

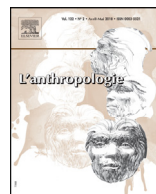


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Original article

Masol (India, Punjab): Horses (*Equus*) and hominins in the sub-Himalayan floodplain as early as 2.95 Ma. A pluridisciplinary synthesis and a hypothesis of dispersal routes from North America (*Equus*) and North Africa (hominins)



Masol (Inde, Pendjab) : des chevaux (Equus) et des hominins dans la plaine inondable sub-himalayenne dès 2,95 Ma. Une synthèse pluridisciplinaire et une hypothèse de voies de dispersion depuis l'Amérique du Nord (Equus) et l'Afrique du Nord (hominins)

Anne Dambricourt Malassé^{a,*}, Alina Tudryn^b, Julien Gargani^b, Anne-Marie Moigne^c, Cécile Chapon Sao^d, Salah Abdessadok^a, Mukesh Singh^e, Dominique Cauche^f, Pierre Voinchet^a, Baldev Karir^e, Surinder Pal^e

^a UMR 7194 CNRS-MNHN-UPVD, Histoire Naturelle des Humanités Préhistoriques, Département Homme et environnement, Institut de Paléontologie Humaine, 1, rue René-Panhard, 75013 Paris, France

^b UMR 8148 CNRS GEOPS, Géosciences Paris-Sud, Université de Paris-Saclay, rue du Belvédère, Bâtiment 504 et 509, 91405 Orsay, France

^c UMR 7194 CNRS-MNHN-UPVD, Histoire Naturelle des Humanités Préhistoriques, Département Homme et environnement, Centre Européen de Recherches Préhistoriques de Tautavel (CERPT), avenue Léon-Jean-Grégory, 66720 Tautavel, France

^d UMR 7194 CNRS-MNHN-UPVD, Histoire Naturelle des Humanités Préhistoriques, Département Homme et environnement, Musée de l'Homme, 17, place du Trocadéro et du 11-Novembre, 75116 Paris, France

^e Society for Archaeological and Anthropological Research, 1447, Sector 22-B, Chandigarh 16002, India

^f Institut de Paléontologie Humaine, Fondation Albert I^{er} Prince de Monaco, Antenne de Nice, Laboratoire de Préhistoire Nice-Côte-d'Azur, 15, boulevard Maurice-Maeterlinck, 06300 Nice, France

* Corresponding author.

E-mail address: anne.malasse@mnhn.fr (A. Dambricourt Malassé).

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ABSTRACT

Late Pliocene fossil deposits outcrop in the Siwalik Frontal Range along the North Western Himalayas. These formations are located in the Subathu sub-basin dispersed over 70 km in different fossiliferous sectors between the 30th and 31st parallels north: the Chandigarh anticlinorium, the Ghaggar-Moginand and Khetpurali sectors and then the Saketi-Kanthro and Haripur sections. Undisputable marks of butchery and lithic industries have been regularly collected between 2008 and 2019 in the fossiliferous Quranwala Zone (QZ) of the Masol Formation located in the Chandigarh anticlinorium. The production of lithic tools was definitively confirmed in 2017 by at least one chopper *in situ*. This biozone, 50 meters thick, perfectly circumscribed and geomorphologically isolated, yielded the First Appearance Datum (FAD) of *Equus* in Eurasia and its oldest co-existence with *Hipparion*. Our magnetostratigraphy dated the Quranwala Zone and hominin activities thanks to a short excursion measured at its lower limit and whose minimum age can be the one at 2.68 Ma and the oldest at 2.95 Ma (Huahine). We present a synthesis of the different fossiliferous localities with their sedimentation rates on a regional scale and which have constrained the age of the excursion to 2.95 Ma. This date allows us to reconstruct the environmental and climatic factors responsible for the appearance and disappearance of the Quranwala Zone by placing them on both regional and global scales. The FAD of *Equus* is explained by its dispersal from North America to Asia thanks to the formation of Beringia during the cold and dry interval MIS G 20 (3.043–3.025 Ma). The FAD of hominin activities since 2.95 Ma can be explained by a northward shift of the Summer Inter-Tropical Convergence Zone (ITCZ) during the final peak of a warming at the end of the Piacenzian at 2.97–2.96 Ma and allowing a dispersal in western Asia. We propose the most parsimonious and consistent paleoclimatic hypothesis of hominin dispersal from latitudes 30°–31° that covered the river systems along the ITCZ from Northern Africa to the Sub-Himalayan plain and which accounts the formation of the Quranwala Zone including *Equus* before the onset of glaciation at 2.75 Ma with a common passage through the Afghan depression of Seistan.

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R É S U M É

Des dépôts fossilifères du Pliocène supérieur affleurent dans des plissements de la chaîne frontale des Siwaliks, le long de la chaîne nord-occidentale de l'Himalaya. Ces formations se situent dans le sous-bassin de Subathu, dispersées sur 70 km, entre les 30° et 31° parallèles nord, en quatre secteurs fossilifères : l'anticlinal de Chandigarh, les sections de Ghaggar-Moginand et Khetpurali, puis celles de Saketi-Kanthro et Haripur. Des marques de boucherie incontestables et des industries lithiques ont été collectées régulièrement entre 2008 et 2019 dans la formation fossilifère nommée Quranwala Zone (QZ) de la Formation Masol située dans l'anticlinal de Chandigarh. La production d'outils lithiques a été

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confirmée définitivement en 2017 par au moins un chopper en place. Épaisse de 50 mètres, parfaitement bien circonscrite et géomorphologiquement bien isolée, cette biozone a également livré la première occurrence d'*Equus* en Eurasie (*First Appearance Datum* [FAS]) et sa plus ancienne coexistence avec *Hipparion*. La magnétostratigraphie a daté la Quranwala Zone et les activités des hominines grâce à une courte excursion mesurée à sa limite inférieure dont l'âge minimum peut être celle de 2,68 Ma et l'âge maximum celle de 2,95 Ma (Huahine). Nous présentons une synthèse des différentes localités fossilifères avec leurs vitesses de sédimentation à l'échelle régionale et qui ont contraint l'âge de l'excursion à 2,95 Ma. Cette date nous permet de reconstituer les facteurs environnementaux et climatiques responsables de l'apparition puis de la disparition de la Zone Quranwala en les replaçant aux échelles régionale et planétaire. La présence d'*Equus* s'explique par sa dispersion depuis l'Amérique du Nord vers l'Asie avec la formation de la Bérangie lors de l'intervalle froid et sec MIS G 20 (3,043–3,025 Ma). La présence d'hominins à partir de 2,95 Ma peut s'expliquer par un déplacement de la Zone de Convergence Inter-Tropicale estivale (ZCIT) vers le nord lors du pic de réchauffement à 2,97–2,96 Ma, à la fin du Piacenzien, permettant alors une dispersion en Asie occidentale. Nous proposons une hypothèse paléoclimatique la plus parcimonieuse et cohérente d'une dispersion d'hominins depuis les latitudes 30°–31° qui couvraient les réseaux hydrographiques le long de la ZCIT depuis le nord de l'Afrique jusque dans la plaine sous-himalayenne. Elle permet de rendre compte de la formation de la Zone Quranwala incluant *Equus* avant l'entrée en glaciation à 2,75 Ma avec un passage commun par la dépression afghane du Seistan.

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1. Introduction

The Mio-Pleistocene geological formations of the Siwaliks, or Siwalik Group, are world-renowned for the richness of their paleontological fauna. Composed of molasses, those Mio-Pliocene deposits border the Southern Himalayan Front (SHF) from the Potwar Plateau in Pakistan to Assam in North-East India (Fig. 1).

Cut and percussion marks have been observed on 4 bones among 1600 fossils collected since 2009 in the geological Masol Formation, more precisely in the Quranwala Zone, a fossiliferous formation identified in the Chandigarh anticlinorium since the 60s (Figs. 2–4). This anticlinorium belongs to the Siwalik Frontal Range (SFR) located in the Subathu sub-basin, Northwestern India (Punjab) (Sahni and Khan, 1964, 1968). The paleontological formation has been perfectly dated to the Late Pliocene (called Tatrot in the Siwaliks) by paleontologists since the 1960s and 1990s by geochronologists (magnetostratigraphy), then by ourselves with a clear and precise delimitation over 50 meters thick well circumscribed on the field and isolated in a comb by surrounding crests (Tudryn et al., 2016; Chapon Sao et al., 2024). The layers are geomorphologically perfectly isolated in the deepest levels of a comb dug on either side of an anticline axis, the whole surrounded by crests (Fig. 5). In addition to these traces of butchery, we have collected artefacts in quartzite (Gaillard et al., 2016; Cauche et al., 2021) scattered in the Quranwala Zone and totaling more than 330 pieces since 2019. These are the sole silts with accumulations of pebbles in the lithostratigraphic log of the comb, which totalizes 175 m of deposits. We also have collected fossils of *Equus* which henceforth corresponds to its First Appearance Datum (FAD) outside North America (Moigne et al., 2016).

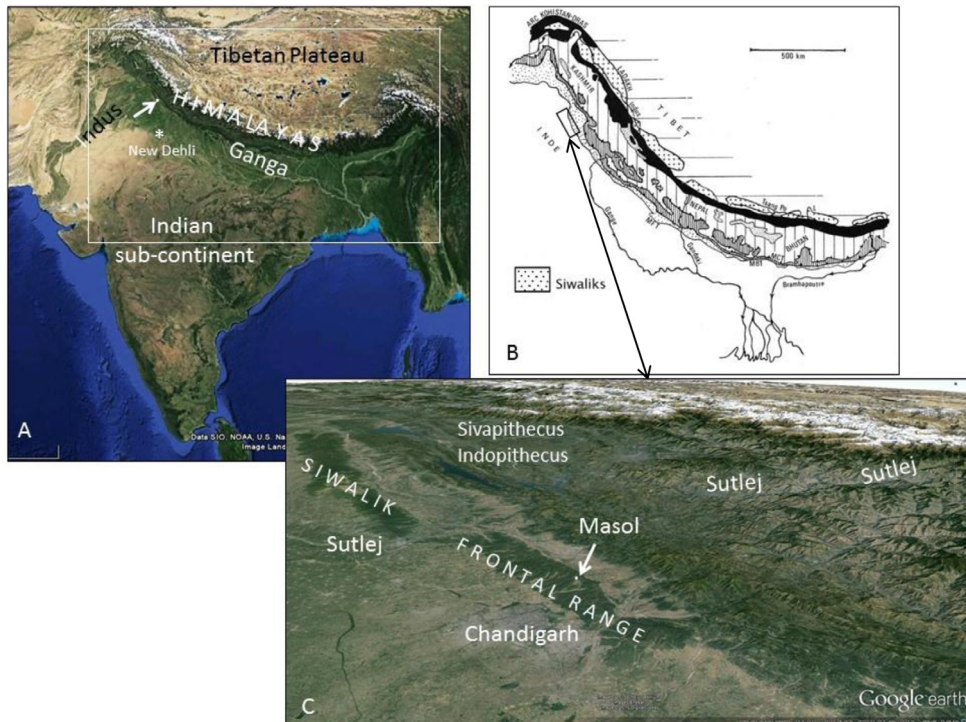


Fig. 1. Location of Masol and the Chandigarh anticlinorium in the Siwalik Frontal Range: **A.** at the subcontinental scale (**white arrow**); **B.** **white box of A**, the geological map of the Himalayan chain and its foothills; **C.** **black box of B**, geomorphology of the Himalayan and Sub-Himalayan region of Masol with the Sutlej River, the last tributary of the Indus (in [Dambricourt Malassé, 2016](#)).

Localisation de Masol et de l'anticlinal de Chandigarh dans la chaîne frontale des Siwaliks : A. à l'échelle sous-continentale (flèche blanche) ; B. encadré blanc de A, carte géologique de la chaîne himalayenne et de ses piémonts ; C. encadré noir de B, géomorphologie de la région himalayenne et sous-himalayenne de Masol, avec la Sutlej, dernier affluent de l'Indus (in [Dambricourt Malassé, 2016](#)).

New artefacts are collected every year on the same silts regularly eroded by monsoon rains ([Gargani et al., 2016](#); [Dambricourt Malassé, 2020](#)). Masol 1 provided 387 fossils and 17 artefacts. The presence of stone tools in the silt has been confirmed in 2017 with a chopper *in situ* uncovered by a meticulous excavation, filmed step by step. The mineralogical analysis of the section demonstrates indisputably that the deposit is in place. This artefact has been shaped on a pebble split by bipolar percussion and was at 45 meters from a shaft tibia with undisputable cut marks uncovered on the same sedimentary unit c3 of our lithostratigraphic sequence ([Cauche et al., 2021](#)). The chopper was at a lower level in the wine lees silt whereas the cut marks come from the yellow silt at the top of c3 ([Fig. 5](#)). This spatial and temporal proximity of cut marks and stone tools is quite consistent with other undisputable traces of butchery and artefacts collected in and on the silt or among concentrations of pebbles visible over the 50 meters thickness corresponds to the Quranwala Zone.

The typo-technological homogeneity of the Masol industry excludes it from the North-Indian tradition called Early Soanian, and from the 2.9 Ma Oldowan culture ([Plummer et al., 2023](#)), but on the other hand, brings it closer to that of the Longupo culture ([Cauche et al., 2021](#)) located in central China (Sichuan Province) ([Boëda and Hou, 2011](#); [Wei et al., 2014](#)), 4000 km east of Masol at the same latitude and dated to 2.6–2.5 Ma ([Han et al., 2017](#)). Our last magnetostratigraphic study of the Masol Formation has assigned to the c3 unit a short excursion with a minimum age of 2.68 Ma and up to 2.95 Ma (Huahine) ([Chapon Sao et al., 2024](#)) ([Table 1](#)). We test the different excursions by placing them in the regional context of the Subathu sub-basin with the sections of Ghaggar-Moginand-Khetpurali and Saketi-Kanthro-Haripur.

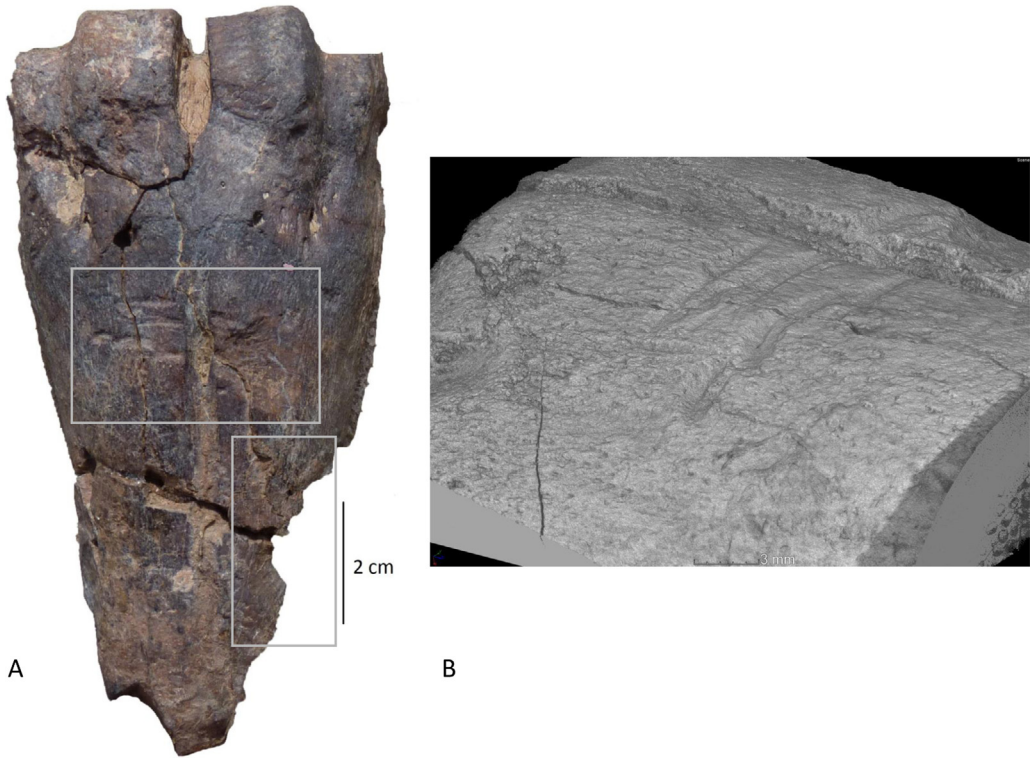


Fig. 2. Marks of intentional percussions on a bovid metapodial showing the reproduction of the profile of the lithic striking edge and the superposition of two impacts. **A:** original fossil; in the upper rectangle, the percussion marks and in the lateral rectangle, the fracture zone. **B:** X rays microtomography showing the superposed marks indicating the direction of the shifting from the dense, impact-resistant part of the bone to the medullary cavity broken by the shock with a bursting of the cortical bone. *Marques de percussions intentionnelles sur un métapode de bovidé montrant la reproduction du profil du tranchant lithique et la superposition de deux impacts. A : fossile original ; dans le rectangle supérieur, les marques de percussion et dans le rectangle latéral, la zone de fracture. B : Microtomographie aux rayons X des marques superposées indiquant la direction du déplacement depuis la partie dense de l'os et résistante aux chocs vers la cavité médullaire fracturée par le choc avec un éclatement de l'os cortical.*

2. The objective: solving the origin and the disappearance of the Quranwala Zone

The indisputable presence of hominin in South Asia at more than 2.6 Ma (probably *Homo* genus) (Coppens, 2014, 2016, 2020; Dambricourt Malassé, 2016, 2020, 2022; Dambricourt Malassé et al., 2016a, 2016b; Cauche et al., 2021; Dambricourt Malassé and Cauche, 2022), constitutes a major paradigm shift in paleoanthropology and prehistory but perfectly consistent with the lithic assemblage of Lomekwi 3 (Kenya) unquestionably in place and dated to 3.3 Ma (Harmand et al., 2019). Lithic assemblages at 2.5 Ma in northern Jordan (Zarqa Valley) (Parenti et al., 2024) is also consistent with an out of Africa before the onset of the North Hemisphere Glaciation ~ 2.75 Ma (Hodell and Channell, 2016; Trauth et al., 2021) as well as Riwat (Pakistan) in the Soan Valley (2.4–2.3 Ma; Dennell et al., 1988). It is noticeable that these Asian sites are located between the latitudes 31° and 32° (Fig. 6). In such a context, stone tools and cut mark at Aïn Boucherit in Southern Algeria (36°), dated to 2.4 Ma (Sahnouni et al., 2018), become even more representative of Late Pliocene hominin North-African corridors.

This study aims to understand the environmental circumstances responsible of the appearance and disappearance of the Quranwala biozone at the regional scale of the Siwaliks. In order to clarify these events we have looking for (1) the climatic, geomorphological and tectonic conditions that allowed the

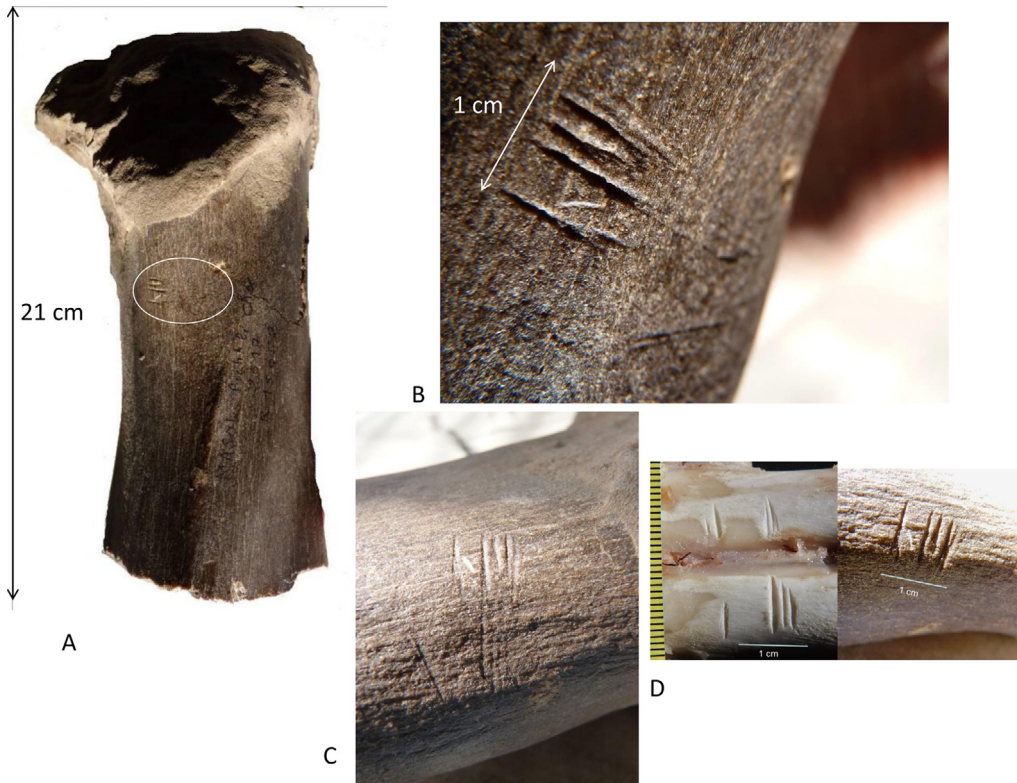


Fig. 3. Cut marks on a tibia of *Stegodon* (A, B, C); D: comparison with traces after cutting the leather and the muscles of a pig's metapodial using a quartzite of Masol split for the experiment.

Marques de découpe sur un tibia de Stegodon (A, B, C) ; D : comparaison avec des traces après la découpe du cuir et des muscles d'un métapode de porc à l'aide d'un quartzite de Masol fendu pour l'expérience

arrival of herds of *Equus* and hominin/human communities in the Upper Indus Basin before the Pleistocene glaciation and (2) the paleomagnetic excursion measured at the base of the Quranwala Zone. To achieve our goal, we have conducted a synthesis with our data and the documentation on the Late Pliocene from other sectors of the Siwalik Frontal Range from the Ghaggar section (Haryana) to Haripur (Himachal Pradesh) (Fig. 7). The synthesis brings together the regional knowledges on fluvial and marsh sedimentations as well as fauna and flora bioindicators and place them at the scale of the Upper Indus Basin. We then discuss the hypothesis of dispersal routes from North America for *Equus*, during the cold and dry interval MIS G 20 at 3.043 et 3.025 Ma, and from North Africa for hominin/ *Homo*, both converging in the Seistan depression and high valleys of the West Hindu Kush which give access to the Upper Indus River Basin.

3. Method: an interdisciplinary approach and a synthesis of data

Before establishing a synthesis of the Late Pliocene sections in the Siwalik Frontal Range, we recall the geomorphological and tectonic context of the Chandigarh anticlinorium with previous studies completed by our lithostratigraphic, geomorphological, magnetostratigraphic and paleontological results. Then, we present the multidisciplinary data of other sections (lithostratigraphy, fauna, flora, paleomagnetism) in order to test the consistency of the Huahine excursion. Once the relevance has been confirmed by the synthesis, we searched in the scientific literature if glacial climatic episodes have been identified in the Northern Hemisphere before the Pleistocene glaciation to explain the FAD

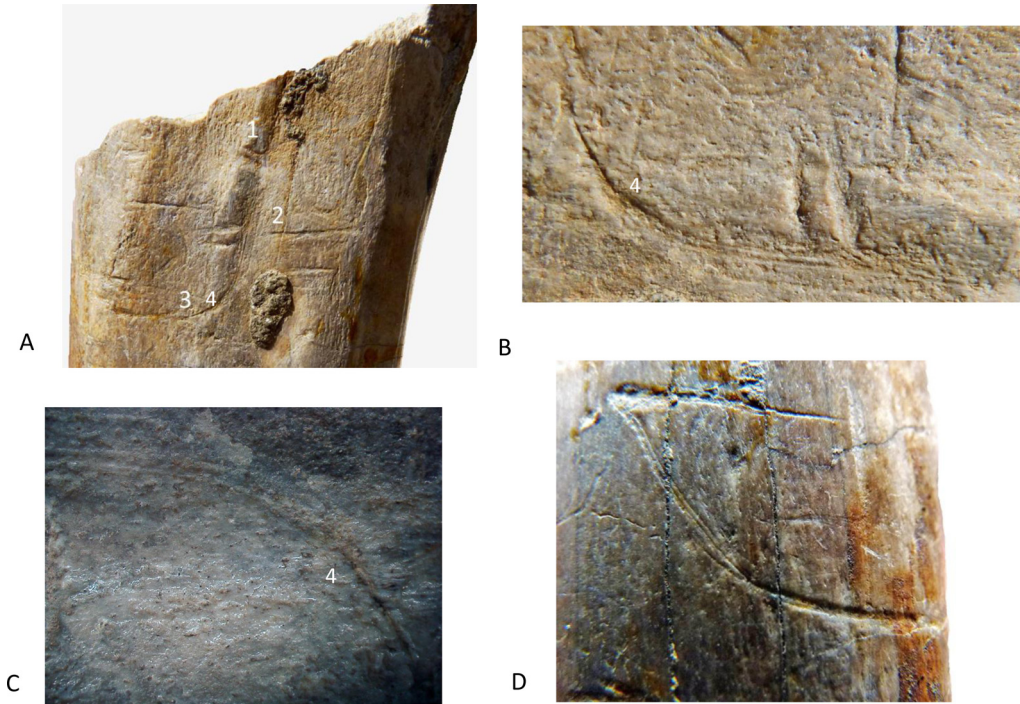


Fig. 4. Marks of intentional cutting on a bovid shaft tibia (Masol 1). **A** and **B**, dorsal face; **C**: image of B with a 3D digital microscope Hirox; **D**: cranial face. **1**: two parallel and short cut marks on the insertion crest, **2**: long parallels cut marks sectioning the crest; **3**: curved path of a cut mark and its resumption in **4**, for the readjustment in order to detach an aponeurosis under the crest. The curve clearly shows the transition from one to two parallel furrows.

Marques de découpe intentionnelle sur le fût tibial d'un bovidé (Masol 1). A et B, face dorsale ; C : Image de B au microscope numérique 3D Hirox ; D : face crâniale, 1 : deux marques de découpe courtes et parallèles sur la crête d'insertion, 2 : marques de découpe parallèles longues sectionnant la crête ; 3 : tracé courbe d'une marque de découpe et sa reprise en 4, pour le réajustement afin de détacher une aponévrose sous la crête. La courbe montre clairement la transition d'un à deux sillons parallèles.

of *Equus* and we refined the paleoclimatic data collection to understand the appearance and disappearance of corpses accumulations in the Sub-Himalayan floodplain during the Late Pliocene.

3.1. The Masol Formation

3.1.1. Geomorphology, tectonics, magnetostratigraphy and lithostratigraphy

Molasses forming the Siwalik Frontal Range (SFR) were gradually unearthed by the tectonic folding in the Himalayan foreland (Bhattacharya, 2005). They were deposited in a basin, which forms today the Subathu sub-basin, a remnant of the continental crust of the Indian plate. The SFR is bordered on the north by the Main Boundary Thrust (MBT) and on the south by the Himalayan Frontal Thrust (HFT) still active (Barnes et al., 2011) (Fig. 8).

The Masol Formation was identified in the 1960s during the mapping of the Chandigarh anticlinorium, which stretches 40 km between the Himalayan Sutlej River in the northwest and the Ghaggar River in the southeast (Sahni and Khan, 1964, 1968). The fossiliferous zone was determined around the village Quranwala with a fauna assemblage typical of the Late Pliocene and placed in a stratigraphic column established for the whole anticlinorium. Masol sections were mapped by comparing their lithostratigraphic and paleontological sequences. When we uncovered the first choppers, flakes and cut-marked bones among fossils in 2009, there was no comprehensive study of the Formation. We only had the lithostratigraphic sequence of the Quranwala Zone, the publication of

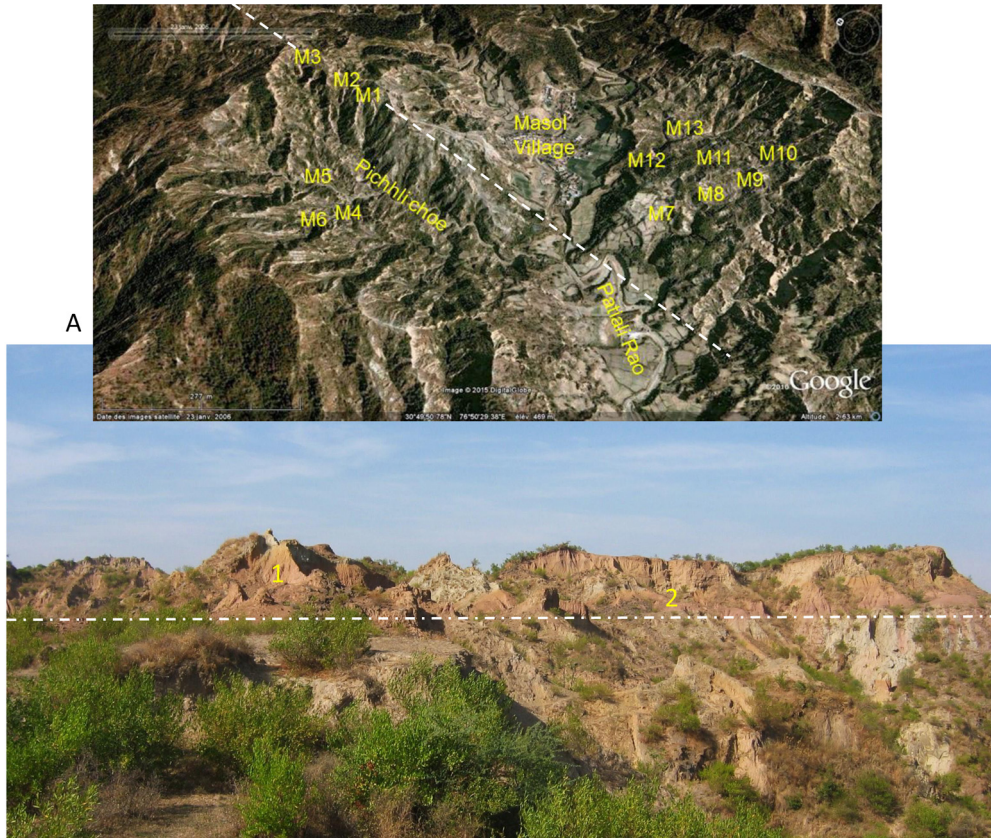


Fig. 5. The archaeo-paleontological localities of Masol in the Quranwala Zone, on the central dome which corresponds to the anticline axis (**dotted line**) (M1-M3) and on each side in lower position due to the dip of the fossiliferous layers (M4-M13), the whole surrounded by crests. **A:** geomorphological view on Masol's site with the 13 localities. **B:** view on Masol 1 at the top of the central dome, **1:** location of a bovid shaft tibia with cut marks, **2:** location of a chopper *in situ*. **Dotted line:** the lower limit of the Quranwala Zone.

Les localités archéo-paléontologiques de Masol dans la Zone de Quranwala, sur le dôme central qui correspond à l'axe anticlinal (**pointillé**) (M1-M3) et de chaque côté en position plus basse en raison du pendage des couches fossilifères (M4-M13), le tout entouré de crêtes. **A :** vue géomorphologique du site de Masol avec les 13 localités. **B :** vue sur Masol 1 au sommet du dôme central, **1 :** localisation d'un fût tibial de bovidé avec des marques de boucherie, **2 :** emplacement d'un chopper en place. **Ligne pointillée :** la limite inférieure de la Quranwala Zone.

geological sections with one map delimiting the Pliocene and Pleistocene (Sahni and Khan, 1964, 1968) and the PhD thesis of Badam (1973) (Fig. 9).

The Masol Formation is visible at the top of an anticline excavated by the watershed of a seasonal torrent, the Patiali Rao fed by the monsoon rains and which ends in the Indus plain (Figs. 5 and 7). The geomorphology is a sub-circular depression bordered by crests to the northwest and southeast at an elevation of 550 meters with a lower central dome (530 meters), which corresponds to the axis of the anticline. The first cut-marked bones and stone tools have been collected on this small dome, the summit of which corresponds to the lower layers of the Quranwala Zone. The geological section of the Patiali Rao valley represents 1296 meters of molasses. The boundary between the Pliocene and the Pleistocene has been the subject of many discussions in the scientific literature, based mainly on fauna assemblages (e.g. Sahni and Khan, 1964, 1968; Badam, 1973; Nanda, 1981, 2002, 2013; Nanda et al., 1991, 2018; Patnaik, 1995; Sangode et al., 1996). The magnetostratigraphy was carried out in the 1990s by Ranga Rao (1993), Ranga Rao et al. (1995) identifying the magnetozones of Gauss (Late

Table 1

Summary of the pre-Gauss-Matuyama reversal excursions recorded in sedimentary and basaltic records. The sedimentation rates were calculated for a thickness of 150 m between the top magnetostratigraphy of the Masol Formation and the short excursion in c3 unit. The duration is calculated between the age of 2.58 Ma for the Gauss-Matuyama reversal and the age of each magnetic excursions.

Résumé des excursions magnétiques enregistrées dans les archives sédimentaires et basaltiques avant l'inversion Gauss-Matuyama. Les taux de sédimentation ont été calculés pour une épaisseur de 150 m, entre la limite supérieure de la magnétostratigraphie de la formation Masol et la courte excursion dans l'unité c3. La durée est calculée entre l'âge de 2,58 Ma pour l'inversion Gauss-Matuyama et l'âge de chaque excursion magnétique.

	Magnetic excursions							
	Huahine Island excursion (Society Island)	Raiatea excursion (Society Island)	L8 excursion IODP 1314	Porcupine IODP Site U1308	L7 excursion IODP 1314	L6 excursion IODP 1314	L5 excursion IODP 1314	Pirnuar, West Turkmenistan
Estimated age in Ma	–	–	2.75 (Ohno et al., 2012)	2.737 (Channell et al., 2016)	2.71 (Ohno et al., 2012)	2.65 (Ohno et al., 2012)	2.62 (Ohno et al., 2012)	2.62
Radiometric age in Ma	2.95 ± 0.03 Ma (Roperch and Duncan, 1990)	2.77 ± 0.02 (Yamamoto et al., 2007)	–	–	–	–	–	–
Duration between the Gauss-Matuyama reversal and the excursion	0.37 Ma	0.19 Ma	0.17 Ma	0.157 Ma	0.13 Ma	0.07 Ma	0.04 Ma	0.04 Ma
Sedimentation rate estimated from the top of the Masol Formation to the excursion c3 unit (150 m thick)	0.41 m.kyr ⁻¹	0.79 m.kyr ⁻¹	0.88 m.kyr ⁻¹	0.96 m.kyr ⁻¹	1.15 m.kyr ⁻¹	2.14 m.kyr ⁻¹	3.75 m.kyr ⁻¹	3.75 m.kyr ⁻¹
Age of the QZ top (Ma)	2.83	2.71	2.69	2.68	2.67	2.63	2.61	2.61

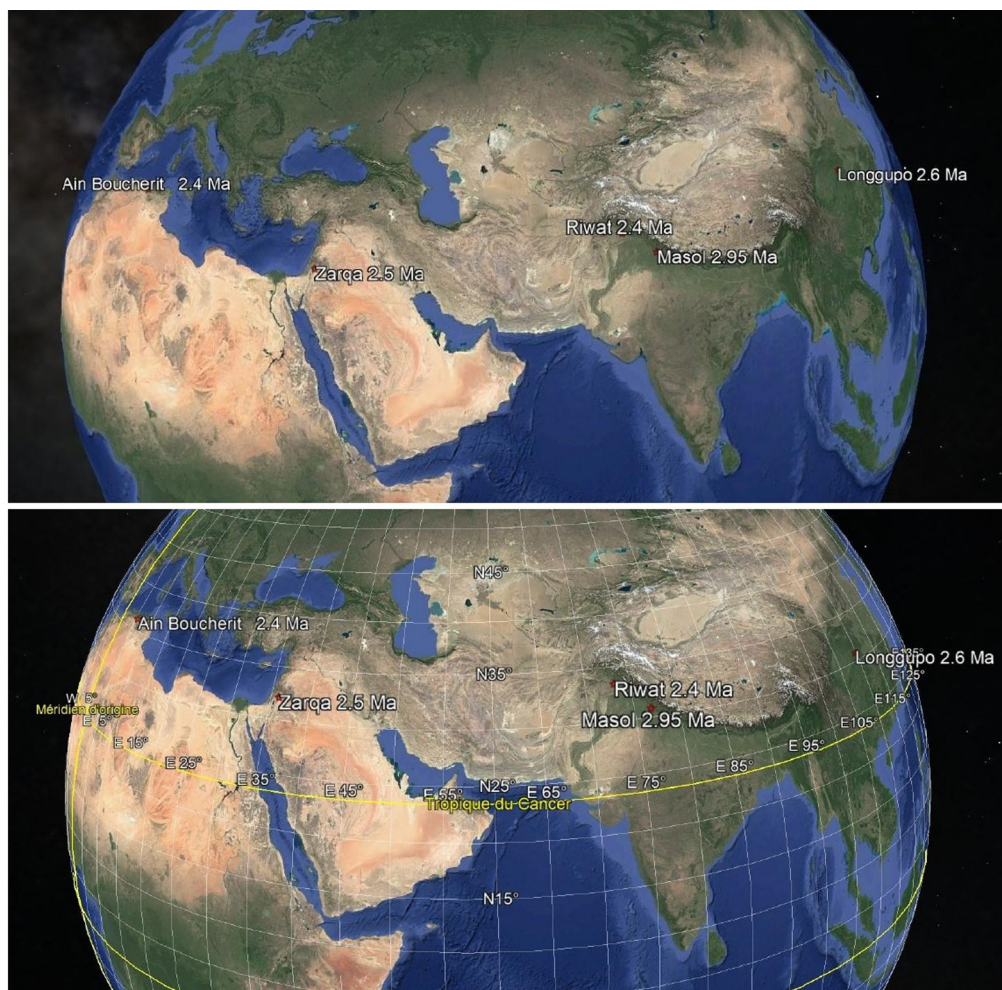


Fig. 6. Late Pliocene and Lower Pleistocene Asian prehistorical sites between latitudes 30° and 32° (Zarqa, Riwat, Masol, Longgupo) and the African site of Ain Boucherit at latitude 36° (Mapdata, Google Earth, 2025).

Les sites asiatiques du Pliocène supérieur et du très ancien Pléistocène inférieur entre les latitudes 30° et 32° (Zarqa, Riwat, Masol, Longgupo) et le site africain d'Ain Boucherit à la latitude 36° (Mapdata, Google Earth, 2025).

Pliocene), Matuyama (Lower Pleistocene) – with the submagnetozones of Réunion, Olduvai and Jaramillo, and Brunhes (Middle Pleistocene). This magnetostratigraphy confirmed the Late Pliocene age of the Quranwala Zone.

We have undertaken multidisciplinary studies of the comb between 2012 and 2019 covering an area of 80 hectares identifying a dozen paleonto-archaeological localities on both sides of the anticline axis and on the central dome. The lithostratigraphic sequence was established considering the geomorphological context and the dip of the layers. We reconstructed the sequences from the bed of the Patiali Rao to the western crest over a thickness of 168 meters (Tudryn et al., 2016; Chapon Sao et al., 2016a) and later on 175 meters passing the crests to the south (Chapon Sao et al., 2024). The lithostratigraphic column is composed of repetitive sedimentary cycles of silt/clays (so-called “c” units) and sandstones that sometimes contain gravel and pebble levels (“s” units), corresponding to the cyclical influx of detrital material in a fluvial environment (Fig. 10). The column is composed, from the base to the top, of silt, sandstone, sands and gravels, and in its upper part of a pebbly sandstone

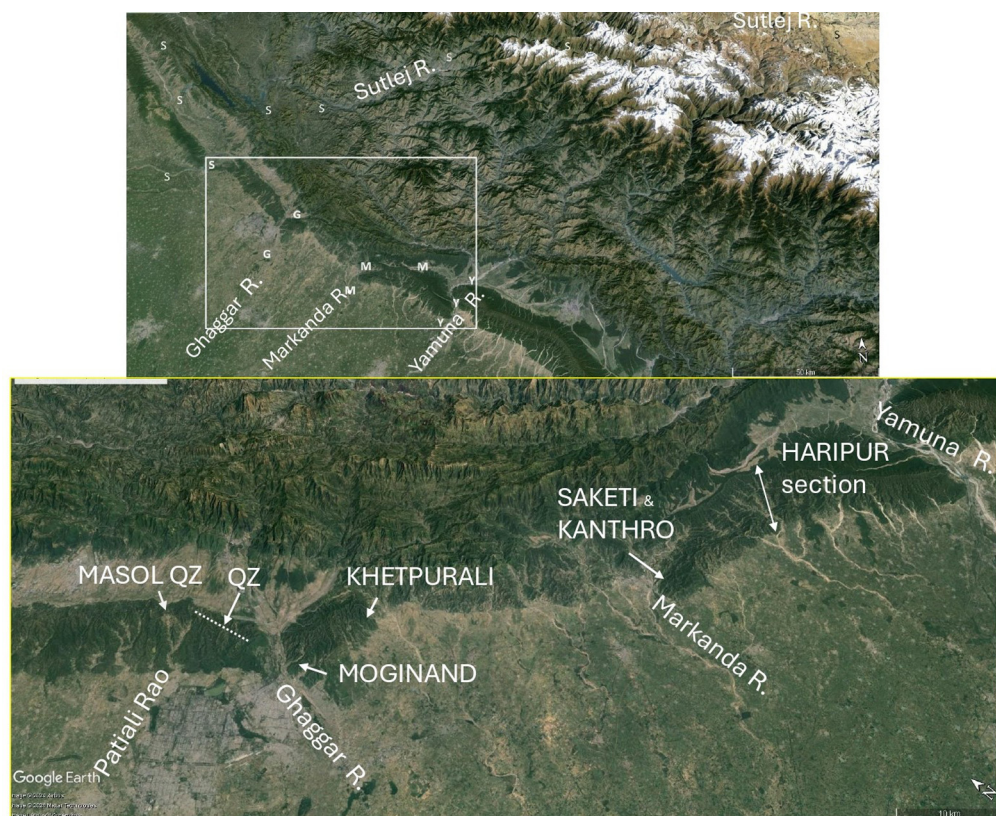


Fig. 7. Satellite view of areas cited. **Top:** Himalayan rivers, **G:** Ghaggar, **M:** Markanda, **S:** Sutlej, **Y:** Yamuna. **Bellow:** Location of the geological sections in the Siwalik Frontal Range: Masol, Ghaggar-Moginand and Khetpurali, Saketi-Kanthro, Haripur (Map data Google Earth 2025).

Vue satellite des zones citées. En haut : rivières himalayennes, **G :** Ghaggar, **M :** Markanda, **S :** Sutlej, **Y :** Yamuna. *En bas :* localisation des coupes géologiques dans la chaîne frontale de Siwalik : Masol, Moginand et Khetpurali, Saketi-Kanthro, Haripur (données cartographiques Google Earth 2025).

bed, in accordance with the sequences of Sahni and Khan (1964, 1968). Badam (1973) called them “conglomeratic beds” which precedes a long sequence of sand with rare silty passages.

All archaeological localities are in the Quranwala Zone limited to 50 meters thick and confined in the lower levels of the depression around and on the central dome on which remain only 5 meters of its lower part (Chapon Sao et al., 2016a; Tudryn et al., 2016). Moreover, for the first time, we have observed lenses of pebbles in these fossiliferous silts composed of a single layer deposited directly on the silts. These lenses correspond to accretion bars formed during flooding and are strictly circumscribed to the biozone (Abdessadok et al., 2016). Stone tools are among these pebble deposits, or always in the vicinity of fossils, on and in the silts leached annually by monsoon rains. Finally, the magnetostratigraphy have identified an excursion in unit c3 at the base of the Quranwala Zone (Fig. 10a) visible at Masol 1-Masol 2 on the dome and at Masol 7-Masol 12 on the eastern side of the Masol anticline (Chapon Sao et al., 2016b, 2024). This excursion dates the oldest cut marks and the chopper *in situ*.

Our recent magnetostratigraphy have also modified the supposed location of the Gauss-Matuyama Reversal, which is higher in the stratigraphy and at least 150–155 meters above the unit c3. The last syntheses concluded the age of the excursion exceeding 2.77 Ma (Raiatea) but not older than Huahine (Chapon Sao et al., 2024) studied by Roperch and Duncan (1990) and dated to 2.95 ± 0.03 (Yamamoto et al., 2007).

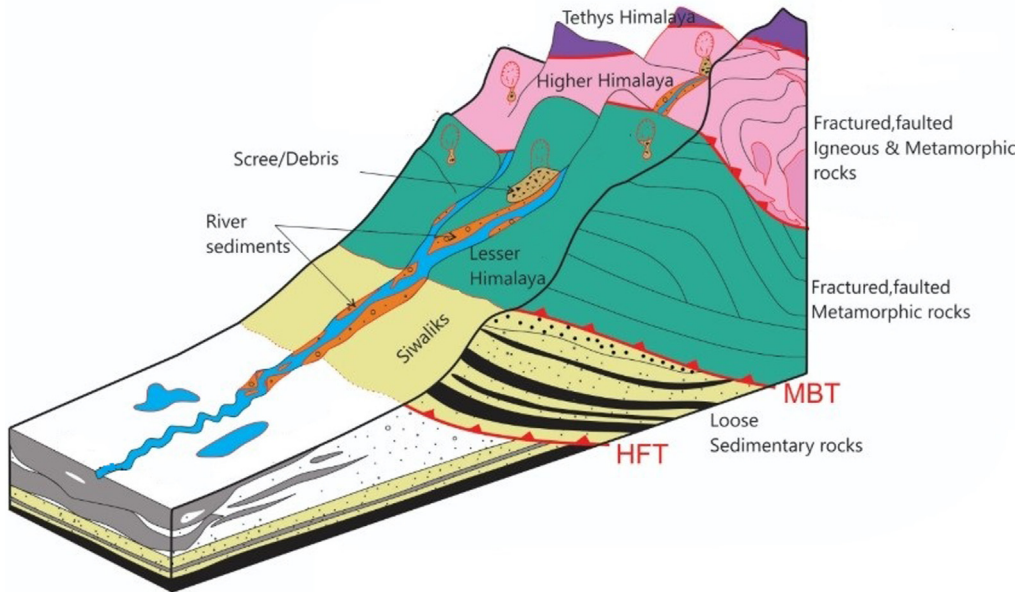


Fig. 8. Block diagram showing the geomorphology and structural geology of the Himalayan range, the foothills, and the Indian plain with its hydrogeological network (S. Abdessadok after an illustration from the website of the Department of Mines and Geology of Nepal).

Bloc diagramme de la géomorphologie et de la géologie structurale de la chaîne himalayenne, des piémonts et de la plaine indienne avec son réseau hydrogéologique (S. Abdessadok d'après une illustration du site du Department of Mines and Geology du Népal).

3.1.2. The Quranwala Zone in Masol: environment, climate, and fauna diversity

3.1.2.1. Resume presentation. The Chandigarh anticlinorium began to fold at about 600 ka as a result of the increased speed of the India-Asia collision system (Gargani et al., 2016). The current tectonic activity combines its effects with the monsoon rains; the Quranwala Zone erodes rapidly, delivering new lithic and fossil tools on its fossiliferous silts every year. The base of the Quranwala Zone (c3) is composed of silt, with discontinuous lenses of pebbles mostly quartzite, paleosols with some pebbles among blocks of indurated silt, fossils of terrestrial and aquatic vertebrates (mammals and reptiles) (Moigne et al., 2016). The Quranwala Zone ends with pebbles and stone tools caught in silts (base of unit c7). Beyond these silts, the stratigraphic sequence continues towards the crests without fossils or pebbles for a thickness of 95 meters of sediment, before a clear change in hydraulic regime attested by the "conglomerate" (Badam, 1973) and the extreme scarcity of fossils (base of s17). Thus, it appeared that (1) the thickness of the Quranwala Zone is limited to 50 meters, (2) QZ is geomorphologically well isolated by crests, (3) this biozone is peculiar for its concentration of fossils, but also (4) for pebble lenses and (5) its lower limit is, at least, 150–155 meters below the Gauss-Matuyama Reversal and characterized by the paleomagnetic excursion Huahine (2.95 Ma).

3.1.2.2. Mineralogy and Himalayan rivers. The environment and climate recorded in the Masol Formation are inferred from the mineralogy and particle size of the deposits, as well as from the fauna assemblages confined in the Quranwala Zone.

Iron minerals such as hematite and goethite are present in low contents in the Masol Formation as a whole and indicate dominant oxic conditions during and after deposition (Tudryn et al., 2016). The distribution of clay minerals shows illite and smectite as principal components of the clay fraction (Abdessadok et al., 2016; Tudryn et al., 2016); their contents are expressed by the smectite versus illite ratio in Fig. 10d. Illite dominates as a whole. However, smectite presents higher contents in the lower part of the sequence and decreases steeply in sediments belonging to the Quranwala Zone. Carbonate

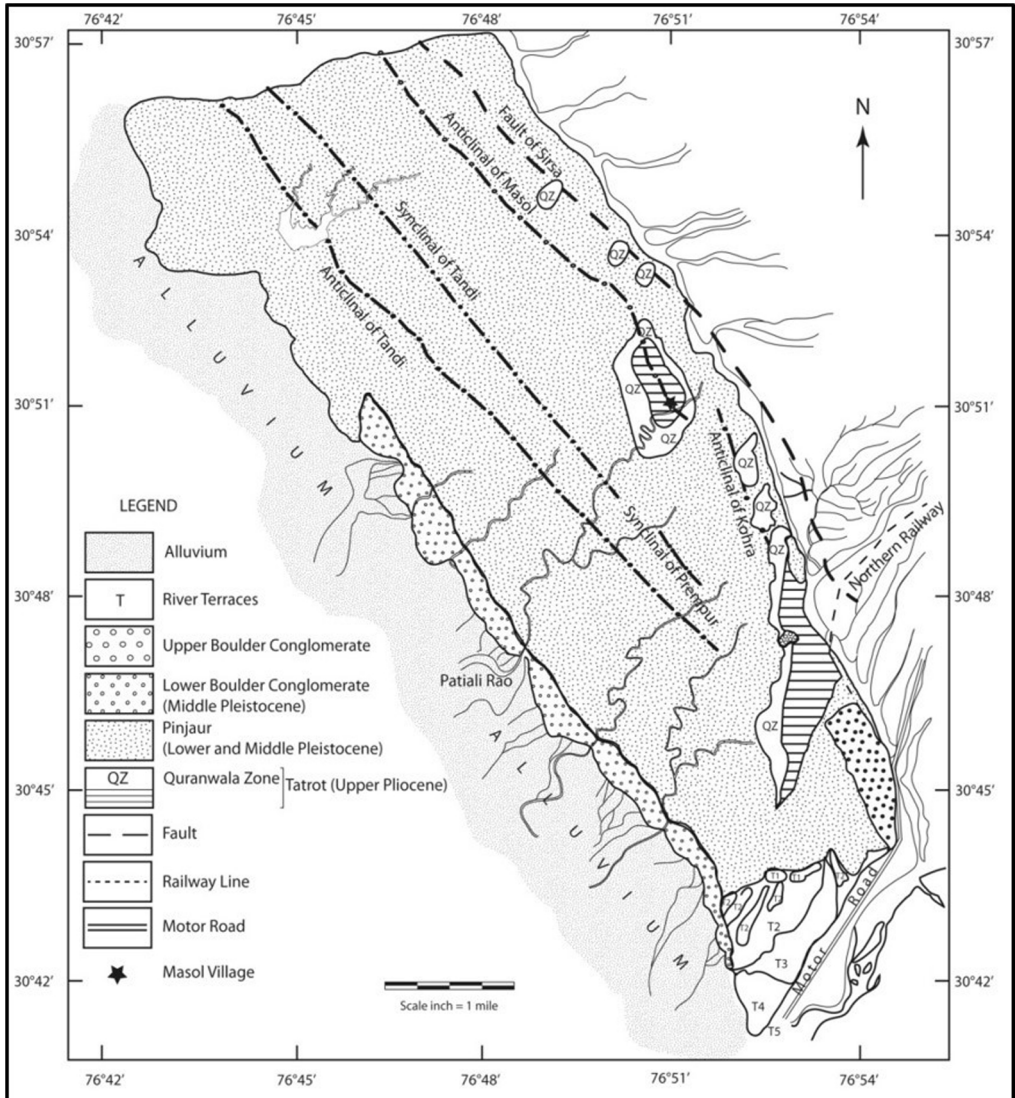


Fig. 9. Geological map of the Chandigarh anticlinorium with the location of the eroded anticline dome of Masol accessible by the Patiali Rao after [Sahni and Khan \(1964\)](#) (recognition by S. Abdessadok et al. in [Chapon Sao et al., 2016b](#)).

Carte géologique de l'anticlinal de Chandigarh avec la localisation du dôme anticlinal érodé de Masol accessible par le Patiali Rao d'après [Sahni et Khan \(1964\)](#) (réalisation S. Abdessadok et al. in [Chapon Sao et al., 2016b](#)).

contents are also changing through the Quranwala Zone, but from low values at the bottom to higher values above ([Fig. 10c](#)). Fe and Mg rich illite is identified through its low chemistry index ([Fig. 10g](#)). Both illite and smectite present very good and good crystallinity all along the sequence ([Fig. 10e, f](#)). The illite composition and crystallinity of both minerals indicates their detrital origin. According to [Suresh et al. \(2004\)](#), the Higher Himalaya is the principal source area for illite, and the Lesser Himalaya is a source area for smectite. Some authors ([Chaudhri and Gill, 1983](#); [Rainverman, 2002](#); [Rainverman and Suresh, 1997](#)) postulated two independent paleo-drainage systems for the Late Pliocene, similar to the present-day Indus and Ganga systems and separated by a water divide along the Subathu sub-basin. However, the presence of detrital smectite originating from the Lesser Himalaya in sediments of

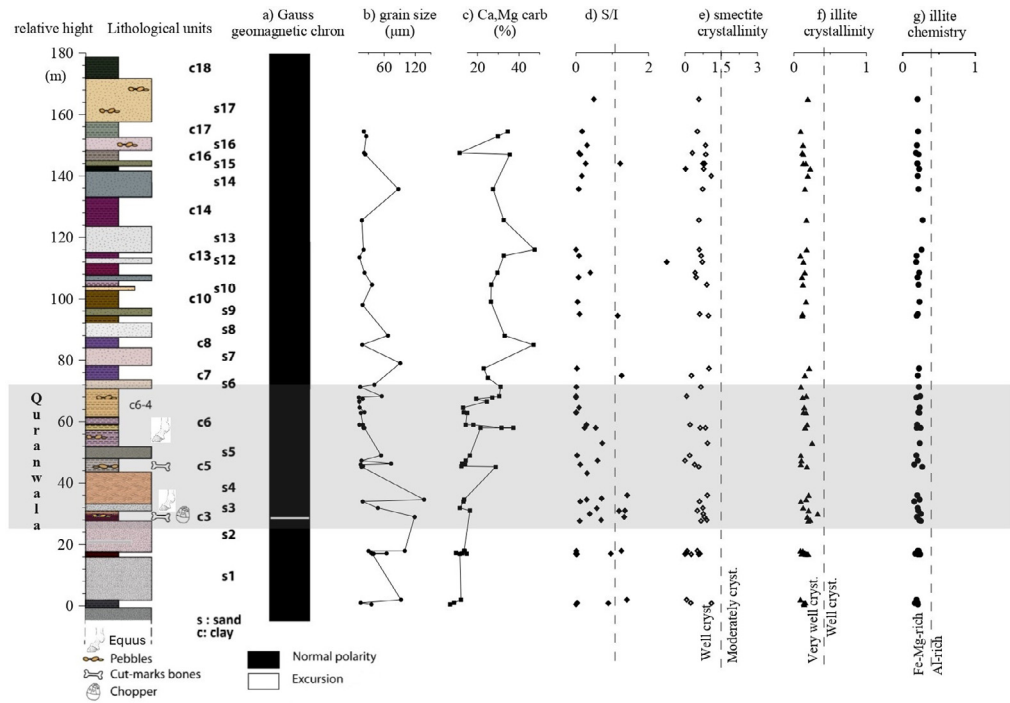


Fig. 10. Sedimentary sequence from Masol anticline with simplified lithology and highlighted Quranwala Zone (after [Tudryn et al., 2016](#) and [Chapon Sao et al., 2024](#)), as well as **a)** geomagnetic normal polarity Gauss chron (after [Chapon Sao et al., 2016a, 2016b, 2024](#); [Ranga Rao et al., 1995](#)); **b)** mean particle size within less than 2 mm sediment fraction; **c)** Ca and Mg carbonate content; **d)** smectite-to-illite ratio; **e)** smectite crystallinity index; **f)** illite crystallinity index; **g)** illite chemistry index. Data from b) to d) (after [Tudryn et al., 2016](#)), data in e), f), and g) obtained from [Tudryn et al. \(2016\)](#) following the methodology described in [Kong et al. \(2022\)](#) and references therein. Chopper symbol: artefact *in situ*.
Séquence sédimentaire de l'anticlinal de Masol avec la lithologie simplifiée et la zone de Quranwala mise en évidence (d'après [Tudryn et al., 2016](#) et [Chapon Sao et al., 2024](#)), ainsi que : **a)** la polarité géomagnétique normale Gauss (d'après [Chapon Sao et al., 2016a, 2016b, 2024](#); [Ranga Rao et al., 1995](#)) ; **b)** la taille moyenne des particules dans une fraction sédimentaire inférieure à 2 mm ; **c)** la teneur en carbonate de Ca et de Mg ; **d)** rapport smectite/illite ; **e)** indice de cristallinité de la smectite ; **f)** indice de cristallinité de l'illite ; **g)** indice de chimie de l'illite. Les données de b) à d) ont été obtenues d'après [Tudryn et al. \(2016\)](#), les données de e), f) et g) ont été obtenues de [Tudryn et al. \(2016\)](#) en suivant la méthodologie décrite dans [Kong et al. \(2022\)](#) et les références qui y figurent. Symbole : chopper en place.

the Quranwala Zone suggests that it had to be supplied from its source area by a major river system. In that case, the Subathu sub-basin was still a paleo-drainage area for major river(s) during the “Quranwala time,” and the following decrease of smectite could reflect the establishment of a definitive water divide after.

3.1.2.3. The fauna of the Sub-Himalayan plain. The fauna list of nearly 1470 fossils in 2014 ([Moigne et al., 2016](#)) and 1600 since 2019 (130 unpublished) includes small to very large terrestrial herbivorous mammals, with grazers and browsers. Grazers are the most numerous in terms of families, with deer (*Cervus*), *Suidae* (*Propotamochoerus*), proboscideans (*Stegodon* and *Elephas*), bovids (*Bubalus*, *Duboisia*), giraffids with *Sivatherium*, and camelids. Browsers were present with bovids *Hemibos* or *Leptobos*, *Hippotragus*, *Sivacapra* (goats), tragulids (*Dorcatherium*), and equids, *Hipparion*, as well as *Equus*, with its first occurrence in Eurasia. Indeed, equids are represented in the QZ sequence in several localities, by at least two species of *Hipparion* (*Hipparion antilopinum* and *Hipparion theobaldi*) ([Moigne et al., 2016](#)), corresponding in size and morphology to the *Hipparions* already observed in the Late Pliocene of the Chandigarh anticlinorium ([Sahni and Khan, 1964, 1968](#); [Badam, 1973](#)). The material allocated to *Equus* have been collected at Masol 2 (unit c3), Masol 3, and Masol 6 (unit c6) and



Fig. 11. **A:** Occlusal view of a lower premolar P4 of *Equus*, Masol R 11459, **B:** molar of *Hipparion* (Masol 3 n° 10050, end of the hammer handle) near a third phalanx of *Sivatherium* (Masol 3 n° 11149), **C:** *Hipparion* molar, **D:** *Sivatherium* phalanx. The hammer give the scale (photo credit: **A:** A.-M. Moigne and **B-C-D:** A. Dambricourt Malassé).

A : Vue occlusale d'une prémolaire inférieure P4 d'*Equus*, Masol R 11459, **B :** molaire d'*Hipparion* (Masol 3 n° 10050, extrémité du manche du marteau) près d'une troisième phalange de *Sivatherium* (Masol 3 n° 11149), **C :** Molaire d'*Hipparion*, **D :** *Sivatherium* phalanx. Le marteau donne l'échelle (crédit photo : **A :** A.-M. Moigne et **B-C-D :** A. Dambricourt Malassé).

consists of dental material (four teeth), a talus, and a very characteristic tibia. The Quranwala Zone is therefore the biozone that provides not only the first occurrence of *Equus* in Eurasia but also its first association with *Hipparion* (Fig. 11).

Its presence in Late Pliocene has recently been confirmed by the discovery of a mandible in the Haripur section, 70 km south of Masol (Singh et al., 2022). The association of both *Hipparion* and *Equus* in the Late Pliocene of Siwaliks (Tatrot) confirms the following conclusion: "The paleomagnetic and biostratigraphic evidence indicates that the Tatrot Beds are between 2.5 and 3.4 m.y. B.P., with a preferred maximum age of 2.9 m.y. B.P. A major faunal event at 9.5 m.y. BP introduced equids, suids, and large giraffes from Eurasia into the Indian subcontinent. A second, more diffuse fauna event between 5.3 and 2.9 m.y. BP introduced several African taxa as well as *Equus* and cervids from Eurasia" (Barry et al., 1982). Recent discoveries in the Khetpurali Formation (Late Pliocene of the Siwaliks) have revealed the existence of a hipparionine horse *Eurygnathohippus* which dates back to the Pliocene of Afar in Hadar, Ethiopia (3.4–2.9 Ma) (Jukar et al., 2019). Authors conclude: "Given the post-Miocene dispersal barriers between East Africa and West Asia across the Red Sea (Fernandes et al., 2006), the most probable dispersal route for *Eurygnathohippus* is via North Africa east through the Levantine corridor, and through the Middle East into South Asia". A fauna dispersal out of Africa was therefore possible at a given time between 3.4 and 2.9 Ma.

In addition to terrestrial herbivores, the fauna list provides wetland and aquatic herbivores with *Merycopotamus* and *Hexaprotodon*. The carnivores are scarce with the hyena (*Crocota*) and the panther (*Panthera*). Terrestrial reptiles include the giant tortoise *Testudo atlas*, a few monitor lizards, and

aquatic reptiles such as the gharial (gavial) and the crocodile. Grazers feed on leaves, shoots, or fruits of tall vegetation, while browsers feed on low vegetation such as grasses. The fauna diversity thus attests to a wooded grassland environment, in a floodplain with marshes and Himalayan rivers of variable regime, in a hot and humid tropical climate, in agreement with the sedimentological data (Abdessadok et al., 2016).

3.1.2.4. The flora. We have not yet undertaken palynological studies; these were carried out by Saxena et al. (1987) in a section from Masol to the northern fringe of the anticlinorium (Kiratpur, Ambala district). The palynoflora is represented by spores of algae, fungi, and pteridophytes (plants without flowers or seeds such as ferns), and pollens of gymnosperms (flowerless plants such as pine and cedar) and angiosperms (flowering plants such as grasses). The list includes 17 genera and 23 species with two new species, *Araucariacites masolensis* (a species of conifer) and *Frasnacritetrus siwalikus* (fungus). The Late Pliocene palynoflora is represented by 9 genera and 11 species and that of the Lower Pleistocene by 15 genera and 20 species, including 8 common species. These plio-pleistocene assemblages are dominated by gymnosperm pollen (61% and 65%, respectively), but the Lower Pleistocene is distinguished by *Pinus*-pollenites (16%) (pine) and *Pinjoriapollis* (*Magnoliaceae*) (10.5%) (*Magnolia*), absent in the Late Pliocene. The palynoflora indicates the predominance of a tropical-subtropical climate with a relatively cooler climate in the nearby upland areas during the Lower Pleistocene sedimentation. The depositional environment is interpreted as fluvial (Saxena et al., 1987).

3.2. Synthesis of Masol Formation and open questions

The presence of pebbles in the Late Pliocene silts had not been mentioned before our fieldwork. This was a real anomaly for this epoch during which hydraulic regimes were lower than in the Pleistocene marked by a greater supply of heavy materials (Kumar et al., 2007). These pebbles were unexpected as well as the lithic industry and cut-marks outside Africa before 2.6 Ma. Nevertheless, these undisputable discoveries are consistent with natural disasters of climatic origins. The enormous accumulation of corpses and pebbles means that the Sub-Himalayan plain has been exposed to recurrent flooding following an increase in the flow of Himalayan rivers dismantling their terraces, and the alluvial fans of the piedmonts. We replace these natural disasters with a paleoclimatic approach in order to understand when and why *Equus* and hominines dispersed in Asia before reaching the Upper Indus Basin 2.95 Ma ago.

4. The Quranwala Zone and the Late Pliocene biozones of the Subathu sub-basin

Since 2007, we have surveyed the Pliocene and Pleistocene paleontological localities of the Siwalik Frontal Range from the Chandigarh anticlinorium to Haripur (Fig. 12). The Quranwala Zone outcrops southeast of the Masol anticline in the Khora sub-anticline for about ten kilometers (Fig. 9). The anticlinorium is then incised by the Ghaggar River and continues 15 km south of Masol in the Khetpurali sector with fossiliferous localities of the Late Pliocene and the Lower Pleistocene (Nanda, 1981, 1994, 2002, 2013; Nanda et al., 1991, 2016, 2018; Patnaik, 1995; Rao and Patnaik, 2001). The Siwalik Frontal Range continues without paleontological deposits for 30 km to the Markanda River, where Mio-Pleistocene fossiliferous formations reappear at Saketi-Kanthro, then in the Haripur region along the Somb Nadi River and its tributary Jamni Khol. The geological section of Haripur is exceptional with the height of its lithostratigraphic sequence, the magnetostratigraphy and the paleoenvironmental studies with fauna and flora (Phadtare et al., 1994; Sangode et al., 1996; Kumar et al., 2007).

4.1. Lithostratigraphy, fauna and magnetostratigraphy

4.1.1. Ghaggar and Moginand

The geological section of the Ghaggar River has been identified with volcanic ash by Tandon and Kumar (1984). Later, the magnetostratigraphy was carried out on 1030 meters in thickness (see Fig. 2

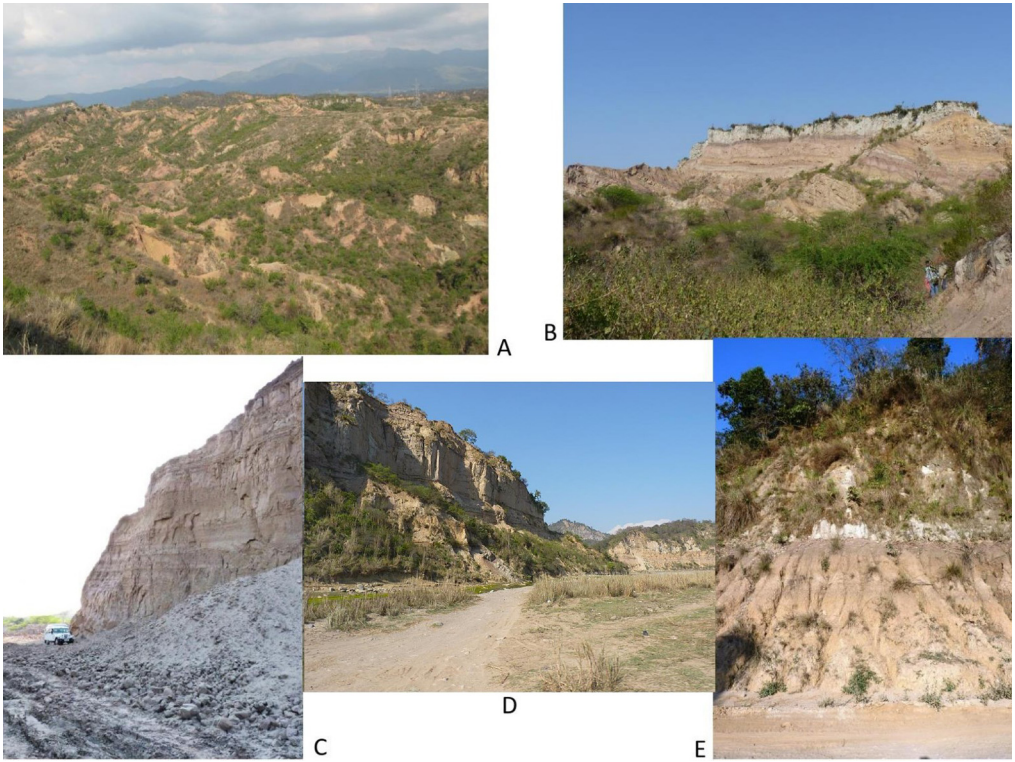


Fig. 12. Geological localities visited: **A:** Masol, folded comb in the Chandigarh anticlinorium, Late Pliocene Formation, 2015; **B:** Khetpurali, Late Pliocene Formation, 2012; **C:** Moginand, Lower Pleistocene Formation, 2010; **D:** Saketi sector, Late Pliocene Formation, 2017; **E:** Haripur, Late Pliocene Formation, 2017 (photo credit: A: A. Tudryn; B to E: A. Dambricourt Malassé).
Localités géologiques visitées : A : Masol, combe plissée dans l'anticlinorium de Chandigarh, Formation du Pliocène supérieur, 2015 ; B : Khetpurali, Formation du Pliocène supérieur, 2012 ; C : Moginand, Formation du Pléistocène inférieur, 2010 ; D : Secteur de Saketi, Formation du Pliocène supérieur, 2017 ; E : Haripur, Formation du Pliocène supérieur, 2017 (crédit photo : A : A. Tudryn; B à D : A. Dambricourt Malassé).

in [Kumaravel et al., 2005](#)). The lithostratigraphic column begins ~ 2.7 Ma and ends ~ 500 ka. The volcanic ash is dated to 2.14 ± 0.5 Ma. The section of the Moginand River completed the stratigraphy and became the reference for the Lower Pleistocene of the Siwaliks ([Kumaravel et al., 2005](#)). The Late Pliocene is visible for only 37 meters, with a gap in the field of 24 meters thick before the Lower Pleistocene deposits, so the Gauss-Matuyama reversal is not identified. Furthermore, no geomagnetic excursion was recorded in the section of the Late Pliocene limited to a maximum of 61 meters under the Lower Pleistocene ([Kumaravel et al., 2005](#)). The Late Pliocene deposits of the Ghaggar section is still too high in the stratigraphy to be compared with Masol. But the sedimentation rate for the Ghaggar section with ~ 45 cm/Ka, was useful as we will see below.

4.1.2. Khetpurali

The sequence of the Khetpurali section totals 900 meters and begins around 5.23 Ma with the Late Pliocene outcropping over 220 meters in thickness (Fig. 3 in [Tandon et al., 1984](#)). The lithostratigraphic column is incomplete but thicker than Masol, and a paleomagnetic inversion has been recorded about 150 meters below the Gauss-Matuyama Reversal; this thickness is close to the one above the c3 unit. In view of the sedimentation rate estimate at 37 cm/Ka ([Kumaravel et al., 2005](#)), this geomagnetic inversion can be dated to 2.99 Ma, which corresponds to the top of the Kaena Subchron: 3.02 ± 0.01 Ma ([Hilgen, 1991](#)), 3.1 Ma to 3.03–3.04 Ma ([Cande and Kent, 1995](#); [Lourens et al., 2004](#)).

4.1.3. Saketi-Kanthro

The analysis of Late Pliocene micromammals from the Saketi-Kanthro section (Patnaik, 2001) is illustrated by the lithostratigraphic column of Verma and Verma (1969), which begins as of the Late Miocene. The Late Pliocene fauna assemblage is similar to Masol with *Hexaprotodon*, *Elephas*, *Sivatherium*, *Cervus*, *Sus*, *Hemibos*, the reptiles *Testudo atlas*, and the crocodile. Nevertheless, the Plio-Pleistocene boundary remains imprecise due to the lack of magnetostratigraphic measurements. These were carried out in the Haripur section.

4.1.4. Haripur

The lithostratigraphic sequence totals 2375 meters of molasses since the Upper Miocene; the Late Pliocene is complete (1300 meters). The fauna list of the Late Pliocene is composed of *Archidiskodon planifrons*, *Stegodon insignis*, *Stegodon bombifrons*, *Elephas hysudricus*, *Hipparion*, *Cormohipparion*, *Cervus sp.*, *Rhyzomiides sivalensis*, *Hippohyus lydekkeri*, and *Hexaprotodon sivalensis* (Nanda et al., 1991, 2016).

The magnetostratigraphy have located the Gauss-Matuyama Reversal ~ 1685 meters above the floor of the lithostratigraphic column (sample PMS75 in Sangode et al., 1996). The Gilbert/Gauss Chron boundary dated to 3.596 Ma is located at ~1350 meters (see Figs. 2, 12, and 13 in Sangode et al., 1996). A geomagnetic reversal recorded in the middle of the Gauss Chron ~1517 meters above the floor and ~168 meters below the Gauss-Matuyama Reversal has been attributed to the Kaena Subchron (see Fig. 13 in Sangode et al., 1996). The upper limit of Kaena is dated to 3.03 Ma. Therefore, the sedimentation velocity between 3.03 Ma and 2.588 Ma should be 37 cm/Ka, like in the Khetpurali section, but authors conclude 32 cm/Ka.

The Haripur section allowed comparing the environments of the Late Pliocene with the Late Miocene-Early Pliocene, on one hand, and the Lower and Middle Pleistocene, on the other. The Himalayan foothills deposition system predominates around 3.2 Ma, suggesting an uplift and denudation of the outer margin of the Lesser Himalaya during this period (Sangode et al., 1996). This is followed by a system of low-sinuosity streams that form important river systems from the Himalayas over 600,000 years of sedimentation (Kumaravel et al., 2005). Then, around 2.6 Ma, the first record of the conglomerate appears, dominated by pre-Tertiary clasts, and the second conglomerate, around 1.76 Ma, is dominated by the tertiary clasts of the foreland basin. Kumar et al. (2003a, 2003b) confirmed these lithological changes of tectonic origin. The Sub-Himalayan plain was crossed by braided river systems in zigzag with a slow sedimentation rate before a reactivation of the Main Boundary Thrust and the Intra-Foreland Thrust around 1.77 Ma (Kumaravel et al., 2007).

4.1.5. Flora

Thakur et al. (2015) took over the study of the Late Pliocene from the Saketi region (Kala Amb-Nahan) and the Haripur section, similar to the list of Rao and Patnaik (2001) (27 genera and 37 species). This distribution represents lowland, freshwater marsh, montane, and back mangrove taxa, indicating a tropical-subtropical climate. The presence of algal zygospores (*Zygnemataceae*) indicates stagnant and shallow freshwater ponds. The montane taxa were transported from the northern highlands of the region.

Palynology has made it possible to reconstruct the climatic changes following the progressive uplift of the Tibetan plateau and the Himalayas (see Awasthi (1991) for a detailed bibliographic review). During the Pliocene, the assemblage was dominated by wetland species, dipterocarps native to Southeast Asia (very large evergreen trees), added to the tropical plant diversity as far as the Sub-Himalayan slopes. Then, in the Pleistocene, with the rise of the Himalaya, the vegetation diversified into tropical and subtropical deciduous species on the lower slopes in the humid zone and deciduous species but with a temperate climate on the drier upper slopes. In detail, there is very little palynological study of the Late Pliocene. The Lower Pleistocene is better documented. Rao and Patnaik (2001) studied the deposits in the Ghaggar River sector over a 2.5-meter section, identifying 28 genera and 37 species, algal, fungal, pteridophyte spores, and pollen. Angiosperms (*Poaceae*, *herbaceae*) and gymnosperms dominate, followed by pteridophytes. The whole corresponds to a marshy depositional environment in a hot and humid tropical-subtropical climate. The pollens of temperate gymnosperms, *Abies* (fir), *Pinus* (pine), and *Picea* (spruce), are thought to come from the highlands of the Himalayas, close to the plain.

The most comprehensive comparative analysis remains that of Haripur by Phadtare et al. (1994). A microflora has been located relative to a botanized mudstone. Such volcanic stratigraphic markers are slightly older than 2.58 Ma. A typical dry grassland flora may have existed before the Late Pliocene period, but it would have been replaced by wet and marshy grasslands and then mainly by ponds before a wet, open, and mixed flora invaded the Sub-Himalayan plain. The fossilized flora of the Lower Pleistocene is characterized by leaf tissues, a high incidence of algae cysts, and relatively little pollen and spores.

4.2. Synthesis

The Late Pliocene period of the Subathu sub-basin corresponds to a warm and humid tropical to subtropical climate. The environments were shrubby grasslands with marshes and rivers flowing from the Himalayas. An unexplained event, which occurred at the end of the Pliocene for a few hundred thousand years, caused and favored the conservation of many corpses and therefore their rapid burial, revealing an important diversity of terrestrial and aquatic herbivore communities, including very large species such as *Stegodon* and *Elephas*, *Sivatherium*, *Hemibos*, and *Merycopotamus*, but also the arrival of *Equus* alongside the *Hipparion* already present (Moigne et al., 2016). Crocodiles and gharials shared the rivers with *Hexaprotodon*. Very few carnivores, on the other hand (Badam, 1973; Moigne et al., 2016), appear in the fauna list of animals. Then the climate deteriorated with a drop-in temperature that would correspond to the entry into glaciation on a global scale, and fossilized fauna is becoming rarer. The Lower Pliocene collections represent only 20% of the specimens collected in the Chandigarh anticlinorium (Sahni and Khan, 1968).

5. Discussion on the age of the geomagnetic excursion of the Quranwala Zone—Masol Formation

The sedimentation rate is the only value which determines what excursion has been recorded in c3 among the 8 known before the Gauss-Matuyama Reversal, from Huahine (2.95 Ma), Raiatea (2.77 Ma) to Pirnuar (2.62 Ma). We have already made a first estimate based on minimum height of the sedimentary column above c3 (155–150 meters), the age of the excursion and the sedimentation rate for each excursion (Chapon Sao et al., 2024). The results are respectively 41 cm/Ka, 79 cm/Ka, 88 cm/Ka, 96 cm/Ka, 115 cm/Ka, 214 cm/Ka, 375 cm/Ka, 375 cm/Ka (Table 1). Then comparing with the velocities of the Late Pliocene and the Lower Pleistocene in the Subathu sub-basin, we have eliminated the averages incompatible with the factual data.

In the section of the Ghaggar below the Gauss-Matuyama Reversal, the sedimentation velocity is 47 cm/Ka. During the Olduvai Subchron (1.95–1.77 Ma) it increases rapidly to 67 cm/Ka because of the Himalayan uplift which supplied detrital materials (Kumar et al., 2002, 2003a, 2003b, 2007; Nanda, 2013). In the Patiali Rao, Ranga Rao retained the velocity of 47 cm/Ka for the Matuyama Chron, specifying that the rate of sedimentation accelerated as in all the Pleistocene sections of the Subathu sub-basin (Ranga Rao, 1993). This average is therefore overestimated for the siltier Masol Formation. The most realistic sedimentation velocity is less than 47 cm/Ka. At Khetpurali, the sedimentation velocity of the Late Pliocene is 37 cm/Ka and in the Haripur section, 32 cm/Ka. None of the excursions after Huahine is compatible with the regional sedimentation rates, they are all much more too fast. When we applied the velocity of 47 cm/Ka to 150–155 meters minimum above c3, the excursion reaches the minimum age of 2.90–2.91 Ma, and with 37 cm/Ka the age become 2.99–3.00 Ma, the age of the Kaena inversion. The short excursion recorded in the unit c3 is necessary youngest. The calculation for 150 meters minimum is 41 cm/Ka, a realistic value between 47 cm/Ka and 37 cm/Ka giving an age of ~2.95 Ma which corresponds to Huahine. With an average of 41 cm/Ka the end of the Quranwala Zone is estimated at ~2.84 Ma.

6. Origin of the Quranwala Zone: Paleoclimatic hypotheses

6.1. Origin of *Equus* in the Western Sub-Himalayan Plain in the Late Pliocene

Equus originated in North America, separated from Asia by the Bering Strait. Dispersal of herds is attested in northern China around 2.55 Ma (*Equus eisenmannae*, Nihewan Basin) (Deng and Xue, 1999;

Sun and Deng, 2019) and in Western Europe around 2.58 Ma (*Equus livenzovensis*, Tuscany, Italy) (Bernor et al., 2018), but never before the Gauss/Matuyama transition (see Singh et al., 2022 for a review of the bibliography). The presence of *Equus* since 2.95 Ma in the western Sub-Himalayan plain implies a drop-in ocean level of the strait during Late Pliocene cooling sufficient for the formation of an intercontinental bridge with Siberia, the Bering Strait Land Bridge, but free of ice due to a climate too dry, turning the land into vast steppe. What could be the Late Pliocene glacial interval allowing the passage of Beringia, and what corridors were used by these herds to reach the Upper Indus Basin?

The formation of an intercontinental bridge between Alaska and Siberia was possible before the Pleistocene glaciation. Indeed, a first peak of glaciation is known in the Northern Hemisphere before the mid-Piacenzian Warm Period (mPWP, 3.264 Ma to 3.025 Ma, even 2.97–2.96 Ma, e.g., Haywood et al., 2010; Berends et al., 2019; Süfke et al., 2022). This glaciation occurred during the Marine Isotope Stage M2 between 3.312 and 3.264 Ma (Fig. 13) and caused a drop-in sea level of 20 to 60 m depending on the author (De Schepper et al., 2014; Tan et al., 2017). In northeast Siberia, the Zhuravlinean glaciation has been well documented during this period (Laukhin et al., 1999; De Schepper et al., 2014). Pollen samples taken from the sedimentary column of Lake El'gygytyn, an ancient 3.58 Ma meteorite crater located to the east of the Chukotka Peninsula (Fig. 14), enabled Andreev et al. (2014)

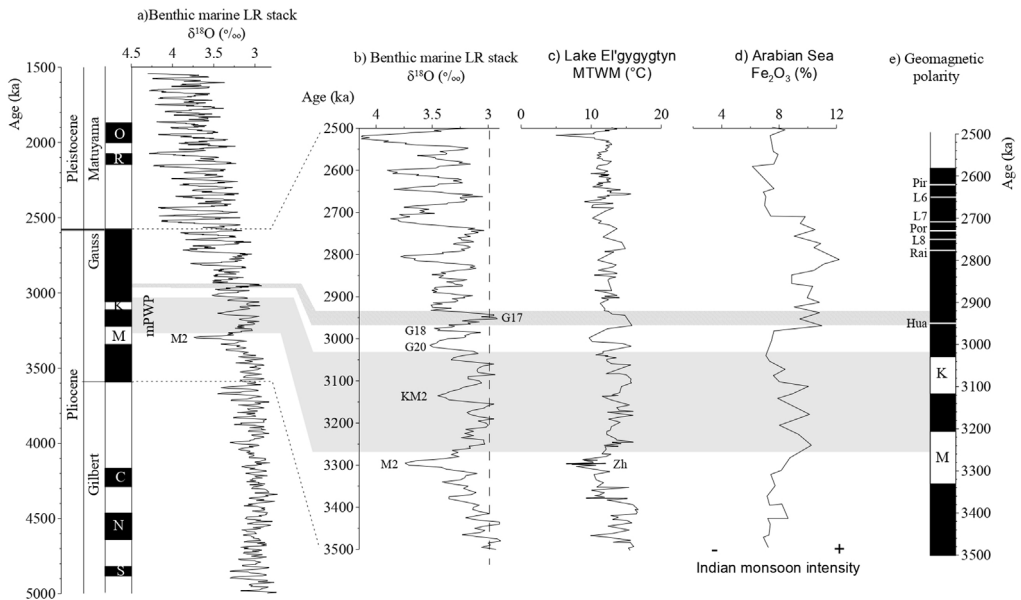


Fig. 13. Variation in certain parameters reflecting climate change over time during the Pliocene-Pleistocene by following the magnetostratigraphy: **Left column**, Magnetic Subchrons (**O**: Olduvai, **R**: Réunion, **K**: Kaena, **M**: Mammoth, **C**: Cochiti, **N**: Nunivak, **S**: Sidufjall); **a**) and **b**) the LR04 benthic $\delta^{18}\text{O}$ stack constructed by correlating the $\delta^{18}\text{O}$ records of globally distributed benthic foraminifera (Lisiecki and Raymo, 2005) at different time scales, with highlighted middle Pliocene Warm Period (mPWP) and Marine Isotope Stages (MIS) M2, KM2, G20, G18, and G17 in the column $\delta^{18}\text{O}$; **c**) reconstruction of the mean temperature of the warmest month (MTWM) at Lake El'gygytyn (after Brigham-Grette et al., 2013) with indicated Zhuravlinean glaciation time as Zh; **d**) the iron oxides content of the Arabian Sea sediments, which reflect the intensity of the Indian monsoon (according to Cai et al., 2019); **e**) geomagnetic polarity (excursions: **Pir**: Pirnuar, **Por**: Porcupine, **Rai**: Raiatea, **Hua**: Huahine, L5 to L8 are unnamed) (synthesis A. Tudryn).

Variation de certains paramètres reflétant le changement climatique au cours du Pliocène-Pléistocène en suivant la magnétostratigraphie: **Colonne de gauche**, Subchrons magnétiques, (**O** : Olduvai, **R** : Réunion, **K** : Kaena, **M** : Mammoth, **C** : Cochiti, **N** : Nunivak, **S** : Sidufjall) ; **a**) et **b**) empilement benthique $\delta^{18}\text{O}$ LR04 construit en corrélant les enregistrements $\delta^{18}\text{O}$ de foraminifères benthiques répartis à l'échelle mondiale (Lisiecki et Raymo, 2005) à différentes échelles de temps et avec la période chaude du Pliocène moyen (mPWP) ainsi que les Stades Isotopiques Marins (SIM) M2, KM2, G20, G18 et G17 dans la colonne $\delta^{18}\text{O}$; **c**) reconstitution de la température moyenne du mois le plus chaud (MTWM) au lac El'gygytyn (d'après Brigham-Grette et al., 2013) avec le temps de glaciation zhuravlinéen indiqué comme Zh ; **d**) teneur en oxydes de fer des sédiments de la mer d'Arabie, qui reflètent l'intensité de la mousson indienne (selon Cai et al., 2019) ; **e**) polarité géomagnétique (excursion : **Pir** : Pirnuar, **Por** : Porcupine, **Rai** : Raiatea, **Hua** : Huahine, L5 à L8 ne sont pas nommés) (synthèse A. Tudryn).

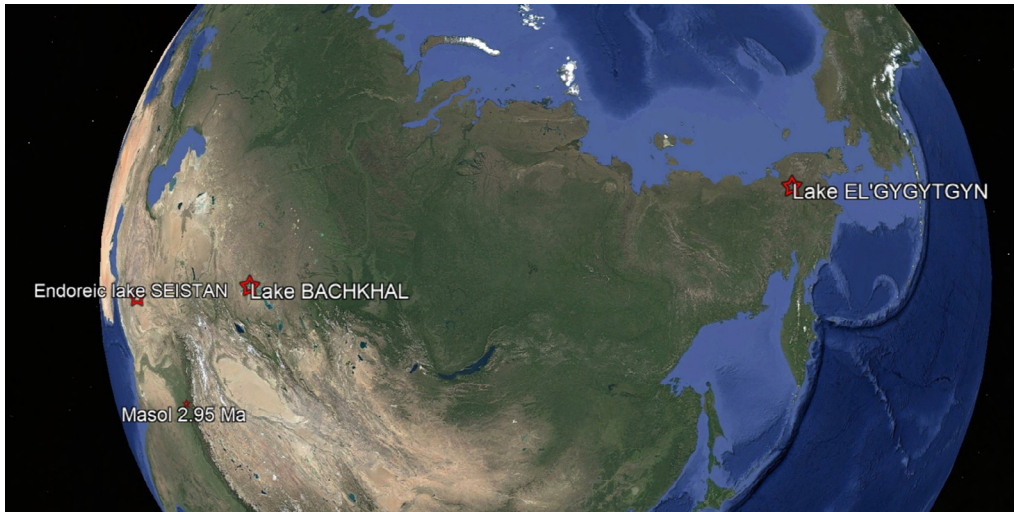


Fig. 14. Location of lakes El'gygytyn (Siberia), Balkhach (Kazakhstan), and the current endorheic lake Seistan (Afghanistan), probably marking out one of the *Equus* dispersal routes before reaching the Upper Indus Basin (Masol) (Map data Google Earth 2025).

Localisation des lacs El'gygytyn (Sibérie), Balkhach (Kazakhstan) et l'actuel lac endoréique Seistan (Afghanistan) jalonnant probablement l'une des voies de dispersion d'*Equus* avant d'atteindre le bassin supérieur de l'Indus (Masol) (Données cartographiques Google Earth 2025).

to identify it between 3.305–3.275 Ma. According to these authors, this glacial period generated very pronounced environmental changes, such as the appearance of permafrost with tundra and cold steppe replacing spruce and larch trees. In addition, numerous spores of coprophilous fungi suggest an increase in the presence of grazing mammals around the lake from the cold and dry intervals that correspond to Marine Isotope Stage (MIS) G 20 at 3.043–3.025 Ma and MIS G 18 at 2.935–2.912 Ma (Lisiecki and Raymo, 2005, fig. 4; Andreev et al., 2014). Beringia likely emerged during these two cold intervals, and herds of herbivores such as *Equus* would have crossed it as early as 3.043 Ma.

Their dispersal depended on grasslands, lakes, rivers, and ponds, the faster routes to reach the Western Upper Indus Basin as early as 2.95 Ma was the vast central Asian steppe until the Amu Darya and Harirud-Murgab basins (Turkmenistan), which originate respectively in the Pamir plateau and the Paropamisus mountains at the western limit of the Hindu Kush, bordering the Northern edge of the Harirud River valley (Figs. 14 and 15).

The rapid elevation of the massifs bordering the Indian subcontinent from west to east (Hindu Kush, Karakoram, Himalayas, Patkai) followed four main tectonic events at 3.5–3 Ma, 2.7 Ma, 2.1 Ma, and 1.7 Ma (Burbank and Johnson, 1983; Sakai et al., 2002; Chakrabarti et al., 2024). At 3 Ma, the reliefs of the Hindu Kush were thus lower than at the onset of the Pleistocene. Western corridors for Equids were suggested on a schematic map for the oldest dispersal routes of *Plesiohipparion zandaense* and Lower Pleistocene *Equus sivalensis* (Rook et al., 2019). This hypothesis is consistent with the conclusions of Kotliá (2013) about the dispersal from Europe of both palaeartic rodents, *Rhagapodemus* and *Kilarcola* in the Karewas (Kashmir), which “may indicate a shift of the Palaeartic province southward during the Late Pliocene cooling” (Patnaik, 2016).

Khan et al. (2020) studied the diet of mammals, the vegetation, and the climate of the Plio-Pleistocene deposits of the Upper Indus Basin in Pakistan with the stable isotopes analysis of carbon and oxygen. These periods correspond to a floodplain environment with increased aridity, favoring the appearance of grasses between 3.6 Ma and 600 ka. The authors note that the faunas have close affinities with African species in terms of diet and ecological niche. Similarly, carbon isotopes of fatty acids of leaf waxes ($\delta^{13}\text{C}_{\text{Wax}}$ values) ($\delta^2\text{H}_{\text{Wax}}$ values) extracted from deposits in the Bay of Bengal suggest an increase in C_4 vegetation on the Indian peninsula between the mid-Pliocene and mid-

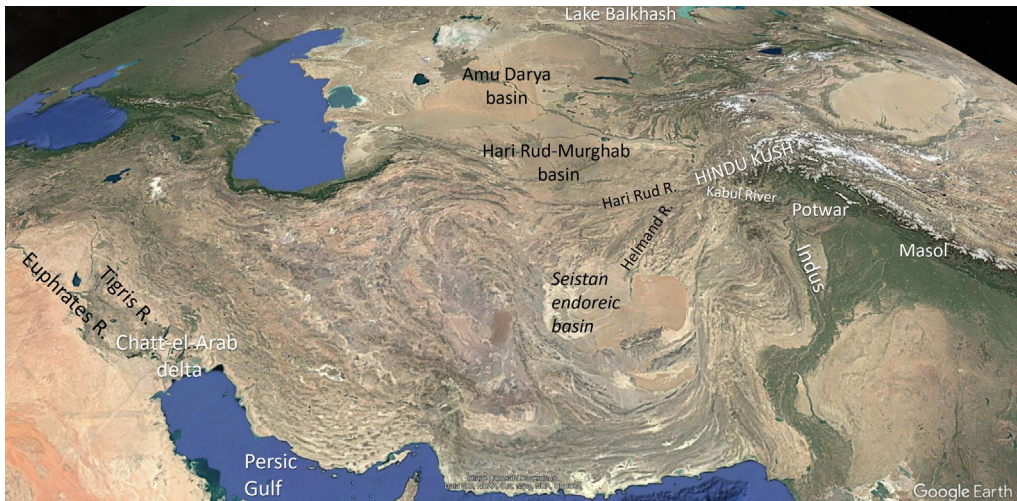


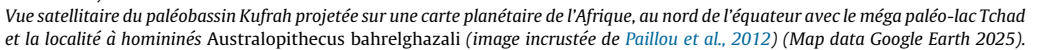
Fig. 15. The different river and endorheic basins most likely crossed by hominins and *Eurygnathohippus* (from the Arabian Plate) and *Equus* (through the High Asia fluvial network) before reaching the Upper Indus Basin (Map data Google Earth 2025).
 Les différents bassins fluviaux et endoréiques très probablement empruntés par les hominins et *Eurygnathohippus* (depuis la plaque arabique) et *Equus* (via le réseau fluvial de la Haute Asie) avant d'atteindre l'Asie centrale et le bassin supérieur de l'Indus (Map data Google Earth 2025).

Pleistocene (~3.5 to 1.5 million years ago) already observed in East Africa and northwestern Australia (Dunlea et al., 2020). According to the authors, these tropical ecosystems surrounding the Indian Ocean remained highly sensitive to hydroclimatic changes after the initial spread of *C₄* plants in the Late Miocene. Thus, the altitude of the western Hindu Kush was not an obstacle to reach the floodplain environment favorable for *Equus*.

6.2. What converging routes of *Equus* and Hominin expansions into the Upper Indus Basin

For scavenging hominins, dependent on watercourses and the daily supply of usable stones, physical and hydrographic geography gives an idea of the dispersal routes from North Africa. The faster route to have found themselves in the Upper Indus Basin at 2.95 Ma lies between latitudes 30° and 32° (Figs. 6 and 15). What climatic episode would account for the dispersal of hominins towards the north of Africa around 3 Ma? The most northerly hominin fossils have been collected on the northeastern edge of the paleolake Mega-Chad at latitude 16° N and attributed to *Australopithecus bahrelghazali* dated at 3.58 Ma (Brunet et al., 1996; Guy et al., 2008). Macho (2015) concludes “The habitat at Koro Toro appears to have been mosaic too, consisting of swamps, patches of forest, wooded savannah, and grassland”. This ecosystem was close to the Quranwala Zone with similar fauna assemblages *Stegodon*, *Hipparion*, *Hexaprotodon*, *Sivatherium*, suids, turtles, and crocodiles (Brunet et al., 1996). The paleolake Mega-Chad is located in the summer Intertropical Convergence Zone (ITCZ) of heavy precipitation. Yet, the ITCZ moves southward during glaciations, which must have been the case during the Zhuravlinean episode (3.305–3.275 Ma) and again between 3.043–3.025 Ma. Assuming that hominins continued to reproduce up to 3 Ma as in Ethiopia and Kenya, it was only after this glacial interval that a dispersal was possible when the summer rainfall of the ITCZ rose again towards North Africa feeding river systems during the warming ~ 2.97–2.96 Ma (Haywood et al., 2010; Berends et al., 2019; Süfke et al., 2022). In 2010, satellite studies have identified a giant paleodrainage system, the Kufrah River, north to the paleolake Mega-Chad in eastern Libya (Paillou et al., 2012) (Fig. 16).

Very probably, hydrographic corridors have favored dispersal of faunas, including hominins and hipparionine *Eurygnathohippus*, towards the Mediterranean Sea. It has been enough for the ITCZ to be



Correlations between warm periods and intensification of the Indian monsoon during the mid to late Piacenzian (3.3–2.7 Ma) has been demonstrated based on the sediments of the Arabian Sea and the Bay of Bengal (e.g., Cai et al., 2019; Sarathchandraprasad et al., 2021). The International Ocean Discovery Program (IODP) in the Arabian Sea identifies the intensification of the Indian monsoon over the western Himalayas through increased detrital input into the Indus submarine fan (Laxmi Basin).

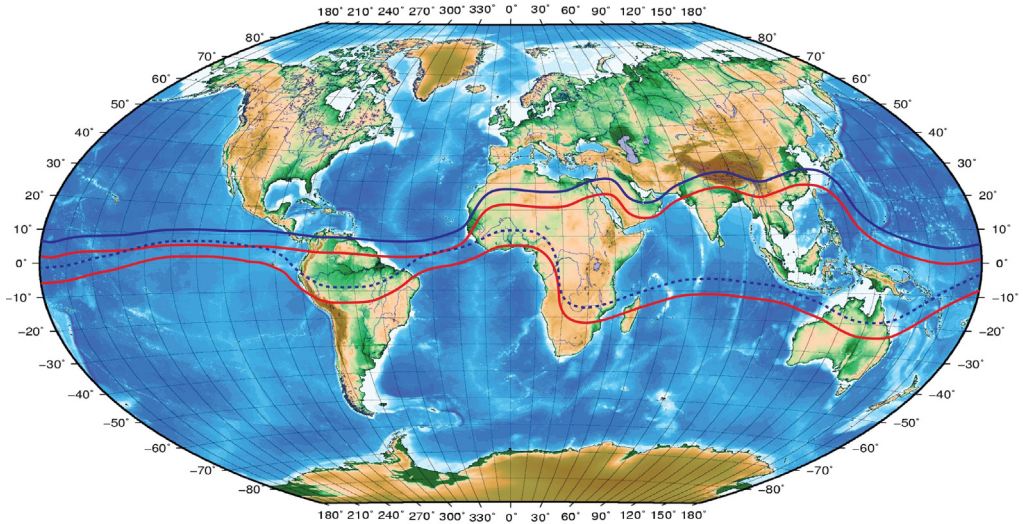


Fig. 17. The current Inter-Tropical Convergence Zone **in red** (in July maximum in the northern hemisphere, in January maximum in the southern hemisphere) and a hypothetical visualization of the northward shift of the summer limit (**blue curve**) during the peak of global warming of 2.97–2.96 Ma (the profile of the winter curve is in **dotted blue** because it results from the displacement of the two **red curves** and is not significant in itself). We can see the superposition with latitudes 30°–32°. The inflection to the south of the Arabian Plate would probably be modified by the distance from the Arabian Sea (curves taken from a map by INHAME, Instituto Nacional de Meteorología e Hidrología, Venezuela; realization S. Abdessadok).

La Zone de Convergence Inter-Tropicale actuelle en rouge (en juillet maximum dans l'hémisphère nord, en janvier maximum dans l'hémisphère sud) et une visualisation hypothétique du décalage vers le nord de la limite estivale (courbe bleue) lors du pic du réchauffement climatique de 2,97–2,96 Ma (le profil de la courbe hivernale est en bleu pointillé car il résulte du déplacement des deux courbes rouges, il n'est pas significatif en soi). On constate la superposition avec les latitudes 30°–32°. L'inflexion au sud de la plaque arabe serait sans doute modifiée par l'éloignement avec la mer d'Oman (courbes reprises d'une carte de l'INHAME, Instituto Nacional de Meteorología e Hidrología, Venezuela; réalisation S. Abdessadok).

This is represented in Fig. 13 by an increase in iron oxides during the mid-Piacenzian Warm Period with a peak at 2.95 Ma and until 2.7 Ma.

Seeking to understand the origin of the intensification of erosion in the Southern Front of the Himalayan chain (SHF), Thiede et al. (2004) studied the Himalayan Crystalline Core in the Upper Sutlej Valley (Fig. 1). The causes are climatic and not tectonic; these are areas on which the monsoon rainfall has been concentrated. "Monsoon rainfall in this region has a strong influence on surface erosion processes. River erosion along the SHF is concentrated in high mountain areas, where the orographic barrier forces the evacuation of more than 80% of the annual precipitation with an average cooling rate of about 4° to 5 °C/Ma during the Pliocene-Quaternary period."

Similarly, Huntington et al. (2006) showed that "there is no evidence of significant changes in the distant tectonics of the Himalayan-Tibetan orogenic system during this interval, suggesting a largely climatic factor of increased erosion at the Himalayan front." Ultimately, the last warming following the end of Piacenzian would have led to the vertical migration of thermal gradients and the snow line in the Higher Himalaya. The intensification of monsoon rains added to the migration in altitude of the 0 °C isotherm, caused significant seasonal flooding spilling in the Sub-Himalayan grasslands with tons of pebbles and drowning herbivores until the decrease of temperatures and the return of the snow line to lower altitudes.

If our climatic hypothesis is correct, the Quranwala Zone would have appeared with the last peak of warming around 2.95 Ma, after the glacial episode MIS G 20 (3.043–3.025 Ma) because of the combination of the melting of glaciers accumulated in the Great Himalayas and the intensification of the monsoon. The QZ disappeared with the gradual cooling of the North Hemisphere, the migration of the 0 °C isotherm to lower altitudes and the glacier extents in the Great Himalayas.

7. Conclusion

The First Appearance Datum (FAD) of *Equus* outside North America is attested in the Upper Indus Basin in the Quranwala biozone (QZ) of the Masol Formation, north of Chandigarh, India. A short geomagnetic reversal measured at the base of QZ (unit c3) is attributed to the Huahine excursion dated to ~ 2.95 Ma. Their presence in the steppes of Central Asia was possible before the Pleistocene glaciation, following the glacial intervals attested in the Siberian peninsula of Choukotka from 3.01 Ma, creating an intercontinental bridge with North America via the Beringia. Their dispersal to the western Sub-Himalayan plain at 2.95 Ma was still possible by passes and corridors from the Hari Rud-Murghab basins (Turkmenistan) and/or to the Seistan basin with the Helmand River, to the Kabul River, a western tributary of Indus, before the intensification of the uplift to 2.7 Ma (Fig. 15).

Following the glacial interval with the *Equus* “exit” from North America ~ 3.01 Ma, the subsequent last warming interval ~ 2.97–2.96 Ma led the summer intertropical convergence zone (ITCZ) to the north of Africa and the Arabian Plate. This climatic shift facilitated the migration of ecosystems with their associated fauna, including hominins in western Asia. Subsequently, these groups dispersed along the intertropical band via hydrographic networks to Afghanistan, converging with herds of *Equus* before reaching the Upper Indus Basin.

It is therefore plausible that the Asian dispersal of *Equus* from North America and that of hominins from North Africa to the great plains of the Upper Indus Basin are the consequence of planetary climatic oscillations before the Pleistocene glaciation, with a glacial episode in the northern hemisphere (3 Ma), and a final peak of global warming in the intertropical convergence zone in Africa between 2.97 and 2.96 Ma.

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