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Geology and geomorphology of Masol paleonto-archeological site, Late Pliocene, Chandigarh, Siwalik Frontal Range, NW India

Géologie et géomorphologie du site paléonto-archéologique de Masol, Pliocène final, Chandigarh, Siwalik, Nord-Ouest de l'Inde

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ABSTRACT

The Masol paleonto-archeological site is located in the Siwalik Frontal Range in the north of Chandigarh (Punjab, NW India). Many fossils and stone tools can be observed in the colluviums that overlap the present topography constituted by Late Pliocene continental sediments. The Masol paleonto-archeological site is located in the center of a trenched anticline compatible with the direction of plate convergence between India and Eurasia. Erosion processes are very actives and efficient in the area. Around 80 m of vertical erosion occurred in the Patiali Rao valley and regressive erosion incised the Siwalik Hills for ~12 km. At least two levels of fluvial terraces are visible in the Patiali Rao valley and laterally apart the Pichhli River. River bank erosion, gullies, collapses, cavities, regressive erosion, landslides and in situ disaggregation have been observed and are responsible of the significant excavation of the anticline. Substrate composed of sand, sandstone and silt is very erodible in case of heavy rain. Slope destabilizations by seasonal monsoon are responsible of a large part of the colluviums overlapping the present slopes. Some colluviums could be due also to in situ disaggregation of sandstone formations. Due to the very active erosion and to their position on the topography, we believe that these colluviums are very recent.

RÉSUMÉ

Le site paléonto-archéologique de Masol est situé dans les Siwaliks, au nord de Chandigarh, dans le Nord-Ouest de l'Inde. De nombreux fossiles et outils lithiques sont présents dans les colluvions qui recouvrent les formations sédimentaires continentales pliocènes. Le site paléonto-archéologique de Masol se trouve au centre d'un anticlinal dont une partie a été

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Colluvions
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érodée. Les processus d'érosion sont actuellement toujours actifs et très efficaces, sous l'effet conjugué de la mousson et de la faible résistance des roches. Une érosion verticale d'environ 80 m d'épaisseur s'est produite dans la vallée du Patiali Rao et l'érosion régressive a incisé les collines des Siwaliks sur environ 12 km depuis la formation des Siwaliks. Au moins deux niveaux de terrasses fluviatiles sont observables dans la vallée du Patiali Rao et dans le Pichhli choe, l'un de ses affluents. L'érosion des berges, la formation de ravines, les éboulements, la formation de cavités, l'érosion régressive et des glissements de terrain sont responsables de l'excavation de l'anticlinal. Le substrat, composé de sables, de grès et de limons, est très facilement érodé. La déstabilisation des pentes actuelles par les pluies de mousson est responsable d'une large part des colluvions qui recouvrent les pentes dans la zone où se situent les sites paléonto-archéologiques. Certaines colluvions peuvent être également dues à la désagrégation in situ de formations de grès. Comme les processus d'érosion sont très actifs et que les colluvions se trouvent sur les pentes actuelles des collines, il est probable que ces colluvions soient très récentes.

1. Introduction

Frontiers of plate tectonics are of primary interest not only to investigate geological and geomorphological processes due to their present activities but also to observe fossil fauna and archeological tools (King and Bailey, 2006). The Masol archeological site (Chandigarh anticline, Siwalik Frontal Range, NW India) is located in a fascinating geological area undergoing active deformation and significant erosion at the southern limit of the Himalayan mountain range. The area is seismically active and the Siwalik Hills are highly dissected by river erosion in a context of monsoon and tectonic activity. The Masol paleontological and suspected archeological sites have been excavated by erosion from the Patiali Rao valley and the Pichhli choe rivulet. These geological and geomorphological processes allowed us to observe now, the Pliocene fossils and contiguous lithic tools on the surface. Numerous fossils and lithic tools are in the colluviums deposits of the Masol hills. The understanding of these colluviums may help in a better interpretation of the origin of some stone tools and their possible relation with cut marks on bones, slightly oldest than in Africa (Chapon Sao et al., 2016a,b; Dambricourt Malassé, 2016; Dambricourt Malassé et al., 2016a,b; Gaillard et al., 2016; Moigne et al., 2016).

Several studies have described large scale geology and geomorphology of the Siwalik Frontal Range (see section 2). Here, we focus on a smaller area and describe processes as well as phenomena occurring at a smaller scale. The aim of this study is to understand the geological background of the Masol paleonto-archeological site and improve our knowledge about the Masol hills geomorphological evolution. We will (1) describe local deformations observed in the field, (2) describe erosional processes acting on the Masol hills, (3) discuss the rate of erosion and the age of colluviums that overlap the present topography.

2. Geological background

The Himalayan chain has accommodated the convergence between India and Eurasia plates since the Early Paleogene to Eocene (Molnar and Tapponnier, 1975) at rates varying from 44 to 61 mm/year (Minster and Jordan, 1978). Subduction of a highly extended Indian lithosphere within the Himalaya triggered a shortening of approximately 2350 km since 52 Ma (Hinsbergen van et al., 2012). The Main Central Thrust (MCT) marks, on the southern slope of Himalaya, the boundary between Higher/Greater Himalaya to the north (metamorphic series) and Lower/Lesser Himalayan sequences (Kundu et al., 2012) toward the south (epi-metamorphic; Fig. 1). The Main Boundary Thrust (MBT) bound the southern sides of the Lesser Himalaya (medium-grade metamorphic) tectono-stratigraphic zones and the Sub-Himalayan sequences. The Siwalik area (Neogene to Quaternary) is bounded by the Himalayan Frontal Thrust (HFT) at the south. Several large earthquakes occurred along blind structures of northwestern Himalaya (Molnar and Pandey, 1989). A scarp of 10 m of tectonic origin has been observed near Kakron village on the bank of the Budki River (Fig. 2A, southward of the Siwalik Hills) and estimated at ~12 kyr (Singh and Tandon, 2008).

The Siwalik Hills contain sediments of Neogene to Quaternary age. The Siwalik was the locus of sedimentation sourced from the uplifting Lesser Himalaya (Burbank, 1992; Kundu et al., 2012) at a rate that ranges between 0.27 mm/yr to 0.71 mm/yr (Ranga Rao, 1993). Quaternary migration of deformation southward from the MBT to the HFT created active foothill uplift and trapping of Quaternary sediments within intermontane valleys (Delcaillau et al., 2006; Kumar et al., 2001). Non-marine mudstone, shale, sandstone and boulder conglomerate of Siwalik formation has a total accumulation > 6000 m and represent deposition by southerly flowing river systems (Khan and Tewari, 2011; Kumar et al., 2003; Ranjan and Banerjee, 2009). Lower Siwalik formation comprises an upward-coarsening mudrock succession of Miocene age. The Middle Siwalik formation (> 1600 m) is mainly composed of sandstones of Upper Miocene/Early Pliocene ages (Khan and Tewari, 2011; Kumar et al., 2003). Upper Siwalik formation consists of conglomerates, sandstones and mudrocks (Kumar et al., 2003), 2300 m thick (Karunakaran and Ranga Rao, 1976 cited in Delcaillau et al., 2006), of Pliocene to Lower Quaternary age (Delcaillau et al., 2006; Ranga Rao, 1993).

In Northwest India, the width of Siwalik Hills ranges from 10 km to 80 km and they consist of folds and faults that

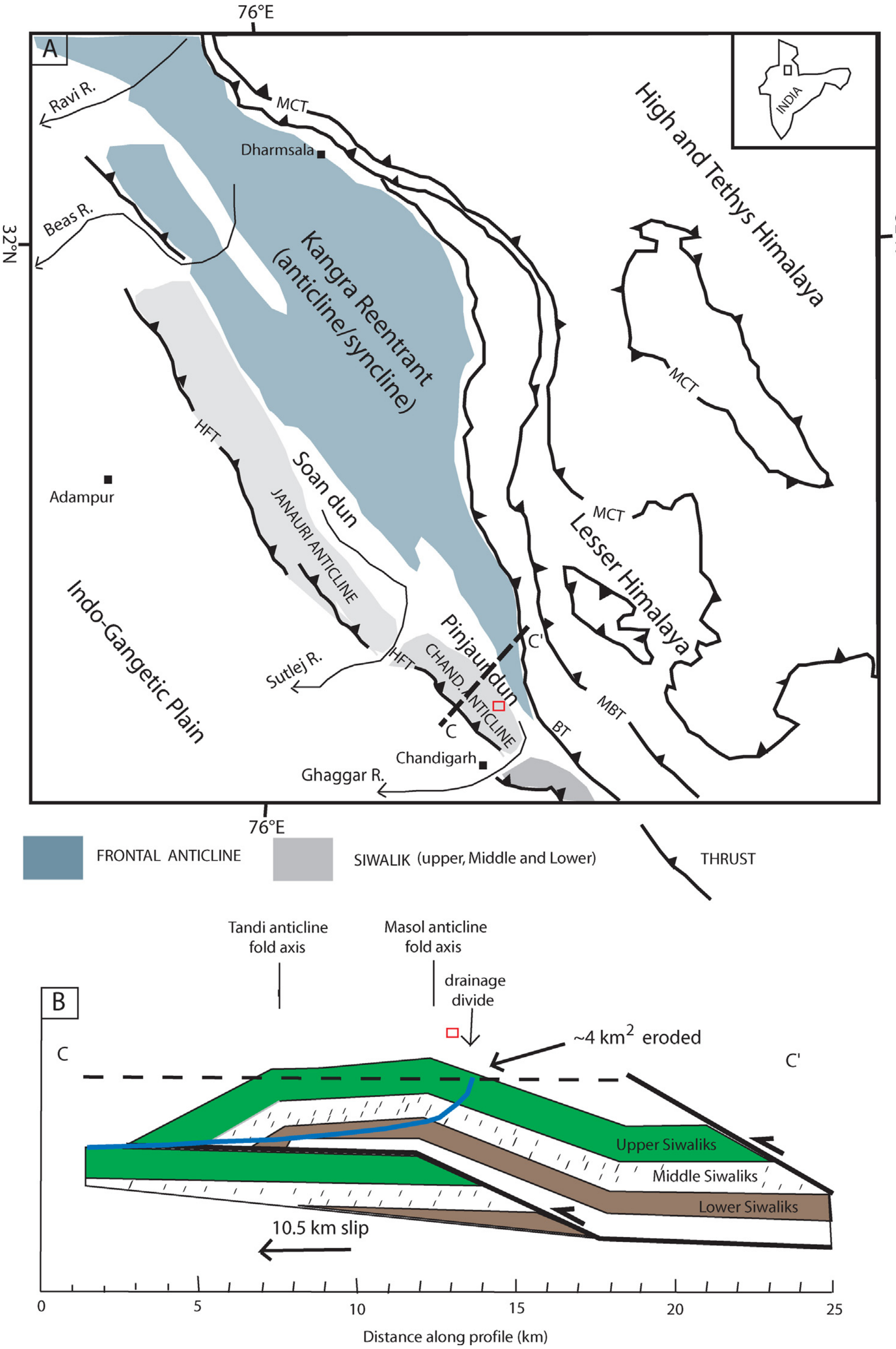

Fig. 1. (Colour online.) Geological background of the Chandigarh anticline, A. Location and main geological unit (modified from Delcaillau et al., 2006). B. Cross section of the Chandigarh anticline (modified from Barnes et al., 2011). The red square corresponds to the location of the paleonto-archeological site of Masol. The initial topography has been partly eroded (dashed line) and the present drainage divide is located at the north. The longitudinal profile of rivers is indicated in blue. MBT: Main Boundary thrust; MCT: Main Central Thrust; BT: Bilaspur Thrust; HFT: Himalayan Frontal Thrust; R: River.

Fig. 1. (Couleur en ligne.) Carte géologique de l'anticlinal de Chandigarh, A. Localisation et principales formations géologiques (modifié d'après Delcaillau et al., 2006). B. Coupe de l'anticlinale de Chandigarh (modifiée d'après Barnes et al., 2011). Le carré rouge correspond à l'emplacement du site paléonto-archéologique de Masol. La topographie initiale a été en partie érodée (trait pointillé) et la limite du bassin de drainage a migré vers le nord. Le profil longitudinal de la rivière est indiqué en bleu. MBT : chevauchement principal ; MCT : chevauchement central ; BT : faille de Bilaspur ; HFT : chevauchement himalayen frontal ; R : rivière.

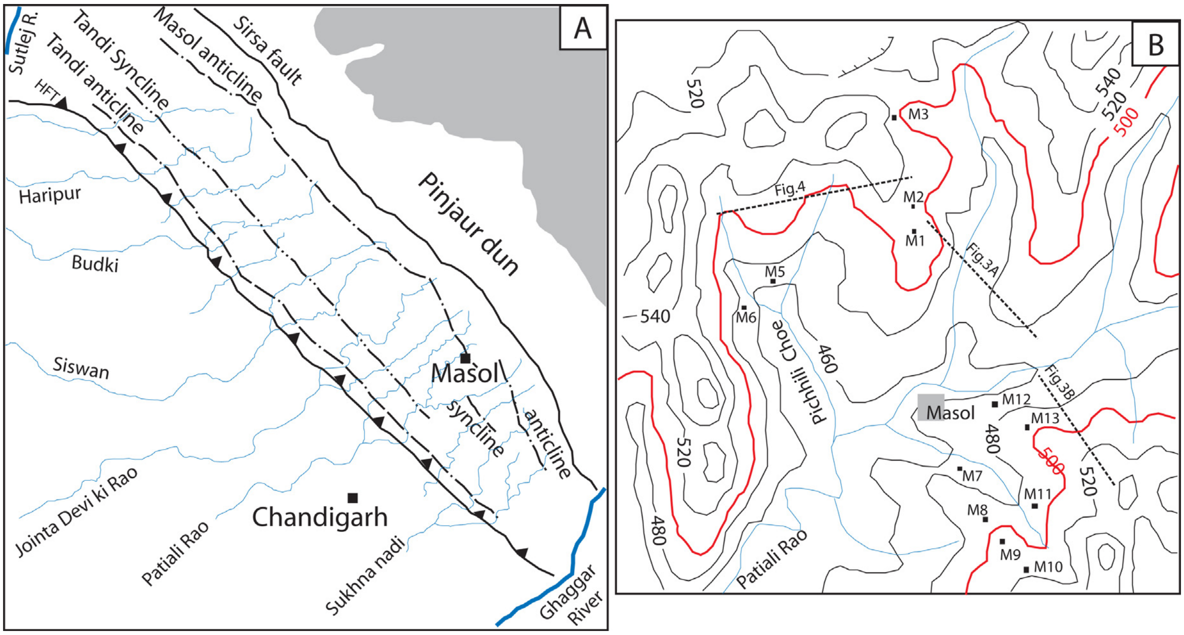

Fig. 2. (Colour online.) Location of the Masol paleonto-archeological site in the geological and topographical context. A. Main tectonic structures in the Chandigarh anticline. B. Detailed location of the paleonto-archeological sites (M1 to M13) near Masol village on the topographic map and location of the interpreted images in Figs. 3 and 4. HFT: Himalayan Frontal Thrust.

Fig. 2. (Couleur en ligne.) Localisation précise du site paléonto-archéologique de Masol dans son contexte géologique et topographique. A. Principales structures tectoniques de l'anticlinal de Chandigarh. B. Localisation des sites paléonto-archéologiques (M1 à M13) à proximité du village de Masol sur la carte topographique et emplacement des Fig. 3 et Fig. 4. HFT : Chevauchement frontal himalayen.

exhibit a large range in shortening (20%–70%) between the MBT and the HFT (Barnes et al., 2011; Powers et al., 1998). We focus on the Chandigarh anticline located between the Satluj and Ghaggar rivers with a northwest to southeast direction (~140°N, Fig. 1). The Chandigarh ridge measures ~40 km–50 km long and ~6 km–12 km wide with summit elevations reaching 600 m. The Chandigarh anticline front is very linear in its central and southern parts. Structural and geophysical data indicate that this anticline is uplifting along a simple ramp flat geometry that constitutes the HFT fault zone, which dips 20–40°NE below the foothills (Barnes et al., 2011; Delcaillau et al., 2006; Kumar et al., 2006; Powers et al., 1998; Thakur and Pandey, 2004). A composite fold with two axes, the Tandi and Masol anticlines, accommodates the deformations (Mukhopadhyay and Mishra, 2004). The blind HFT in the Chandigarh hills is characterized by a rapid increase in elevation and by the presence of the Tandi fold which dips ~20–30°SW (Mukhopadhyay and Mishra, 2004) close to the flat topography of the Indo-Gangetic plain. The presence of a zone of steady relief between the Tandi and Masol fold axis suggests that this area has experienced the same vertical uplift. The uplift rate is estimated to be 4 mm/yr–8 mm/yr using geometric considerations (Barnes et al., 2011). However, the maximum relief position and the direction of plate convergence indicate that the northern flank has experienced an uplift more recently than the southern flanks (Fig. 1B). A back thrust on the northern side of the foothill with a dip to the south is sometime postulated (Delcaillau et al., 2006; Singh and Tandon, 2008), but not systematically (Barnes et al., 2011). At the north of the Chandigarh anticline, the Pinjaur Dun is known as a synclinal piggyback basin that separates the fold from the main mountain front (BT and MBT). The sediment accumulation rate within the Pinjaur Dun is unknown (Barnes et al., 2011) but the sediment accumulation is probably thick and initiated before 57 kyr (Delcaillau et al., 2006). The intermontane valleys are composed of Late Pleistocene to Holocene sediments overlying the Miocene-Early Pleistocene succession of rocks (Singh and Tandon, 2008).

The youngest deposit that constitutes the Chandigarh anticline is the Upper Siwalik formation estimated to be 0.63 Ma old (Ranga Rao, 1993) and suggests that uplift began post 0.63 Ma. In the eastern part of the Siwaliks, detrital apatite fission-track data indicate deformation since 1 Ma (Chirouze et al., 2013). Assuming maximum regional slip rates of 18 mm/yr (Kumar et al., 2006; Powers et al., 1998), the fold began to form no later than 0.58 Ma. However, assuming the minimum fault slip rate of 6.3 mm/yr (Malik and Nakata, 2003) and a slip of 10.5 km on the HFT ramp (Mukhopadhyay and Mishra, 2004), the fold could be 1.22 Ma–2.44 Ma old (Barnes et al., 2011). Lateral expansion of the Chandigarh anticline and fault tip propagation occurred (i) from the northwest to the southeast (Delcaillau et al., 2006), (ii) laterally apart from the central part (Singh and Tandon, 2008), i.e. laterally apart from the Patiali Rao River. Assuming a slip rate of 6 mm/yr–18 mm/yr (Kumar et al., 2006), Barnes et al. (2011) estimate a fault tip propagation of 60 mm/yr–180 mm/yr for the Chandigarh anticline lateral growth. Thus, the ~40 km long Chandigarh anticline is 112 kyr–332 kyr old using this method.

Wind gaps have been identified by Singh and Tandon (2008) in the drainage divide as a record of fossil rivers flowing straight across the Siwalik Hills. Before the complete emergence of the Chandigarh and Janauri anticline, rivers flowed to the southwest from the Himalayan mountain range to the Indo-Gangetic plain (Fig. 1). The uplift of the Siwaliks created progressively an orographic barrier that has deviated the rivers (Singh and Tandon, 2008). The drainage divide of the Chandigarh hills is asymmetric and is positioned offset northward to the front of the HFT. Numerous rivers flowing from the northeast to the southwest eroded the Chandigarh hills (Fig. 2). Streams draining the frontal flank deeply incised Upper Siwalik conglomerates bedrock. Relief averages ~100 m and peaks ~200 m near the drainage divide (Barnes et al., 2011). The Chandigarh ridge presents a strongly dissected topography. South-flank relief values up to 50 m are gained over a lateral distance of ~1 km. Then a gradual increase to the maximum relief occurred for ~10 km. Northern flank relief is gained rapidly along a lateral distance of 1 km–3 km and is steeper than the southern flank.

Northwest India (Chandigarh and Punjab) is a region where Asian monsoons were active since several million years. Highly seasonal rainfall leads to the mean annual precipitation rate to range between 1 m/yr to 3 m/yr in the Siwalik Hills (Bookhagen and Burbank, 2010; Burbank et al., 2003). An average 50% of total rain in the Siwaliks ends in run-off (Singh, 2002) and seasonal stream occurred. Upper Siwalik formation is more erodible than middle and lower Siwalik formations (Barnes et al., 2011). Erosion of the Siwalik ridge is significant as indicated by the progressive filling of the Sukhna reservoir lake at the northeast of Chandigarh (Singh, 2002). The Siwaliks of central Nepal have an erosion rate of 10 mm/yr–15 mm/yr (Lavé and Avouac, 2001). Singh (2005) estimated an average soil loss value of 80 t/ha/yr (i.e. 8 kg/m^2/yr) using field data and Universal Soil Loss Equation (USLE) method. The soil loss estimated by Singh (2005) ranges between 25 t/ha/yr–165 t/ha/yr (i.e. 2.5 kg/m^2/yr–16.5 kg/m^2/yr) in the downstream part of the Patiali Rao valley and could reach value of 165 t/ha/yr–300 t/ha/yr (i.e. 16.5 kg/m^2/yr–30 kg/m^2/yr) in the upstream part.

Four surfaces have been identified into intermontane valleys (Singh and Tandon, 2008) and are a possible result of intermontane valley uplift: (1) the Kalka surface is the highest and the oldest one (~55 kyr ± 6 kyr, Singh and Tandon, 2008), (2) the Pinjaur surface, (3) the Jhajulla surface and (4) a younger terrace (an equivalent of younger terraces occurring near the Ghaggar River exit within intermontane valley are deformed by tectonic activities at ~A.D. 1200 yr and ~A.D. 1700 yr (Kumar et al., 2006).

3. Field observations: tectonic structure and geomorphology

3.1. Geological structure

We performed a field study in the Chandigarh Hills near the archeological site of Masol (30°49′47′′N, 76°50′37′′E) in NW India. In the field, sandstones, sands, conglomerates and silts have been observed. In some cases, the thickness, the color and the global aspect of layers allowed us to identify the different geological units easily. For more precise descriptions, laboratory analyses were performed (granulometry, mineralogy) and material has been collected for ESR datation. The detailed sedimentological analysis was performed at the French National Museum of Natural History and at Paris-Sud University (Abdessadok et al., 2016; Tudryn et al., 2016). Magnetic susceptibility of rocks has been measured in the field and samples were collected for magnetostratigraphy (Chapon Sao et al., 2016a,b; Tudryn et al., 2016). Numerous Pliocene fossils and stone tools were found (Dambricourt Malassé et al., 2016a,b) and identified (Gaillard et al., 2016; Moigne et al., 2016).

These rocks and fossils have a continental origin. Fluvial features (paleo-channels) have been identified. Quartzite and metamorphic rocks were observed in conglomerate which came from the disaggregation of the internal zone of the Himalayan mountain range. The thickness of layers may change laterally. This is not surprising due to their continental origin. Sedimentary layers observed in Masol are Pliocene in age (Ranga Rao, 1993). More precisely these layers have been described as being part of the Upper Siwalik formation (Ranga Rao, 1993; Tudryn et al., 2016). Field investigations allowed us to determine various geological units in which different paleonto-archeological sites were (Masol 1 to 13).

Satellite imagery and field studies allowed us to observe the main anticlines structures of the Chandigarh anticline (Fig. 2). The Chandigarh Hills are constituted by two parallel folds axes: the Tandi anticline at the southwest and the Masol anticline at the northeast. The two anticlines are separated by the Tandi syncline. The fold axis of these anticlines is ~140°N. This fold axis indicates a main stress direction of ~50°N and is compatible with the convergence direction between India and Eurasia (Fig. 2A). Small reverse faults have been observed in the field and are compatible with a compressive stress direction oriented ~50°N. Fault dips range between 10°W and 30°W in the Masol archeological sites area. Fault directions range between 100°N and 180°N. The village of Masol, where various archeological sites are located (M1 to M13, Fig. 2B), is the locus of anticlines structures which are of significant length (Figs. 3 and 4). Field investigations suggest that geological layers near the Masol archeological sites have been deformed and are inclined with gentle slope. The village of Masol is the centre of an anticline that has been excavated by erosion. In the field, it can be observed that geological strata are dipping to the SSE to the east of Masol (Fig. 3B). In the west of Masol, geological layers are dipping towards the west (Fig. 4). Locally, the fold structure is not purely cylindrical. The archeological sites are located at the eastern extremity of the Masol anticline and a shifting between the folds axis took place near the village of Masol (Fig. 2A). The sedimentary layers are excavated by erosion and visible in the landscape allowing to identify a geologic structure oriented ~140°N (Fig. 3 A and B).

3.2. Geomorphological observations

We would like to describe here the morphological features resulting from the intense erosion that affected sedimentary layers in the Siwalik area and more precisely

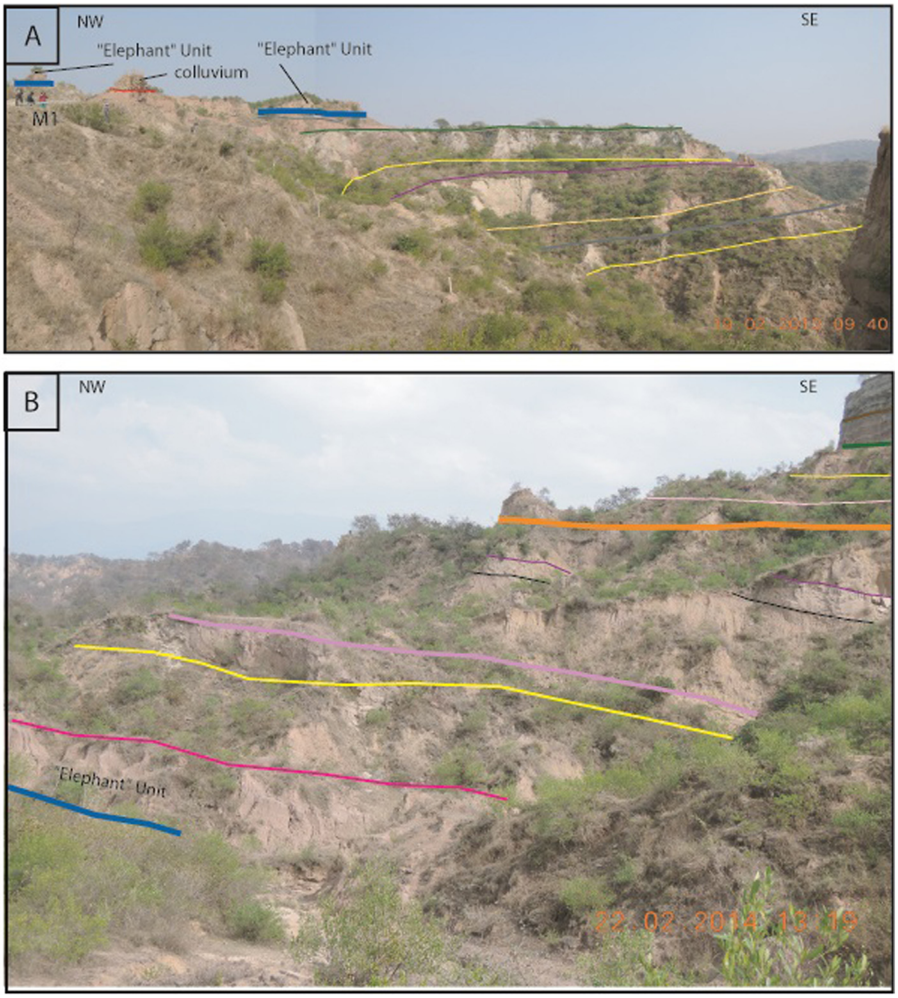

Fig. 3. (Colour online.) Detailed geological structures of Masol paleonto-archeological sites. A. Geological layers are sub-horizontal in the Masol 1 locality. B. The geological layers are inclined in the southeast direction close to the Masol 13 locality. In the two localities, we find again the same sand layer containing Proboscidean fossils ("Elephant unit", above the blue line). Pictures are localized on Fig. 2B.

Fig. 3. (Couleur en ligne.) Structures géologiques précises à proximité des sites paléonto-archéologiques de Masol. A. Stratification sub-horizontale de la localité Masol 1. B. Stratification inclinée vers le sud-est à proximité de la localité Masol 13. Dans les deux localités Masol 1 et Masol 13, on retrouve la même formation sableuse contenant des fossiles de Proboscidien (« Elephant unit », au-dessus du trait bleu). La prise de vue est localisée sur la Fig. 2B.

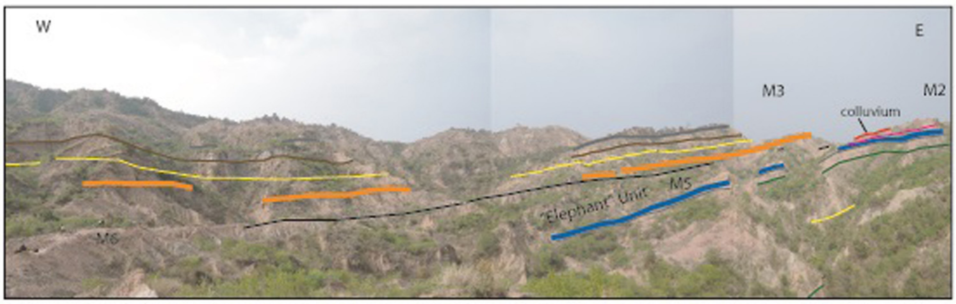

Fig. 4. (Colour online.) Detailed geological structure of Masol localities. The geological units have a slope dipping to the west. The localities M2, M3, M5 and M6 are indicated. The sand layer containing Proboscidean fossils ("Elephant unit", above the blue line) can be observed as on Fig. 3. For clarity, another geological formation containing silts of different colors is highlighted with a thick orange line and corresponds to the one in Fig. 3B. Location is given in Fig. 2B.

Fig. 4. (Couleur en ligne.) Structure géologique précise des localités de Masol. La stratification a un pendage vers l'ouest. Les sites archéologiques M2, M3, M5 et M6 sont indiqués. La formation sableuse contenant des fossiles d'éléphants (« Elephant unit », au-dessus du trait bleu) est présente comme sur la Fig. 3. Pour repère, une formation géologique limoneuse multi-couleurs pouvant facilement être repérée sur le terrain est indiquée (trait épais orange). La prise de vue est localisée sur la Fig. 2B.

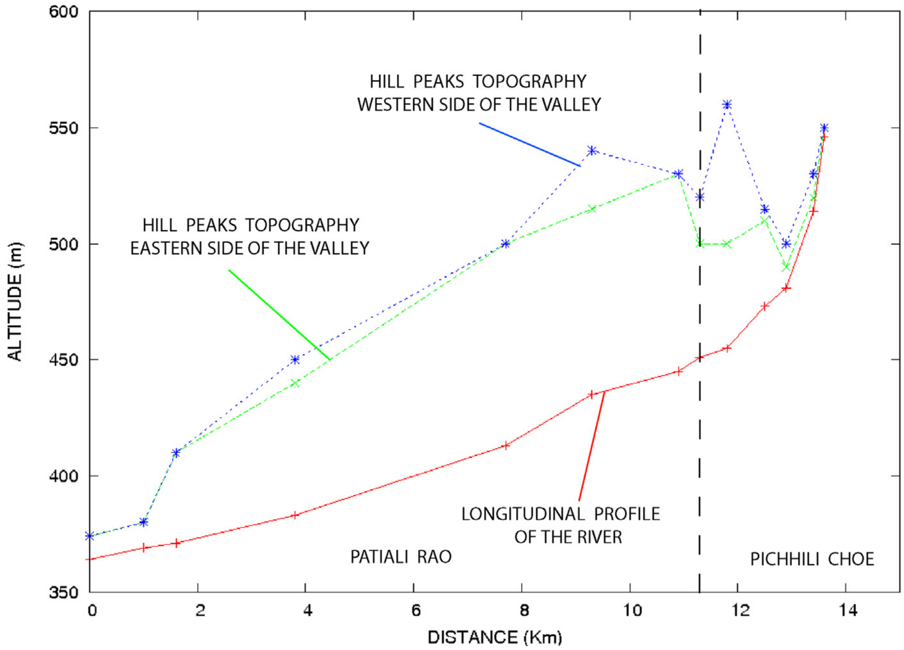

Fig. 5. (Colour online.) Longitudinal profile (red line) of the seasonal river Patiali Rao (below 450 m) and the Pichhli choe in the upstream part (above 450 m). The hill peaks topography near the Patiali Rao and Pichhili choe is also represented: hill peaks are measured on both sides of the rivers, laterally apart from the centre of the valley.

Fig. 5. (Couleur en ligne.) Profil longitudinal (ligne rouge) de la rivière saisonnière Patiali Rao et du Pichhli choe pour la partie amont. La topographie des crêtes des collines de part et d'autre de la vallée, à l'est et à l'ouest du thalweg, est également représentée.

near the Masol archeological site. River erosion by the Patiali Rao and its tributaries played a significant role in the entrenchment (excavation) of the Masol anticline. Streams draining the frontal flank deeply incised Siwalik bedrock from northeast to southwest, perpendicular to the HFT (Fig. 2A). The Chandigarh hills are strongly dissected and have a dissymmetric topography. The southwestern flank of the Chandigarh anticline is more eroded with a gentler slope than the northeastern flank. Relief averages ~80 m in the Patiali Rao valley. Hills peaks reach ~180 m above the Indo-Gangetic plain near the drainage divide (Fig. 5). The Patiali Rao thalweg topography (longitudinal profile) is concave and numerous small tributaries exist. This area is the most deeply eroded area of the Chandigarh anticline and has resulted in exposure of the older geological formations and fossil records of Late Pliocene age at Masol.

The vertical erosion reaches ~100 m near Masol from the Patiali Rao River to the higher peak (Fig. 5). The width of the Patiali Rao channel is of ~10 m at Masol. The Pichhli choe, a tributary of the Patiali Rao at the west of Masol (Fig. 7) has a width of 3 m–5 m close to Masol. They are dry during most part of the year. Several levels of fluvial terraces, containing pebble, silt and sand, can be observed laterally apart from the Patiali Rao (Fig. 6) and from the Pichhli choe (tributary of the Patiali Rao at the west of Masol, Fig. 7). Fluvial terraces are positioned several meters above rivers (~4 m for T1 to 10 m for T2) indicating that significant fluvial erosion takes place in the Patiali Rao River. The Pichhli choe has at least two levels of fluvial terraces at 1.70 m and 3 m (Fig. 7).

In the upstream, fluvial terraces and colluviums are sometimes difficult to distinguish. Colluviums can be observed on the hills and are constituted by sandstone principally but also by metamorphic rocks. These colluviums could produce an armoring of the surface and protect it from run-off erosion along hillslope during monsoon season. Colluviums are deposited on the present topography and have a thickness of 10 cm to 1 m generally. The colluviums are recent because (i) erosion is very significant, (ii) colluviums are observable almost everywhere except on the active flow pathway. In many parts, the active and efficient regressive erosion has not remobilized colluviums and transported them downstream yet.

Sandstone and sand formations could also be disaggregated without significant transport. Such a case has been identified in M2 paleonto-archeological site. The colluviums are very thick at this place (i.e. ~2 m, Fig. 8A) and contain sandstone blocks that range between 10 cm and 50 cm (Fig. 8C). Sandstone rocks contained in the colluviums of M2 archeological site have very complex morphologies (Fig. 8C) that are not compatible with significant transport. The sandstone blocks originate from the sandstone formation located stratigraphically just above (Fig. 8B and in orange in Fig. 4) in the area where the layers are sub-horizontal. The same process can be interpreted for the archeological site M7 (Fig. 2B). However, this in situ disaggregation process has not been observed in many places.

Various processes triggered the disaggregation of Chandigarh hills (Fig. 9). Regressive erosion is observable in several places. Characteristic morphological features of regressive erosion, such as step or scarp in the river channels indicate that this process is still active (Fig. 9C

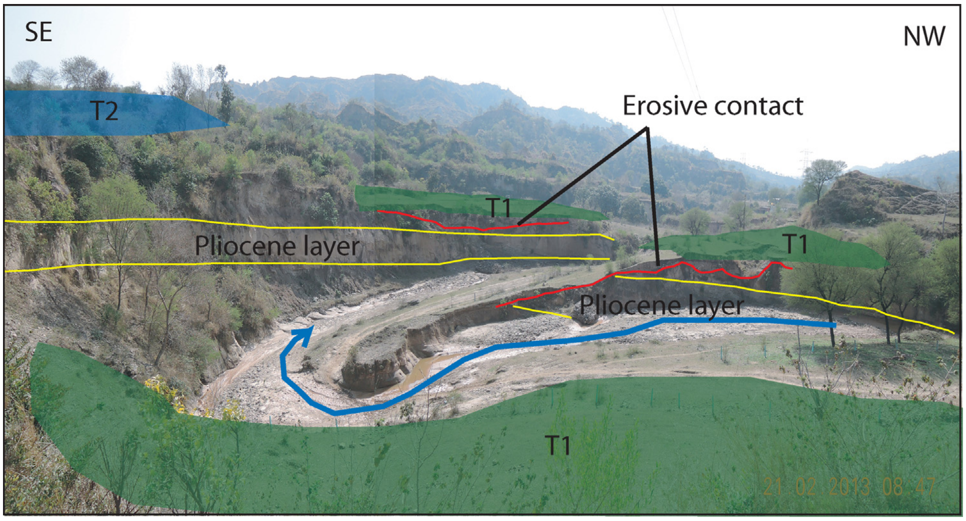

Fig. 6. (Colour online.) Patiali Rao fluvial terraces, south of Masol village, Chandigarh anticline, Siwalik, NW India. Two levels of fluvial terraces are visible ~4 m and ~10 m above the river.
Fig. 6. (Couleur en ligne.) Terrasses fluviatiles du Patiali Rao au sud du village de Masol, dans l'anticlinal de Chandigarh, dans les Siwalik, dans le Nord-Ouest de l'Inde. Deux niveaux de terrasses fluviatiles sont observables à ~4 m et à ~10 m au-dessus de la rivière.

and D). Rivers are able to transport material with a diameter > 10 cm. Steps occur when regressive erosion is in contact with more resistant rocks and layers. Scarps of 1.5 m–2 m have been observed in the river channel and were armored by a thin layer of resistant conglomerates. Regressive erosion is a very efficient process in the area, which started from downstream to upstream. As a consequence, deep strata located downstream are eroded more rapidly than the geological formation located upstream where regressive erosion is less intense and water discharge less abundant.

In the case of the Pichhli choe stream, steps of 10 cm–50 cm in height can be observed in the channel. The different mechanical properties of silt and sandstone in

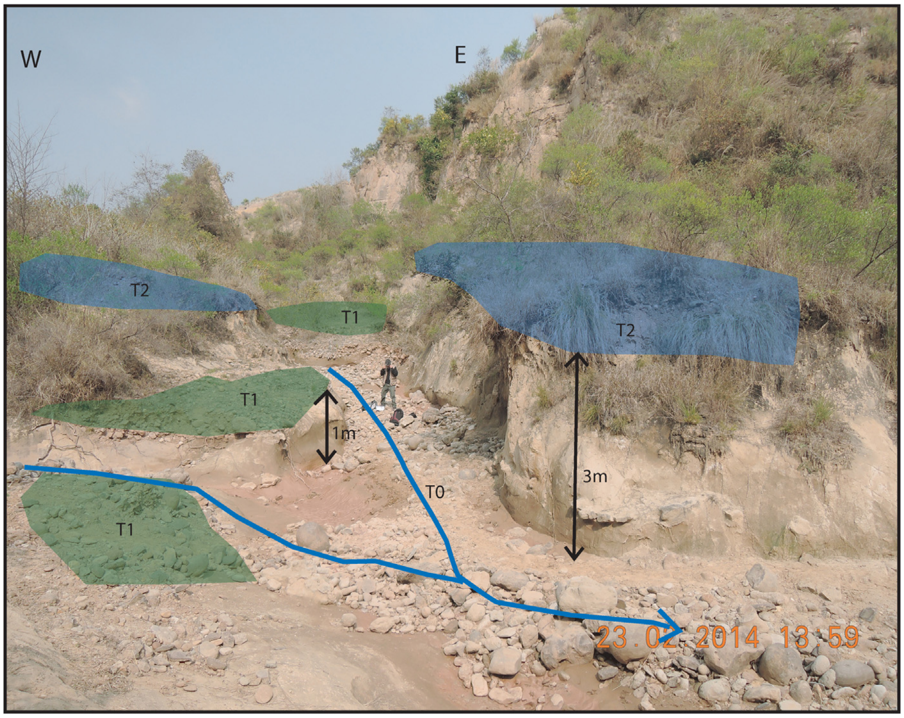

Fig. 7. (Colour online.) Fluvial terraces in the Pichhli choe, Chandigarh Hills, NW India. Two levels of terraces are observable.
Fig. 7. (Couleur en ligne.) Terrasses fluviatiles du Pichhli choe, affluent du Patiali Rao, dans les collines de Chandigarh, dans le Nord-Ouest de l'Inde. Deux niveaux de terrasses sont observables.

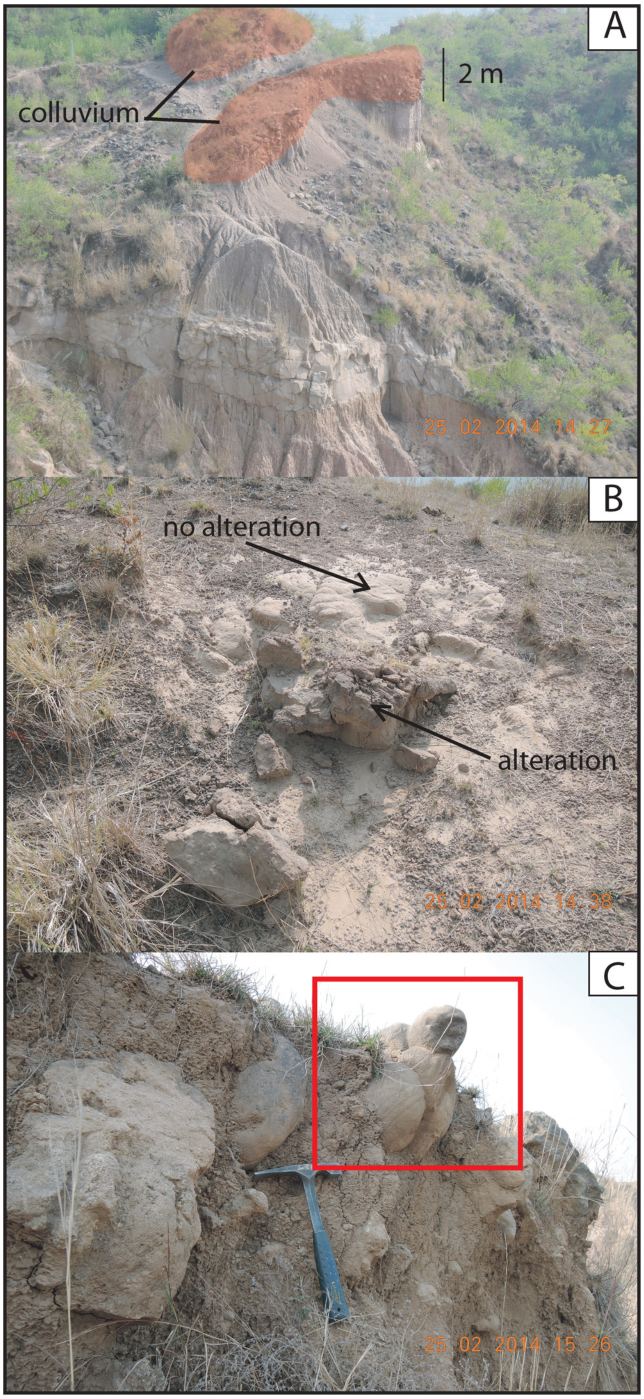

Fig. 8. (Colour online.) Colluvium: A. Thick colluviums deposits (~2 m) near Masol 2 and observable in the landscape in Fig. 4. B. Sandstone formation which formed the colluviums of Masol 2 after being subjected to erosion/alteration. C. Block of sandstone into the colluviums with a complex morphology that indicates that erosion of sandstone occurred without significant transport.

Fig. 8. (Couleur en ligne.) Colluvions : A. Colluvions épaisses (~2 m) à proximité de la localité Masol 2, dont on peut localiser l'emplacement dans le paysage sur la Fig. 4. B. Formation gréseuse d'où proviennent les colluvions proches de Masol 2 après érosion/altération. C. Bloc de grès avec une morphologie complexe à l'intérieur des colluvions, indiquant que l'érosion s'est faite sur place, sans transport.

contact with water flow lead to the preferential erosion of silt in the river channel but also in the river banks (Fig. 9A). After the erosion of silts in the river banks by the water flow, the poorly consolidated sandstones located just above the silts collapsed under their own weight. The collapse of sand and sandstone happened after that part of the material located below had been removed by the water flow (Fig. 9B). A landslide of significant length (~10 m–20 m) is

Fig. 9. (Colour online.) Various erosion morphologies and processes in the paleonto-archeological site of Masol, Chandigarh anticline, Siwalik, NW India. A. Differential erosion between silt and sand in the Pichhli choe. B. Rock fall. C. Regressive erosion. D. Regressive erosion constrained by the presence of a conglomeratic layer. E. and F. Cavities in sand formations. G. and H. Colluviums.

Fig. 9. (Couleur en ligne.) Différentes morphologies et processus d'érosion observables à proximité des sites paléonto-archéologiques de Masol (anticlinal de Chandigarh, Siwalik, Nord-Ouest de l'Inde). A. Érosion différentielle entre les limons et les sables dans le Pichhli choe (rivière). B. Chute de bloc. C. Érosion régressive. D. Érosion régressive contrainte par une couche indurée formée d'un conglomérat. E. et F. Cavités dans des formations sableuses. G. et H. Colluvions.

also observable near the Masol village involving silt and sand formations.

Sand and sandstone formations are highly porous and permeable and are not very resistant to erosion. As a consequence, subsurface flows are able to erode significantly the material and to trigger cavity formation (Fig. 9E and F). Horizontal cavities (Fig. 9E and F) could be large (1 m–6 m) and located in sand cliffs. Small vertical cavities have also been observed on the ground in M1 and near M6 archeological sites.

4. Discussion

Youngest sediments deposited in the Chandigarh anticline are 630 kyr old (Ranga Rao, 1993). As a consequence, erosion has begun 630 kyr ago at the maximum. Vertical erosion can reach ~80 m in the Patiali Rao and regressive erosion is approximately of 12 km (Fig. 5). So the minimum vertical erosion rate is estimated to be locally ~0.13 mm/yr and the regressive erosion rate is ~19 mm/yr in the Patiali Rao Valley. The regressive erosion rate is of the same order than the regional slip rate, which ranges between 6.3 mm/yr (Malik and Nakata, 2003) and 18 mm/yr (Kumar et al., 2006; Powers et al., 1998). If the correlation between vertical uplift erosion rates is well known (Gargani et al., 2006; Lavé and Avouac, 2001), it is not evident that the regressive erosion rate is always of the same order than the regional slip rate. It could be a coincidence and this mechanism must be studied more accurately. In the Patiali Rao valley, regressive erosion rate is more than ten times higher than vertical erosion rate. Even if this regressive erosion rate seems significant, it is smaller to the regressive erosion rate of the river Rhône (France) and of the river Nile during the Messinian crisis which reach ~3 m/yr (Gargani, 2004a) and 2.5 m/yr (Gargani et al., 2010) respectively.

Concerning the minimum vertical erosion rate, it can be compared to erosion rates of the Siwaliks of central Nepal estimated to be of 10 mm/yr–15 mm/yr (Lavé and Avouac, 2001). This significant difference can be due to the over-estimation of duration of erosion. Indeed, the Chandigarh anticline uplift above a simple ramp (Fig. 1B) has not triggered erosion immediately everywhere on the anticline. Erosion started and stopped first on the southwestern flanks than on the northeastern flanks. More precisely, the progressive uplift from the southwest to the northeast and the mechanism of regressive erosion have generated a delay between the beginning of erosion in the south-western flank of the anticline and the beginning of erosion in Masol archeological sites. Gabet et al. (2008) estimated present erosion rate to range between 0.1 mm/yr and 2.0 mm/yr in the Massyandi catchment during the monsoon. This is in the same range that the minimum vertical erosion rate of ~0.13 mm/yr that we can estimate in the Chandigarh hills. However, Singh (2005) estimated an average soil loss value of 80 t/ha/yr (i.e. 8 kg/m^2/yr). Assuming a sediment density of ~2400 kg/m^3, we obtain an average erosion rate of ~3 mm/yr. These estimations confirm that the vertical erosion rate of 0.13 mm/yr is certainly underestimated and that the duration of 630 kyr for erosion is over-estimated in the Masol archeological area. A vertical erosion rate of 2 mm/yr–4 mm/yr could trigger 80 m of vertical erosion in 20 kyr–40 kyr.

The significant erosion occurring in the Siwalik is due to (i) uplift, (ii) significant rainfall during the monsoon, (iii) poor mechanical resistance to erosion. Tectonic uplift created a knick point on the southern flank of the Chandigarh anticline and increased the local slope at the front of the HFT. The presence of a knick point and steeper slope favored regressive erosion (Begin et al., 1981; Gargani et al., 2006). Furthermore, the climatic conditions in northern India, where seasonal monsoon occurred, triggered 1 m–3 m of rainfall (Burbank et al., 2012). Abundant presence of water is known to generate landslide, rock fall and colluviums (Gabet et al., 2004; Gargani et al., 2014). In the area of the archeological site of Masol, colluviums are present almost everywhere at the surface and rock falls can be observed at several places (Fig. 9B, G and H). Landslide is also seen in the area. Finally, material is eroded and transported by the river. Rivers (i.e. Patiali Rao and Pichhli choe) are able to transport pebbles > 10 cm. Only water flux with a velocity > 10 ms^{-1} can erode and transport such a material (Gargani, 2004b). In NW India, precipitations are higher in summer and occur principally during monsoon (Burbank et al., 2012). River flow is concentrated during this period. Monsoon is known to have occurred since several million years and to have been influenced by Himalayan-Tibetan plateau uplift (An et al., 2001; Patnaik, 2003).

The colluviums deposited on the Masol hills are recent because in many cases they are located on the top of the present slope. Soil creep, rock fall, splash erosion (triggered by kinetic force of rain), run-off during monsoon could explain slope deposits. These colluviums contain sandstone and metamorphic rocks, but also archeological tools (choppers; Gaillard et al., 2016) and Pliocene fossils of continental origin (Dambricourt Malassé et al., 2016a,b; Moigne et al., 2016). Only active gullies have reworked this detritic material. In some cases, colluviums are perched ~1–2 m above the ground (Fig. 9G) and may protect the surrounding formations from erosion. If the vertical erosion rate in the Siwalik Hills ranges between 0.1 mm/yr (Gabet et al., 2008) and 15 mm/yr (Lavé and Avouac, 2001), it means that perched colluviums at ~2 m above the ground have an age between 130 yr and 20,000 yr. However, the rate of 15 mm/yr has been estimated in a river channel (fluvial terraces) and it may over-estimate the erosion rate on hillslopes. Inversely, the erosion rate of 0.1 mm/yr may underestimate the erosion rate. Assuming a vertical erosion rate of 2–4 mm/yr (Gabet et al., 2008; Singh, 2005) permits to estimate an age comprised between 500 and 1000 yr for many colluvium formations perched ~2 m above the ground. The extreme values for present erosion loss estimated in the upstream part of the Patialia Rao valley near the Masol paleonto-archeological site reach 165 t/ha/yr–300 t/ha/yr (Singh, 2005) which corresponds to 6.9 mm/yr–12.5 mm/yr. These extreme values for present soil erosion are close to the fluvial erosion rate (~10 mm/yr–15 mm/yr, Lavé and Avouac, 2001) but can also be explained by recent anthropic deforestation since 1960 (Singh, 2005). Concerning the fluvial terraces of the Patiali Rao stream located at 4 m and 10 m above the river bed (Fig. 6), their approximate age range between

~300 yr–400 yr and 660 yr–1000 yr respectively assuming a fluvial erosion rate of 10 mm/yr–15 mm/yr. Such a significant erosion rate on hill slope and for river bed may explain (1) why only a so small number of fluvial terraces have been recorded and (2) the difficulty to conserve any fluvial material that corresponds to the "wind gap" of Singh and Tandon (2008).

5. Conclusion and perspective

The Masol archeological site is located in an active area where a small-scale anticline structure is observable in the field. This relatively small structure and the faults are the result of the Indian and Eurasian plate convergence and of the Chandigarh anticline formation. The deformation and uplift of this area, as well as the intense monsoon, triggered favorable conditions for erosion. In the field, various morphologies of erosion have been identified: (1) cavity due to sand excavation, (2) rock fall, (3) landslide, (4) river erosion, (5) colluviums. These morphologies are due to the concomitant influence of uplift, monsoon and highly erodible material (sand and silt). Colluviums seem very recent but absolute age is needed to improve our knowledge about this key target for archeological tools and fossils. The estimates of the regressive erosion rate of the Patiali Rao valley (19 mm/yr) seem to be of the same order than the regional slip rate.

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