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GENERAL ARTICLE

INQUA in India: Some Reminiscences and Some Anticipations

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ABSTRACT

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A brief narrative on early development of Quaternary Sciences in India and its association with International Quaternary Union is presented. A discussion on expectations that accrue from increasing demands on the use of geoscience as services is presented along with some thoughts on recalibration of scientific objectives, resource augmentation through enhanced inclusivity of other disciplines and capacity building in Global South, are outlined, both for the Indian and the international context..

EARLY DEVELOPMENTS

INDIAN subcontinent's tryst with Quaternary Studies was almost contemporaneous with the early developments in Europe. The period between the breakthrough publications of Lyell (1835) on *Principles of Geology* and Darwin's (1857) work, *On the origin of Species*, were also the foundational years for the first work on the Quaternary in India. Between 1830-1840, officers of the British East India company such as Proby Cautley and Hugh Falconer (Brown, 1980) accumulated a large collection of fossils from the Siwalik's. Cautley was a civil engineer, more acclaimed for his work on canals and for the founding of Roorkee College which now is the Indian Institute of Technology, Roorkee. Falconer, though trained in medicine and working as the superintendent of Saharanpur Botanical Garden, had wide-ranging interests in botany, geology and anthropology. Their collection of fossils from Siwalik's were published in 1846 (Falconer & Cautley, 1846). In 1859, encouraged by Falconer, Joseph Prestwich and John Evans visited Abbeville in France, where they observed insitu stone tools in sediments which also had extinct animal fossils (Prestwich, 1860; Evans, 1860). And this was the birth of Prehistory. At the same time fossils from the Narmada alluvium were also reported by W. T. Blanford in the first few issues of the *Asiatic Society of Calcutta Journal* in 1869.

The establishment of the Geological Survey of India in 1851 under the East India company, to estimate and manage coal, natural minerals and other natural resources in India for their riches, did also lead to a systematic study the Geology of India. However, till 1970's, Quaternary studies formed an insignificant part of the geological studies. In India, initial foray into Quaternary Sciences was by archaeologists who recognized the symphony of relationship between humans and their environment. Discovery of the first stone tools by Dr. R. B. Foote in 1863 initiated the research in Human Environment interactions and the field of geo-archaeology took roots in India.

During the seventies and eighties, thanks to the support by the Department of Science and Technology, major programs to create facilities and understanding of Quaternary sequences in India were taken up. Notable inter disciplinary contributions were made and a reasonably detailed frame work of Quaternary Stratigraphy of India is now available. A review by K. R. Gupta and Sangode in 2010, estimated over 700 publications on the Quaternary from India. This number exceeds several thousand at this time due to a large community of scientists working in India. Fig. 1 chronicles the growth of Quaternary in India in the global context.

Over the years, Quaternary Geology and Geomorphology have been established as major disciplines. Most institutions teaching Geology now include Quaternary Geology as an integral part of their curriculum. During late sixties and early seventies, major groups working on varied aspects of Quaternary Geology were at Deccan College Pune (Profs. H. D. Sankalia, V. N. Misra, S. N. Rajaguru, K. Paddayya, G.L. Badam, Shaila Mishra and Shanti Pappu); Centre of Advanced Studies in Quaternary Geology and Department of Archaeology at the M.S. University of Baroda (Profs. S. S. Merh followed by B. Roy, L. S. Chamyal and others, and K. T. M. Hegde, respectively); the Palynology group at the

Birbal Sahni Institute of Palaeobotany (now Palaeosciences; Profs. Vishnu Mittre, Gurdip Singh, Chayya Sharma, Anjum Farooqui and many others); Oceanography and Climate sciences group at the Physical Research Laboratory (Profs. D. P. Agarwal, R. K. Pant, S. Kusumgar, V. N. Nizampurkar and later Dr. M. G. Yadava and Dr. N. Juyal); Archaeology Departments at Allahabad University (Profs. G. R. Sharma, V. Tripathi and V. Jayswal) and at Banaras Hindu university (Profs. A. K. Narain and K. K. Sinha); Department of Geology at the Lucknow University (Prof I. B Singh); the Central Arid Zone Research Institute at CAZRI (B. Ghosh, R. P. Dhir and Amal Kar); University of Roorkee (Prof. B. Parkash), Wadia Institute of Himalayan Geology (Prof. K. S. Valdiya, V. C. Thakur and later P. Srivastava); University of Pune (Profs. V. S. Kale and S. Sangode) and Drs. D. K. Bhatt, L. Fermer, Gopendra Kumar, S. K. Raina, A. Sonakia, H. S. Saini, S. P. Shukla, C. P. Vohra, S. K. Wadhawan and many others at the Geological Survey of India who provided substantive inputs on the mapping, regional Quaternary studies and stratigraphical aspects. A map of Quaternary Geology of India was published as a set of 42 maps by GSI in 2014.

Important technological developments that aided Quaternary Research in India include, the establishment of Radiocarbon laboratories at TIFR in 1960 (this laboratory later moved to Physical Research Laboratory, Ahmedabad during early 1970's) and at BSIP since mid-1970s; Luminescence dating laboratories at the Bhabha Atomic Research Centre at Mumbai and PRL during mid 1970s and thereafter establishment of over 11 Luminescence laboratories spread across India; pioneering development of the science of cosmogenic radioisotope dating at PRL by Prof. D. Lal and the recently established National Geochronology facility at the Interuniversity Accelerator Centre at Delhi (Drs Sandeep Chopra and P. Baghel); development of Remote Sensing capabilities in India by the Indian Space Research Organization. DST also generously supported creation of several experimental facilities at various institutions across India. More recently by Ministry of Earth Sciences (MoES) has been supporting many National initiatives.

Important major programs include studies on the Narmada fossils by GSI and many other groups; multidisciplinary studies on Thar by groups at Baroda, Pune, Ahmedabad, CAZRI and others; understanding of Coastal Deposits and Rann of Kachchh by groups at Baroda, Pune, GSI and PRL, Ahmedabad; studies on Karewa Deposits in Kashmir by GSI, and a multidisciplinary program led by PRL, Ahmedabad; Ganga Plains led by Lucknow University; Studies on soils and tectonics by University of Roorkee; Studies on Himalayan

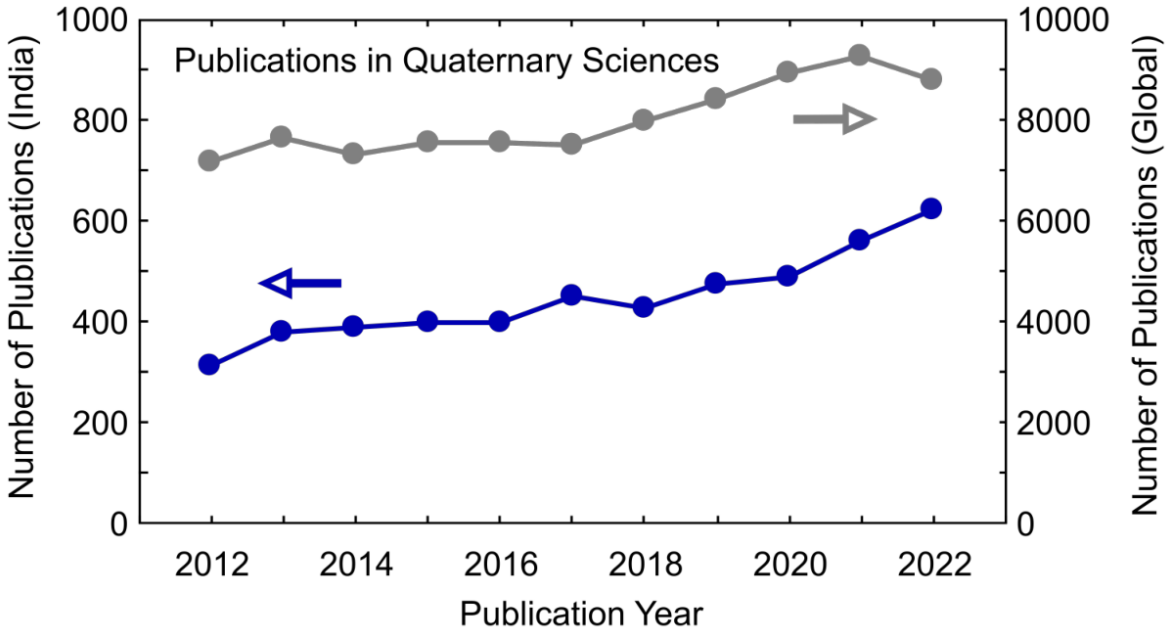

Fig. 1—Growth of Quaternary Science in India. Since 2010, from a total of ~ 700 publications till then, the total number of publications is an order of magnitude higher and the rate of publications during the past decade, has more than tripled. That said, it is sobering to realize that despite this increase, the Indian contribution to Global Quaternary Science literature is only about 7-8%.
The Data was kindly provided by Dr. P. Kannan of INFLIBNE, Gandhinagar, using Scopus and Goodgle Scholar databases for the key words: *India, Quaternary, palaeoenvironment, paleo seismicity, glacial moraines, Thar, paleoclimate. luminescence dating, radiocarbon dating, glaciology, coastal deposits*.

lakes led by groups at Kumaun University, Nainital, BSIP, Lucknow and Bose Institute, Kolkata. Studies on glacial geology by groups at GSI, National Centre For Polar Research at Goa, PRL Ahmedabad and the studies on glaciers through the use Remote sensing by the Space Applications Centre and the Indian Institute of Sciences. Several other University Departments, Indian Institute of Technology, Delhi and Indian Institutes of Science and Education Research have contributed to these studies. India also has programs on Quaternary Geology and Geomorphological studies in Antarctica and more recently in the Arctic.

A dedicated society, *Indian Society of Prehistoric and Quaternary Studies* was formed in 1977, and this has been assiduously publishing a respected journal, *Man and Environment* since 1981. Besides, numerous and regular annual conferences, their proceedings and peer reviewed publications, some of major contributions that provide a flavor of Indian Quaternary through time include, e.g. Agrawal & Pande (ed., 1977); Agrawal & Kharakawal, 2002; de Terra & Patterson, 2017; Dhir *et al.*, 2018; Wadia *et al.* (eds., 1995); Singhvi (ed) 2004; Singh, 1996; Tiwari *et al.* (eds., 2023).

Several international experts who enriched the understanding of Quaternary Environments, Archaeology and Stratigraphy include (in alphabetical order), Profs. B. Allchin, V. Baker, D. W. T. Blanford, D. Burbank, D. Clarke, H. de Terra, R. B. Foote, A. Goudie, K. A. R. Kennedy, L. Owen, T. T. Paterson, R. J. Wasson, J. D. West, M. A. J. Williams, F. E. Zeuner and many other distinguished scholars.

INDIA IN INQUA

India formally joined INQUA as a national member in 2007. Fifteen years hence, the acceptance of India's invitation to host the four yearly INQUA Congress in India in 2027 reflects India's increasing engagement with INQUA activities and its vibrant programs. This is reflected in regular and elegantly produced, quarterly newsletter of the Association of Quaternary Researchers, that was formed in 2019.

INQUA congress in 2027, provides a rare opportunity to Indian Quaternary Sciences to enhance its activities and add new dimensions to its research programs. In the following, I chronicle the past developments and present a few suggestions on a possible recalibration of future focus for INQUA based activities, to align their programs with changing contours of science-society relationship. The same is true for Quaternary Studies in India so that aspirations as reflected in the theme of 22nd INQUA congress, *Quaternary Sciences as Societal services*, are effectively realized.

PAST TWO DECADES

INQUA congress in India is both a great news and a great responsibility. In a sense, this was a culmination of over two decades of efforts in interfacing Indian Geosciences with international events and towards making India an active partner in shaping future geoscience agendas at international forum. This journey began with successful efforts to send a larger numbers of scientists to various international meetings, that was achieved with support from the Department of Science and Technology (DST), the Indian National Science Academy (INSA) and later on by the Ministry of Earth Sciences (MoES). Currently, Indian participation easily reaches over 50-100 in each of such congresses/meetings.

During this period and with considerable persuasion, INSA approved India's adherence to INQUA; it upgraded India's adherence level to IUGS and approved Indian bids for an IUGS congress with eventual success by hosting the 36th International Geological Congress in 2020. The theme for this congress was appropriately chosen as *Geosciences: The Basic Science for a Sustainable Future.*

India also made a successful bid for the IGCP-PAGES 4th Open Science Meeting (OSM) on the theme-*The Past: A Compass for Future Earth***.** This OSM was successfully organized by MoES-ESSO-NCAOR (now NCPOR; National Centre of Polar and Ocean Research), in 2013 with participation of ~500 scientists from ~50 countries. Concurrently, a IGBP-PAGES young scientists meeting with participation of about 100 from 27 countries was also held. Two meetings of the International Executive Committees of INQUA and one of IUGS, were held in India at Ahmedabad and Goa, and these accompanied extended presentations and discussions on various aspects of the Indian Quaternary studies. The foundation for the *Association of Quaternary Researchers* was laid down during the INQUA meeting in Cairns and then formalized during the INQUA meetings in Bern and Dublin for its launch in 2019.

A new tradition of four-yearly, detailed Indian Reports to IUGS with thematic reviews of work during the past four years, was initiated in 2008. And, this has continued with the results of the two most recent meetings being published as special issues of the *Proceedings of Indian National Science Academy* of about 600-700 printed pages comprising 40-50 peer-reviewed summaries of research in India. A good fraction of these reports comprise themes of relevance to the Quaternary period. The reports to IUGS have been well received nationally and internationally, and being open access, have additionally served as teaching aids for college and university teachers with limited access to current scientific literature.

Other efforts included, the proposal and establishment of the National Geo-chronology facility at the Inter University Accelerator Centre Delhi (NGF-IUAC; now mostly functional) with a truly generous support from the Ministry of Earth Sciences. The motivation was to enable every scientist and teacher in India, with a definitive science question, gets an access to, state-of-the-art facility to further his research, without difficulty and with financial support, if needed.

Formation of the Federation of Geosciences Association of India (FIGA) was another effort initiated in 2005 with a vision of creating synergies between various specialists' groups/associations in geosciences to create AGU or EGU like annual meetings to provide platforms for interdisciplinary interaction for new science initiatives. It is hoped that this dream will also be realized in the near future.

Initiatives outlined above helped:

a) build capacity for science and use the rich geological record of the region for fundamental discoveries of global consequence.
b) create appropriate infrastructure with open access to all, based only on their science, such as the NGF-IUAC.
c) create synergies between disciplines and people (especially college teachers and active researchers) to improve pedagogy and research in geosciences.
d) develop large scale, coordinated, interdisciplinary programs that would inform conceptual and applied initiatives and meet national needs.
e) create a platform for an annual Indian geoscience meeting on the lines of the AGU or EGU to facilitate interdisciplinary interactions and for capacity building through training of young minds by providing them with a wholesome exposure to inter disciplinary areas and themes beyond their immediate research.
f) develop a framework concept for a National Geosciences Data Policy such that all data/samples/results created using public money can be archived and made accessible for future access. A report by the Geosciences PAMC of MoES is being examined by the MoES.
g) Proactively use Indian expertise/programs for capacity building, especially in regions south of the Brandt line through their participation in our training programs.

Much of the above has been realized and the hosting of PAGES OSM, IGC-2020 and INQUA congress in 2027 are clear reflections of their impact.

THE INDIAN CONTEXT

It may be apposite to recall that, India offers a unique setting for geological research with its very old rocks; rising mountains; large foreland basin(especially the Ganga with a dispersal system that transfers sediment from the mountains to the oceans); hot and cold deserts in the Thar and Ladakh; well mixed and closed oceans in the Arabian Sea and Bay of Bengal; records of active and passive volcanism from the Barren Islands to the Deccan; large and small lakes, lagoons, and mangroves; an exceptionally long coast line; rich geo-heritage; enormity of geohazards and a unique climate system (the Monsoons and the westerlies). Above all, extraordinary Human impact on geological systems makes India a good laboratory to understand human impact on geological systems and the impact of geological systems on humanity.

Indian geosciences have provided several new results of global consequence. Some of the important results include: Decipherment of the Core Mantle boundary; Theory of Isostasy; Granulite formation Theories; Out of India Mammalian Hypothesis; Seasonal Reversal of Coastal Ocean Circulations; Coastal hypoxia and methodological advances in geochronology in particular leadership in the conceptualization and development of cosmogenic radioisotope dating; the luminescence dating of deserts (and other Quaternary sequences including, glacial and Antarctic ice, costal dunes, glacial moraines); GNSS/GPS measurements across India that provided estimates of velocity of Indian plate converging with the Asian plate with important new insights on potential seismic hazards and more recent deep drilling in the Koyna region.

With such a rich tradition of scientific contributions, the time is now ripe to take geosciences in India to a higher, theory and process based quantitative results and to provide evidence-based solutions for society.

As of 2023, besides the opportunities of hosting major congresses, currently India has several national initiatives that were developed through a judicious combination of bottoms up/top-down approaches and with due diligence of discussion between experts with diverse and complementary expertise and institutional backgrounds. Such programs are at various stages of implementation. Completed programs include the National initiative on the *Geological records of Tsunamis along the Indian coasts*, the *National Geo-chronology facility,* and the formation of *FIGA*. Programs approved and underway include the *Science of the Critical Zone*; *The evolution of Indian Lithosphere*; *New approaches to prediction of fault related Landslides in Himalayan towns*; *Geobiology: integration of molecular biology with geology, and more recently a National facility for High Pressure-Temperature studies* to be functional by 2025. Another initiative on the *Himalayan Observing System* with dedicated observational satellites and intelligent sensors for disaster warning have been discussed and hopefully will be taken forward.

Most of these have been supported by the MoES and have involved typically 10-15 or more institutions, working independently and at the same time seeking convergence to advance science of societal relevance. It's a well-reasoned hope that these initiatives will add to the Indian Geosciences in a meaningful manner and that MoES will continue to be benevolent through its generous support for such scientific endeavours, that provide a large measure of fruit-bearing science.

The Department of Science and Technology, Government of India, recently announced National Geospatial Data Policy 2022 and the development of National Geosciences Data Repository online platform. See https://www.surveyofindia.gov.in/pages/national-geospatial-policy-2022.

FUTURE-INQUA

We consciously chose the theme for INQUA as *Quaternary sciences as Societal Services* by recognizing the fact that the current expectations from the society are, that we convert our publications to usable products; i.e., we walk an extra mile to convert our light-bearing science to fruit-bearing science and assist society through critically evaluated, secured scientific evidences to inform policy making, (e.g., Wasson, 2017).

This becomes more relevant as the country has been making investments in large infrastructural projects, that need sound and unbiased, evidence-based inputs; be it highways in the difficult terrain of the Himalaya, hydel-power plants, large airports, major tourism related initiatives, to the program on toilets and the need to avoid long term health hazards through soils contaminated by sewage discharge that impact both the surface and ground waters.

Science needs to assess and inform hasty policy prescriptions and expedient decisions which may appear attractive at the present time, may lead to long term disasters. Therefore, sound geological inputs with cost and risk to benefit assessment for each of such activities, are the need of the day. And, the onus is on the community of geosciences to provide robust evidence-based inputs to these initiatives as *cause-effect* scenarios, their time scales and potentially adverse impacts, and this has to be done assiduously in larger interest of security of life and investments in large infrastructures. Recent series of catastrophes across India are a wakeup call that geosciences have to play an important role in informing the plans and policies for new infrastructure (see e.g. Pant & Saini, 2023).

INQUA@2023

Some of the areas of emerging concerns and the possible actions needed in the immediate future, have been discussed elsewhere, (Singhvi, 2020). The following discussion is with the premise that INQUA 2027 could serve as a vehicle for change in the way the Quaternary studies and geosciences more generally, have been carried out and the focus is largely based on land-based records.

INQUA has a well-crafted structure of five commissions, that includes *Coastal and Marine Processes; Humans and Biosphere; Paleoclimates Stratigraphy and Chronology and, Terrestrial Processes, Deposits and History*. These have served well, but increasing societal needs demand augmentation and recalibration in the scope of its programs and that new technologies coupled to emerging computational and instrumentation capabilities are developed and used. The time is therefore ripe to enlarge the scope of INQUA Commissions by **specifically and explicitly** bringing in newer dimensions that cater to Societal Services, Security and Sustainability. It will therefore be appropriate to see a *relevance statement* added to the description of each INQUA commission and working groups, to inform and convince the stake holders-the public, as to why entities like INQUA need to exist and be generously supported.

Aspects such as mathematical modelling of landscapes and associated quantification; paleorecord-based scenario building for various hazards from floods, to inundation by tsunamis, damage by landslides and glacial lake outbursts; creation of inundation maps from extreme events with due consciousness of changing hazards under increasing sea level; AI-based instrumentation for real time monitoring extreme events and hazards evacuation strategies; assessment of seismic hazard under changing population densities and development of evacuation scenarios are the need of the day and should be integral to our research and will need scaling up to technological inputs.

Modelling of carrying capacity of a geomorphic units in respects of services provided by them including the aspects of growing urbanization, increasing built-infrastructure, impact of enhanced water-use on surface and subsurface architecture for town planning; assessment/prediction of the flooding styles (including the urban and nuisance floods) due to increasing urbanization, sewage discharges and the sea level rise, call for our attention and prescriptions in near real time. Creation of region-specific geomorphic scaling laws in both the spatial and temporal domains, validity of chronologies in large basins and assessment of intra-basin changes in sedimentation styles, chronology and changing bio-geochemistry to name a few (e.g. Mischke *et al.,* 2013).

We need to create observatories of tipping points in large ecosystems based on paleoecology and modern process understanding. In creating such scenarios and prescriptions, it will be prudent to include local knowledge systems, historical records and social practices as was done by a PAGES led program (Dearing *et al.,* 2012)

Thus, INQUA would need to explicitly bring new disciplines including social sciences, applied physicists, applied mathematicians, molecular biologists besides data and computer scientists on board. I am aware that studies of the type mentioned are being carried out at various levels based on individual initiatives but a formal emphasis on each of these disciplines by INQUA, through formation of new commissions through capacity augmentation and dedicated working groups will help sharpen the focus, intensify the efforts and create impactful interfaces. It will be good to see interdisciplinary approaches comprising geophysical, biological and mathematical modelling in all of INQUA programs.

I repeat, that INQUA needs to move ahead from an informal to a formal emphasis on inclusion of these programs and create critical capacity to deliver on them. A limited bibliography of select references is appended at the end to provide a view into new development and possibilities. I would therefore venture to suggest a revisit of the scope of

INQUA focus/working group to create products on Societal Services to Sustainability and from microbes to modelling and instrumentation and data analytics.

INQUA would also do well to intensify its efforts and allocate more resources to enhancing Science and capacities in the **Global South**, to create a pool of local scientist, who will then deal with such emerging issues at their local levels. And, this needs to be done on a mission mode with definitive time lines. In these efforts, due care and conscious effort will be needed to avoid both the *parachute science* and of *repetitive patronage* of a select few individuals from the global south and the Early career researchers, due to familiarity and convenience. We need more people to benefit, participate and be enthused by its science.

Let a good fraction of Executive Committee meetings and scientific workshops of INQUA be held in institutions in Global South and less developed nations and during these dedicate a day on local issues to develop programs relating to the science and capacity building in such regions. INQUA may wish to proactively encourage online training programs on a continuing basis. I think of each of active Quaternary Scientists volunteering to mentor/support/assist/collaborate with one or two colleagues in a less develop regions. Such a crowd sourcing of volunteer mentors will provide a win-win situation for all. Collaboration with the Third World Academy of Sciences (TWAS), World Meteorological Organization, UNESCO and UNEP may help develop useful and meaningful interfaces for Global Good.

I must reiterate here, that there is *nothing new* in what is said above and in what follows, but at times, a reiteration of the known may be both useful and necessary. I do with a clear realization that the expectations from society for benefits from science are increasing and there is an ongoing debate about who should manage science-the scientists or bureaucrats or politicians or management experts. The Covid experience has many lessons for the scientific community and its credibility. It must be clearly realized that, to try and keep our domain of expertise sacrosanct, we need to travel from being scientifically good to being obviously good and by being useful to society that nurtures us and supports our science. And, this will happen only when our publications get converted into ready to implement, reliable science-based products.

An important aspect that is only partly realized is the availability and interoperability of data in a well-designed GIS format so that this can be in a ready to use format for future studies. Quaternary studies have the potential to inform and monitor the role and influence of geological factors such as changes in trace elements to mineral dust (and then soil health and thence nutrition of crops), to release of microbes due to defrosting of permafrost, on emerging geogenic health issues. Thus, result from Quaternary studies if presented in an interoperable form, can provide baseline data on medical geology, geo-pharmaceuticals, geo-forensics, without any added cost. These will also aid understanding of environmental impacts of human migrations that will only increase with time. It may be worthwhile that INQUA discusses setting up of a working group on data archival aspects with a mandate to develop a universal format through synergies with existing local data bases. Discussed below are a few potential focus areas in the realm of terrestrial records with due consciousness that many more and other novel ideas exist to be developed into new commissions and working groups.

Let this contribution initiate a discussion on future possibilities.

INQUA-2027

Sediment records-correlations

The time is ripe to transition from mere field observations, simple minded laboratory analysis and dating followed by correlation to global trends. This approach implicitly assumes instantaneous responses of terrestrial sediments to global or regional forcings and ignores the fact that only the preserved records are seen and therefore by definition only a fraction of a forcing signal, lagged in time, is recorded in sediments. We do know that all terrestrial sediment records are more records of gaps and less of sediment and to quote Ager (1993), *the stratigraphic record is more a gap than a record.* We need to revisit these relationships through process-based scaling up of point scale measurements of a geological section, to the basin scale, and attempt global geological correlations **only** with due care for causality (involving forcing, sediment creation, sediment-transport,-deposition and-preservation), geomorphic thresholds, the dynamic range and response time of proxies, the fragmentary nature of the preserved record and its completeness. It is my firm conviction that in geology, and in particular sedimentary deposits belonging to Quaternary time scales, there are no correlations sensu-stricto because of spatial and temporal lags and leads, thresholds and the response times of individual sub-systems/proxies.

Our understanding is often limited by the resolution of measurements and by what proxies can be measured. Indeed, I have often felt bewildered, whenever a correlation between a terrestrial record with ice core or marine isotopic stages, based either on (field observation, occasional chronology and laboratory analysis and sedimentation style), are attempted without a statement on causality. Ignorance of causality is the casualty in Quaternary sciences can lead to missing out on important environmental or tectonic message the sediments can provide. It is time to realize that we need to revisit all our former interpretations/ land sea and land ice correlation and understand them based on the process-based scenarios, especially for the late Quaternary. For older records, perhaps

dating errors may not permit delineation of lags between forcings and sedimentation, but they must exist.

Literature is increasingly making us aware of issues in interpreting sedimentary records and some publications are listed in the bibliography. It is worth a reiteration that lags, leads and thresholds need to be understood if we are to attempt long-term planning of dynamic landscapes and for this, use of multiple chronological methods and proxies on the same sequence, with due consciousness of causality and the nature of the event in a sediment record that is dated by specific techniques, will be needed. My humble appeal to all is that do not seek to correlate to global forcing, but first seek to understand the message from individual point measurement, thereafter ask a question of its own climatic/tectonic message and only then correlate with a cause-effect scenario, i.e. why should a marine isotopic signature be seen in a sequence on land at a place x and what processes led to a synchronous occurrence of two disjointed sedimentation regimes. Also, we need to understand that absence of sediment record is also a record of a process or processes.

In deriving scaling laws and process, current remote sensing capabilities permit technological possibilities to simultaneously measure events in a basin on multiple spatial scales, i.e. from a sub-meter scale to hundreds of kilometres scale. These needs to be exploited and scaling laws for individual basin need to be determined.

In terms of products, some good examples for the Indian context, will be to collate, synthesize and model the regional scale changes in equilibrium line altitude (ELA) across the Himalaya through time and understand the sensitivity of glaciated terrains to climate and tectonics or to anticipate future changes; or collate dune records of the Thar to talk in terms of albedo/wind changes through time; or to understand the factors causing floods and their geomorphic signatures for risk assessment of infrastructure. I repeat that in all these, due care will be needed in remembering that we access only the preserved record, that possibly represents a fraction of created record that too under a transitional regime.

All these are common sense, but rarely do our publications mention these aspects and their implications. It is essential that these be stated in as *deutlich* a manner, as possible. We need to create scenarios of possible events over the next hundred or a few hundred years' time scale also for scenarios for, e.g. one in a hundred years extreme event. In attempting to predict the future landscape and ecosystem responses due cognizance of non-linearity at every stage from proxy response to landscape will be needed, given that in many instances, we have crossed planetary boundaries. A good example of geosciences-based, socially relevant product is provided by Wasson *et al.,* (2013) and there could be many other such studies.

Quantitative methods in geomorphology needs to be introduced rigorously at both the bachelor's and master's level with due attention to the theoretical basis of the discipline, a training in mathematical modelling and data analytics which should be integral to all geoscience courses. Exposure to conceptual/philosophical development will help students gain perspective on how geological reasoning has evolved, (Morthekai, 2018). Some formal beginning in mathematical models/data analytics has been made by IIT Gandhinagar.

Past monsoon variability

Often the inferred records to the monsoon from land and from the oceans are correlated. Given that the terrestrial records are created through a complex sequence of sediment production, availability, transport and preservation and that foraminiferal records in the ocean are a surrogate for winds, modulated by riverine inputs, and their amplitude depend on the location of sample. Therefore, relationship between oceanic wind proxies for upwelling to spatial variability of rainfall on land and its sedimentary record is complex and has not been examined rigorously. The need is to revisit the existing data critically, relate them to meteorological data on spatial variability of monsoon, and examine common time slices to elucidate spatial and temporal relationship and the underlying processes, better.

This will require a considerable clean-up effort in understanding the chronologies, correcting them for various sample-dependent effects and then compare with process-based records on land, to arrive at an understanding of correlations or their absence. Causality in either case will need to be established to gain new insights. It is worth a reiteration that the absence of record is also a record and possibly as valuable an information as the record itself.

For the immediate future, it will be instructive to consider developing east-west transects of sediment-based proxy climate records from lakes, ponds and temple tanks across 24-27° N and 9-12° N longitude. Existing data can be revisited for new insights and these should then be confronted with paleoclimate models to understand processes and thereby enhance predictive capabilities. A linked aspect of practical use will be to develop vegetational/molecular proxies to document changes in the onset, extreme events and duration of rainfall, through time. Such an information may inform the agricultural practices.

Soils and the Critical Zone

We need to understand and model the soil forming processes better, given that techniques now enable us to follow, measure and model the dynamics, geochemistry, biology and the fates of single grains in a soil profile. It is now time ripe, to develop dedicated program on soil processes and time scales. It is being increasingly realized that biology plays a substantive role in geology-from mineral transformation and weathering to sub-surface heat production. The role of biology

in Quaternary processes needs elucidation as do the impact of climate change through the release of dormant biological species now frozen deep underneath. Analysis of deep core in frozen ground may provide some clues for the future. We therefore need to integrate biology at the molecular level into our studies and begin understanding Quaternary processes more holistically. A beginning has been just made in India and a suite of research projects will soon be reviewed and funded by MoES, (Srivastava *et al.,* 2023).

A linked effort would be reconstruction of paleoecology using the large corpus of palynological and vegetation data generated by institutions such as Birbal Sahni Institute of Palaeosciences, by creating appropriate transfer functions similar to the work on the lines of Oxford group on long term ecology. This can be a novel contribution to recreate long time base line data on ecological changes on the Indian landmass. This, as of now is limited to past few decades of data.

Also, it is particularly important in the times when strains of new microbes emerge and dent the health and economics globally. Metagenomics/proteomics paired with climate records may be used to reconstruct microbial responses to climate and build future scenarios in the context of anthropogenic changes.

The program on the Critical Zone Observatories, initiated with the support of MoES, needs to be intensified in regions yet unreached and unresearched. A beginning has been made but new observatories should be created and sustained for the next decades, (Sarkar *et al.,* 2023; Singh *et al.,* 2020). Synergies between groups and laboratories may make the entire effort cost effective.

Hazard Maps and scenarios

There is need to develop hazards maps on various spatial and time scales, be that for floods, earthquakes, or landslides. A great opportunity is available to us through the construction boom. Let each local geology department log each trench that is dug in their city for construction and place the trench logs in a GIS framework to inform seismic micro-zonation effort. A national effort to coordinate these meaningfully and with minimal costs is called for to create useful data and build capacity in the process, (Singhvi, 2010). It is also necessary to standardize and synthesize the available paleo-seismic data across Himalaya for newer regional scale insights to inform, both regional scale geodynamics and seismic hazard evacuation studies. The need is, to transition from a *jugad* type ad hoc response to catastrophes, to a well thought out plan of anticipated events and responses with development of standard operating procedures. Education of public, repeated at regular intervals is the needed.

A multi-institutional program on landslides in fault zones is currently underway with support from MoES. This will be an all-inclusive program incorporating experts in structural geology, geomorphology, geophysics, remote sensing, computational sciences, sensor networking and design engineers for optimization efforts and will be first such effort (Mukul *et al.,* 2018; 2024).

Given the increasing frequency of disasters in Himalaya, it appropriate to think in terms of a dedicated geosynchronous satellite for observing Himalaya and develop a multi expertise centre (virtual or physical), to observe processes on its surface and model them to mitigate hazards. It is painful to see major catastrophes occur and lives are compromised with increasing regularity, just because proper geological knowledge was either not available or not used (e.g. Pant & Saini, 2023). This could be on the lines of Tsunami Early Warning System at MoES-Indian National Centre for Ocean Information Services, Hyderabad and such a program can be nested as a virtual centre, at the Wadia Institute of Himalayan Geology or the National Geophysical Research Institute in close collaboration with the National Remone Sensing Centre at Hyderabad.

An interesting new development has been the use of real time instrumentation for prediction of landslides developed indigenously through an MoES supported program (Sudheer *et al.,* 2023; Thirugananam *et al.,* 2022). Such instrumentation efforts need to be intensified, replicated and refined manifold.

A critical need at the moment is a geomorphic analysis-based estimation of probabilities of these events buttressed with real time measurement for disaster mitigation. We need also to work on hazard mitigation, on evacuation strategies based on scenarios for the progression of disaster. Such studies need to take roots in India.

Population Migrations

Another area that needs our attention is climate and hazard induced population migration and its attendant effects on ecology and resources. We witness annual migration of populations during periods of droughts and floods. Climate projections suggest an increase in such extreme events, and therefore increasing migration of people will occur. Impact of such migrations need to be examined and researched in totality, with scenarios of increasing urbanization, impact on local ecosystems, hydrology and health, so that as a nation, India does not end up with surprises. This will also need a close collaboration between Quaternary science experts, social scientists, archaeologists, and modellers.

To summarize, future Quaternary Science in India will for sure need to comprise more data, more quantification, more theory, more modelling, and more futuristic scenario building such as the impact of an abiotic Earth on geomorphic processes; impact of interlinking of rivers on transfer of geochemical and ecological elements on productivity and agriculture; thresholds and response time of landscapes due to human and climate perturbation; measurement of extreme

events through sensor networks activated remotely. As discussed above, data handling and archival are the need of the day and should not be ignored. Every single geological data requires considerable human effort, machine time and understanding and it is our social obligation that this is made available in a ready to use, seamless and universal format, so that as the science develops data analytics can be used to glean knowledge for societal use.

A dedicated and active participation of applied physics and applied mathematics is called for, and the expertise and involvements of local departments of Physics, Mathematics, Biology and Chemistry can be utilized effectively and provide a win-win situation for all.

AI-based intelligent instrumentation has made useful progress in India. Some practical examples will be assessment of vulnerability of large-scale infrastructure projects such as airports and dams through an understanding of Quaternary geomorphic processes occurring over one in hundred-year time frame or more, so that investment is not wasted due to inadvertent ignorance or conscious greed. Recent past is full of examples, where geoscience inputs have been and are being ignored at a large cost of life and infrastructure.

Field trips, Science and Capacity Building

An immediate task that needs to be taken up for INQUA 2027 is the refinement of field and laboratory data for the proposed field trips. We must make all the proposed field transects rich with state-of-the-art analysis of all possible kinds such as, remote sensing, change detection, geophysics, geochemistry, biology and palynology, chronology and human impact. Towards this, I suggest creation of working groups of *volunteer scientists* for each field trip, that brainstorms on what new could be done in terms of observations, measurements, synthesis modelling and the services this science could inform.

A two-year, intense field and laboratory-based activity is needed for each of selected field trips and both MoES and DST will need to ensure that these studies are funded expeditiously i.e., in a time frame of 4-6 months. An upgrade of our understanding of 20 field areas covering over 10,000-line kms and about a million sq. km, will benefit all. I feel convinced that an investment of a few crores of Rupees now, will provide rich dividends in the form of data that inform safety for both humans and infrastructure and through creation of competent manpower and synergies at all levels.

Cardinal to in this initiative will be a conscious involvement of teachers from colleges and universities so that we use these field trips both for their research insights and for their training to develop more informed teachers working at the cutting edge to help create a platform for new pedagogy for the future. This is a time to up the ante and join hands for academic synergy.

It will also be good to develop training programs on emerging areas. A two week long, Oil India-INSA supported program on Quantitative Geomorphology at IIT Gandhinagar with a judicious combination of faculty from India and overseas was a success. Such programs need to be replicated and geosciences-based industry would do well to support such initiatives. Workshops on themes such as development of mathematical scenario building, data analytics, AI-assisted instrumentation for extreme events, and molecular proxies are needed. In these workshops, it will be desirable to have the best possible international and national faculty available for an extended and continued interactions and collaborations. These programs could and should include scientists from neighbouring regions and from regions south of the Brandt line. The net outcome from these in terms of capacity building and for global good will be enormous and this also could be an activity with some support from INQUA and it providing a global interfacing and expert faculty. This will be Science Diplomacy in real action.

In conclusion

Various initiatives outlined above could be used as vehicles for acceleration of Quaternary Science activities in India and its neighbouring regions for the simple fact that geology does not recognize political boundaries. As a community, we need to use this opportunity to the fullest possible extent and deliver wholesome outcomes that benefits Quaternary Science of the region, creates new data, develop capacity and help society in a meaningful manner. The potential exists and a simple task of realizing this will need conscious effort, confident resolve, mutual trust, and willing financial support.

All of this is possible and should be attempted and in saying so, I am reminded of an observation by Sir Arthur C. Clarke who said, *the only way to discover the limits of possible is to go beyond them into the impossible.* Let us do it and, deliver good science that society is justifiably proud of Quaternary Sciences.

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