuichauki Hill south of Kathmandu. The activity was then gradually extended to a network of 21 short period seismic stations distributed regularly over the Lesser Himalaya and Subhimalaya of Nepal. The network is operated by the National Seismological Centre (NSC) in collaboration with the French Department of Analysis & Surveillance of Environment. Recording of the digitised signals from local, regional and teleseisms is done in the central office of NSC at the headquarters of DMG in Kathmandu and in a second, regional centre at Surkhet in western Nepal. The data are used for regional and global earthquake location, for related seismological and seismotectonic investigations, and as database for seismic hazard assessment.

Petroleum exploration in Nepal began in the late 1970s – early 1980s, when several western exploration firms under agreements and in cooperation with the DMG undertook preliminary geophysical investigations in the Siwalik Hills and the Terai Plain in the southern foreland of the Himalaya

– a region underlain by the northern part of the Ganges Basin and considered as hydrocarbon-prospective. The results of aeromagnetic and seismic reconnaissance surveys carried out over the entire zone encouraged the Government to establish, in 1982, a "Petroleum Exploration Promotion Project" under the administration of the DMG. The prospective zone was divided into 10 Exploration Blocks, each of about 5000 sq km size, which in 1985 were opened for bidding. In 1986-1990, Shell Nepal B.V. carried out an exploration program in Block 10 in the extreme southeast. The program included gravity and additional seismic work and drilling of an exploration well; the well, which was dry, was drilled to a depth of 3520 m without reaching the basement. Further studies included geochemical analyses of potential source rocks and of oil samples from a seepage in western Nepal, as well as modelling of basin history and source rock maturation.

The results of these early oil exploration activities were assembled by the DMG in a data package made available to interested international companies. Subsequent exploration programs in 7 of the 10 blocks, executed under successfully negotiated production sharing contracts with two western petroleum companies, were, unfortunately, disrupted or retarded by the deteriorating security situation during the civil war (1996-2006). There is, however, no doubt that with the normalisation of the political situation, the results obtained so far will be sufficiently encouraging for renewed exploration efforts in the region.

The traditional mineral exploration and geological surveying activities of the DMG were considerably expanded and diversified, whereby contributions by researchers of other Nepali institutions, particularly the Geology Department of Tribhuvan University, became increasingly important. Cooperation with foreign institutions showing an unabated interest in geological, structural and geophysical investigations of the Himalaya as a "collided range" was continued.

The newly established National Seismological Centre contributed significantly to seismotectonic, neotectonic and similar studies. Basic geological mapping was intensified and modernised. The old 1 quarter inch : 1 mile maps of the Indian Survey as topographic base were abandoned and replaced by 1 : 50,000 standard sheets. Field observation was supplemented by air and satellite photo interpretation. Marked developments took place in various fields of applied geology, in particular engineering geology related to road and bridge construction, hydropower plant projects, selection of waste disposal sites and foundation studies. Exploration for building stones and cement raw material to satisfy the requirements of the building industry in the rapidly growing agglomeration of Kathmandu became an urgent need. Special attention was paid to evaluation of natural hazards such as landslides, debris flows, floods, and earthquakes. Categorisation of certain hazards, e.g. landslides, was used to prepare special hazard risk maps. A remarkable example of basic geological surveying of a selected area in western Nepal combined with a parallel landslide hazard risk evaluation, including the two respective, overlapping maps, is given by Dhital et al. (2002 a and b).

Prior to 1980, the majority of publications dealing with the geology of Nepal had been written by foreign investigators. Little of the survey work of the DMG had been published, although reports and maps were generally made available for public use. A few noteworthy articles by Nepali geologists appeared in the early 1980s in foreign media, e.g., a review of the geology of the Nepal Himalaya by Bashyal (1984) in the Reports of the 27th International Geological Congress in Moscow. Among the first publications of the DMG was a generalised Geological Map of Nepal at the scale of 1 : 1000,000 compiled by Amatya and Jnawali (1994).

In 1980 the Nepal Geological Society (NGS) was founded with J. M. Tater, Chief Geologist of the DMG, as first President. The Society became a strong promoter of the professional interests of Nepali geologists, publications in particular professional. One of the declared aims of the Society was the issue of a regular Journal, whose first number appeared already in 1981. The annual Volumes and the Special Issues of the NGS Journal have become an important platform for Nepali geologists and many of their foreign colleagues to publish the results of their explorations in the Himalaya. The Central Department of Tribhuvan University in addition publishes reports and maps of its research workers. The NGS also acts as a propagation and sales agency for the maps now published by the Department of Mines and Geology. Among the DMG maps already available are a number of geological maps of the 1 : 50,000 standard quadrangle series, several geological maps of larger divisions of the country at 1: 250,000, and special maps at various scales such as Engineering and Environmental Geological Maps of the Kathmandu and Pokhara Valleys, a Mineral Resources Map of Nepal, an Epicentre Map of Nepal, and other ones.

In 1998, the Nepal Geological Society has received the United Nations' "Merituous Certificate for Disaster Prevention" (UN-Sasakawa Disaster Prevention Award) for its efforts in spreading awareness and disseminating scientific knowledge of natural disasters and their prevention.

The present issue of the NGS Journal containing the Proceedings of the 5th NGS Geological Congress gives an insight into the great variety and professional quality of geological activities undertaken today in Nepal and shows also that in these activities a reasonable balance is maintained between theoretical and applied geology.

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