# Sole markings of extraordinary size and variety in Crocker sandstones of Sabah

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**Abstract:** Sole markings are arenaceous casts of impressions, typically scoured by water currents on cohesive mud surfaces. Scouring may be effected by clear or by debris-laden moving medium. Debris carried along in traction, in saltation and in suspension leave unmistakable imprints that often manifest as indicators of stratigraphic facing, flow direction, or relative distance from source. The Eocene-Lower Miocene Crocker Formation of Sabah hosts an exceptional assemblage of large to gigantic sole markings near Kaung Village on the mid-slope of Mount Kinabalu. Two forms, hitherto unmentioned in publications, are enterolithic casts and preserved effects of turbulent flow. Representatives of the *Nereites-Zoophycos* ichnofacies at this locality, along nearby Samalang River and in the heart of Kota Kinabalu confirm bathyal-abyssal depth of deposition. Where determined in other localities of the Crocker Formation in Sabah, paleocurrents ran Northward. The only exception of southerly directed sediment transport near Kaung Village poses a formidable challenge to understanding Sabah's tectonic evolution.

Keywords: sole marking, Crocker Formation, enterolithic cast, turbulent flow, palaeocurrent

#### BACKGROUND

Sole markings consist of casts of impressions made by (a) current-derived features, by (b) gravity-induced and modified structures, or by (c) organic activity. The latter is grouped as ichnofossils or trace fossils. Settling and compaction of sediment may deform all three types of sole markings which are then classified as load-casted structures. Current-related sole markings developed from mud-silt-sand carrying sea-floor-hugging currents, from debris in a range of sizes transported in traction-saltationsuspension, and also from fast-moving clear water bodies. Sole markings require coarser grained sediment overlying coherent argillaceous sediment. Such situation is commonly provided by turbidite sequences, hence the predominance of sole markings being observed and utilised as sedimentenvironmental indicators and provenance studies. It has been pointed out that strong currents develop similar impressions in other sedimentary environments. The bibliography on sole markings is extensive. In the earlier part of the 20<sup>th</sup> century prior to the general acceptance of *Plate Tectonics*, sole markings were dealt with in descriptive terms spawning a glossary of sometimes confusing complexity. Sole markings have proved most useful in paleocurrent studies. Research in the past four decades focussed on sole markings in the context of basin analysis, including depositional architecture. It suffices for the need of this article to refer to the following pioneers who have defined the subject: Bouma (1962), Crowell (1955), Dzulynski et al. (1959), Dzulynski & Sanders (1962), ten Haaf (1959), Ksiazkiewicz (1952), Kuenen (1957), Pettijohn & Potter (1964), Potter & Pettijohn (1963), and Shrock (1948).

The purpose of this article is to highlight the occurrence of sole markings in the Eocene to Lower Miocene Crocker Formation at several localities in Sabah. Stauffer (1967) derived consistent palaeocurrent directions that deposited the Crocker beds. The Malaysian Geological staff, especially those of the Sabah office, have known outcrops displaying these markings and provided Hamilton (1979, pages 90-91) to acquire the field photographs of sole markings in outcrops at the western border of the Kinabalu National Park. In this general area, the Crocker sole markings are of large to giant size and consist of diverse cast forms. Ichnofossils are also common. My personal experience with sole markings had been in outcrops of Sungai Samalang in the Ranau area, and sole markings in Crocker sandstone at the western and southern boundaries of the Gunung Kinabalu National Park. Another outcrop of sole markings is the Bukit Istana steep slope behind the Shangrila Hotel in central Kota Kinabalu (Figure 1). Sole markings in these three areas exhibit extraordinary large size, whose groove casts reach at least 7 meters length which appears



Figure 1: Index map of the sole markings studied in the Crocker sandstone of Sabah.

only limited by outcrop expanse; other large types of sole markings abound. The outcrop displays has been facilitated by intense synsedimentary and tectonic deformation that provided overturned beds.

## GEOMETRY AND NOMENCLATURE OF SOLE MARKINGS

An instructive summary on sole marking nomenclature has been provided by Pettijohn & Potter (1964). This labeling is generally followed in the present article. Figure 2 sketches the probable origin of the markings. Emphasis is given to the types of sole markings contained by the Eocene to Early Miocene Crocker Formation. Its extended geological age has been attributed to absence of shorter-period index fossils. The geological age bracket of the formation follows that used by Collenette (1958).

The upper part of Figure 2 (inside the boxed in area) schematically shows plan view (bed view image) while in the lower part are profiles of the features whose casts -bed-bottom view- are the subject of this paper and illustrated as photographs.

**Chevron features** are ruffles of the surface of a cohesive mud surface caused an object ("tool") being transported in traction by the current (large arrow on top of the Figure 2). The literature recorded acute V-shaped ruffles to sometimes change into rounded fronts. The tool-in-traction possibly became embedded at relatively shallow depth in the mud. The groove bisecting the chevrons records the track of the tool-in-traction.The chevron pattern points into the down current sense.

**Prod features** are relatively deep holes of asymmetrical profiles, its deeper end developing at the down side (see profile). This asymmetry is a reliable indicator of current sense.

**Push features** develop at the down current end of toolin-traction. This down current end of the object typically consists of several subparallel crescentic ridges alternating with grooves. On the lee side of a crescentic ridge eddies may have been imprinted to form an irregular pattern of pits representing turbulence of the moving medium. The hard object may or may not have remained in place.

**Bounce features** are shallow depressions formed by hard objects ejected at comparatively shallow angle from the mud surface. A bounce impression usually consists of a single ridge at the down current end of the shallow depression. In the Crocker outcrops described in this article, irregular perturbations of the "bounced" mud surface on the lee side of the bounce ridge possibly represent imprints of eddies of the transporting medium. On the stoss side of a bounce feature may occur fine, parallel lines that probably record the grazing track of the bounce object.

Horse shoe features are moats formed by currents in front and alongside obstacles. Such features are also common on muddy beaches and fine-grained sediment on the floor of natural as well as artificial channels.

**Spiral-ornamented groove**. The lowermost sketch of Figure 2 is a groove scoured out by a moving fluid that

also carried a small hard object. If the moving fluid moved spiral-fashion, the hard object may leave a trail the registers as a fine groove on the wall of the main "channel". Its cast shows up as a fine spiraling ridge. The example in Figure 2 resulted from a clockwise (CW) down current vortex. In the Crocker beds to be described below, deformation of spiraling feature may be several centimeters deep. Loadcasting sometimes deform the groove into sausage-like spiraling segments that through advanced deformation result in strings of irregular pinch-and-swell forms, It is suggested to call these *enterolithic casts* (Figures 4 and 8 show examples).

**Groove casts** in the Crocker outcrops featured in this article are well represented and may reach extraordinary length. Groove casts of several meters length and up to 30 centimeters wide are common. Spiral groove casts with CW or CCW (counterclockwise) vortices appear consistent in neighbouring turbidite sequences. Further study is needed to sort out any significance of this observation.

Flute Cast. This type of sole markings unambiguously define stratigraphic sequence and paleocurrent direction. At the Crocker outcrops these casts have not been wellrepresented, which probably suggest proximal positions of the studied turbidite sequences. Figure 3a shows welldeveloped flute casts on the bottom side of a calcareous flysch; the paleocurrent was from right to left. Figure 3b is a profile of similar flute casts preserved at the bottom of a calcarenite bed that overlies mudstone. The steep to slightly overhanging sides of some flute casts suggest incipient deformation by loading. The sedimentary sequence is of the Late Oligocene-Early Miocene Cinambo Formation (Martodjojo, 2003) near Eretan in the Majalengka sub basin of West Jawa. The formation is a turbidite that in the Cinambo (river Nambo)) is composed of calcarenite and marl interbeds.



Figure 2: Geometry and kinematics of current features and sole casts in the Crocker sandstone.



**Figure 3: a-** Flute casts as sole markings of calcarenaceous turbidites in the Cinambo, a major river in the Majalengka sub-basin, West Jawa. Paleocurrent was from right to left. Width of photograph is approx. 25 cm. **b-** Profile of flute casts in the Cinambo. Incipient loadcasting is indicated by steep walls of the casts. Photos by: Tjia in 1962.

## CROCKER SANDSTONE SOLE MARKINGS

## Bukit Istana Slope Behind Shangrila Hotel, Kota Kinabalu

The Crocker turbidite sequence at this locality strikes 025° and dips 67° ESE, or into the hill. Individual graywacke/subgraywacke sandstone beds may reach massive thickness of 2 meter and more, possibly representing channel fills. Sandstone-mudstone interbeds are of normal decimeter thickness After restoration to the horizontal, current ripples and sole markings indicate a general northward sense of sediment transport.

Figure 4 are load-casted flutes; the smaller flute casts in the lower left-hand corner indicate the paleocurrent to have traveled from right to left parallel to the 12 cm long pencil. A groove cast is to the left of the pencil tip. Smaller linear casts diagonal to the paleocurrent direction may be ichnofossils.

Figure 5 shows a few groove casts (G) and sets of broad low-relief casts interspersed with parallel narrow lineations (now showing up as low ridges on the underside of the beds). These are interpreted as drag casts (D). Two of the groove casts possess spiral ornamentation (E) that resulted from incision by hard objects transported by paleocurrent vortices. Note also that both casts represent formation by clockwise vortices. Loadcasting transformed the spiral features into sausage-like forms, for which the term enterolithic casts is proposed. The large cast of sigmoidal outline (X top center) may be a bounce cast. Width of the photograph is 50 cm.



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**Figure 4:** Load-casted sole markings in Crocker sandstone outcropping behind Shangrila Hotel, Kota Kinabalu.. Softsediment deformation probably transformed the large flute casts into more bulbous shapes (Fld and Flv). The pencil (12 cm long in the photograph) indicates paleocurrent sense. Unidentified ichnofossils formed small tubes crossing the paleocurrent indicators. Key: Fl=flute cast; Fld=flute load-cast; Flv = flute cast with twisted upcurrent tip; G = groove cast; P = prod cast; E = enterolithic groove cast; I = ichnofossil formed another scouring period. Figure 6 contains groove casts (G) and spiral-groove casts (Sp). The vortex forming the Sp cast was CW. A group of knobbly casts (Tu) may have resulted from turbulence in the transporting medium. The knob at the down current end of the group is a prod cast (P). Ch 1 indicates Sparsely occurring flute casts (Fl) determine the paleocurrent direction. A patch of *Paleodictyon* (PD) confirms bathyal depth of environment. The pencil is 15 cm long.

Three parallel elongated casts are distinct on Figure 7. One groove cast is associated with chevron (Ch) casts. At the end of the pencil are broad/flat groove casts. To the left of this feature is a load-casted flute (Fl) that down current is followed by a much thinner groove cast. Combined these casts resemble a mouse-and-tail feature. Down current of a small horse shoe cast (H1) is a fan-shaped arrangement of flute casts, probably reflecting the dispersal flow of the medium.

Broad/flat interpreted drag casts (D) coexist with spiral groove casts, Sp (Figure 8). The more pointed ends of some of the drag casts suggest them as flute cast. Paleocurrent could

have been from right to left. The spirals (Sp casts) indicate CW vortices in down current direction. In a lenticular area between the two types of casts, in the center of the figure are deformed enterrolithic casts (E) showing a in a chaotic pattern of knob casts lined with narrow furrows The furrows were originally "longitudinal current ridges" that Dzulynski (1965) was able to reproduce in laboratory experiments.

Figure 9 shows deformed casts (S) of sole markings that have been referred to as squamous (Dzulynski, 1965) or syndromous (Potter & Pettijohn, 1964) casts. These are loadcasts of grooves and flutes. Paleocurrent sense indicated by the 15-cm long pencil was interpreted based on the chevron casts.

The pattern of casts in the focal area of Figure 10 resembles *Paleodictyon*, usually interpreted as indication of bathyal environment. The different sizes may be attributed to ichnofossils of different age groups or types. The hexagonal outline of this trace fossil has been masked by load-casting? Dzulynski (1965) named similar forms "cushion-like markings".



**Figure 5:** Wide but comparatively low-relief drag casts (D) dominate the view. A probable bounce cast is marked X. E (enterolithic casts) are loadcasted/deformed spiral groove or flute casts. Flute casts (Fl) suggest paleocurrent from lower right to upper left. Key: D=drag cast; Fl=flute cast; G=groove cast; E = enterolithic cast; X = possibly a bounce cast. Bukit Istana steep slope behind Shangrila Hotel, Kota Kinabalu.



**Figure 6:** Prominent broad, low-relief groove cast. Key: G = groove cast; P = prod cast; Fl = flute cast; H = horse shoe cast; Sp=spiral-groove casts. Bukit Istana slope behind Shangrila Hotel, Kota Kinabalu.

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**Figure 7:** Prominent groove cast (G) with associated chevron casts (Ch); flute casts being deformed by loadcasting into syndromous casts (within the boxed-in area). Other solemarkings are prod cast (P) and horse shoe cast (H). Bukit Istana slope behind Shangrila Hotel, Kota Kinabalu.



**Figure 8:** Distinct are spiral casts (Sp) developed by current vortices in grooves or flutes. Right off center is a patch of enterolithic casts, probably formed by loadcasting of groove or flute casts. Other markings are groove casts (G), flute casts (Fl) and horse shoe cast (right mid-edge of the figure). The 15 cm long pencil is parallel to paleocurrent direction. Bukit Istana slope of Crocker turbidites behind Shangrila Hotel, Kota Kinabalu. Photo captured in 1976.

## Kaung Village, Southwest Mid-slope Gunung Kinabalu and Samalang River

On the west side of the north-flowing Kadamaian River near Kaung Village, Southwest mid-slope of Kinabalu Mountain (locality 2 on Figure 1), a large roadcut of the Crocker Formation contains large to giant sole markings. The Crocker Formation in the greater area between Kaung Village and Ranau town crops out as very large overturned folds associated with complex structures The intensely deformed appearance resulted from tectonic overprinting of large-scale soft-sediment slumping and form part of the Kinabalu Suture (Tjia, 1988). Structural style of the mentioned area is represented in the upper Figure 11. Such large recumbent structures facilitate excellent access to sole markings.

In the mid 1980s along the gravel road leading to Kaung village, a few hundred meters before the village bridge crop out steeply inclined Crocker sandstone beds exhibiting a plethora of large to giant sole markings The overturned bed of sole markings strike N030°E dipping 65° to Southeast. On this overturned surface the giant grooves pitch 195°/37°. After restoring the bed to horizontal, the associated large flutes indicate paleocurrent from N010°E



**Figure 9:** Soft-sediment loading produced the syndromous casts (S), that probably developed from flute and groove casts.. Chevron casts (Ch) indicate paleocurrent and in turn allows interpretation of the horse shoe cast (H) and groove cast (G). The Crocker sediment dips steeply into the Bukit Istana slope (away from observer).

running in southerly direction. The extraordinary large size of the markings is sufficiently compelling for their preservation. A visit ten years later found this large outcrop hidden by scree and vegetation, partly consisting of pineapple plants. The lower part of Figure 11 illustrates a small portion (photograph is about 4 meters across) of the outcrop. The large groove casts doubly extend their length beyond the width of the picture and farther beyond the outcrop exposure. Other types of sole markings are also several times larger than the couple-of-decimeter size



**Figure 10:** Trace fossils of at least two sizes of deformed (by loadcasting?) *Paleodictyon* (PD) occurs as sole markings in the Crocker beds outcropping at the Bukit Istana slope, Kota Kinabalu. The width of the photograph is about 20 cm.

referred to in the listed references. The horse shoe cast (H) is about 60 cm across. Noteworthy are the spiral (Sp) sole markings and a chaotic pattern of knobbly casts (Tu). The latter may represent effect of turbulence; the spiral groove cast (Sp) suggests formation by a CCW (viewed in down current direction) current vortex. Paleocurrent from upper right to lower left is indicated by flute casts (e.g. right of center of the photograph). A chaotic pattern of small knobs (Tu in the left bottom corner) suggests load-casted impressions of turbulence. The horse shoe casts (H and h) were moats hugging obstacles. Relatively wide surfaces with parallel ridges (such as in the lower right hand corner) are drag casts (D).

The unusually large size of sole markings at the Kaung village outcrop is also exemplified in Figure 12 and the following photographs. The coin is about 2 cm across, In the upper Figure 12 flute casts (FI) indicate the palaeocurrent traveled from upper right to lower left (arrow). The asymmetrical section of prod casts (P) confirm the paleoflow direction. Casts of spiraling tracks (Sp) associated with some groove casts suggest current vortex was CW down current. Two notable markings are shown on the lower Figure 12. The large blade-like prod cast (P) adorned with stripes of a drag cast (D; center of view) probably represents a broad-sided scythe-like cut in a muddy substrate by a similarly shaped hard object. Concentric crescentic casts (Hm) may represent multiple moats about a shifting obstacle adjusting to pulses in current strength. A push cast (Pu) is believed



**Figure 11:** Structural style of the Crocker Formation in the area Southwest to South of Mount Kinabalu. Sole markings definitively determine stratigraphic facing of this large recumbent syncline (upper). Part of the large outcrop of Crocker sandstone near Kaung Village exposing unusually large to giant sole markings (lower). The long groove casts (4 m in the photograph and labeled G) reach over 7 meter in length in the outcrop face and certainly extends beyond the outcrop limit. Flute cast (Fl) indicates paleocurrent flow from upper right to lower left. The spiral groove cast (Sp) formed in a counterclockwise (CCW) vortex. Other sole markings are drag (D), horse shoe (H), part of an other horse shoe (h), and a rather chaotic assemblage of knob-like casts (Tu) interpreted to have filled impressions generated by turbulent flow.



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bedding surface. The 2-cm coin represents scale.

cm. (Lower). The two nested crescentic casts (former moats) may represent push effects. Paleocurrent flow is derived from flute casts and prod casts occurring elsewhere on the same

(Tu and circled) probably developed as fillings of pits by turbulence. Width of figure is 60

to have formed the curving ridge cast (originally a moat; lower right hand corner).

In both photographs (Figure 13) are large nested horse shoe casts (HH and H). The HH horse shoe cast appear to exist of three part-concentric ridges (former moats). The paleocurrent direction was definitively determined from flute casts and prod casts. It is proposed that nested horse shoe casts probably developed around a donwcurrent shifting loose obstacle. The current-resisting obstacle may have adjusted its position to pulses of stronger current flow. Other sole markings in cast were formed as groove (G), drag (D), brush (B), and prod (P). The chevron cast (Ch in the lower Figure 13) is represented by only one flank of the pattern; the other side was possibly destroyed by the neighbouring drag cast (D). Scale: upper photograph is 60 cm wide; coin is 2 cm.

The upper of Figure 14 shows a large oval knob like cast interpreted as an unusual large flute cast (Flg) with a more pointed upcurrent end. Groove, drag, and prod casts are also identified. The nested horse shoe cast (HH) is the prominent feature in the lower Figure 14. The U-shaped cast pointing down current is interpreted as a push cast (Pu). Other sole markings are groove casts (G), drag casts (D) and prod casts (P). The coin is 2 cm across.

Both parts of Figure 15 again document the large size of sole markings in the Crocker sandstone outcropping neat Kaung Village. The upper figure is 60 cm wide; the coin provides scale in the lower figure. The confused pattern of knob-like casts (circled) probably record the effect of turbulence (Tu). Since the paleocurrent sense (from upper right to lower left in both figures) is known from flute casts elsewhere in the outcrop, the large crescentic shaped casts facing down current and associated markings helped in labeling these markings as bounce casts (Bo) and as push casts (Pu). The latter consists of two large crescentic ridges (former moats) distinctly separated from one another.

The upper part of Figure 16 shows the down current end of a large groove cast with spiral ornamentation (Sp) The associated vortex was CCW. The shapes of flute casts (Fl), a horse shoe cast (H) and small push cast (Pu) are consistent with paleocurrent from upper right to lower left. The same paleocurrent is indicated by the large bounce casts (Bo) and prod cast in the lower Figure 16, Scale is shown by the 2-cm coin.

A large flute cast (Fl) is prominent in Figure 17. Other paleocurrent indicators consist of smaller flute casts (Fls) and a horse shoe cast (H). Drag casts (D) occupy broad swaths of the surface. The photograph is 40 cm wide.

Figure 18 shows a large horse shoe cast (H), 15 cm wide. The knob-like casts (Tu) at the upcurrent end filled impressions scoured by turbulent flow. The streamlined arrangement of knobs and neighbouring casts provides excellent indicators for paleocurrent direction that is independently shown by flute casts (Fl) and prod casts (P).

Load deformation may affect only part of the bed as shown by Figure 19. In the left side of the figure are welldeveloped syndromous casts. On the remainder of the figure the observer can still recognise a push cast (P) and flute casts (Fl), albeit displaying signs of incipient load-deformation. These markings indicate the paleocurrent direction (arrow). Crocker sandstone near Kaung Village.

The Kaung Village outcrop of Crocker Formation and those along the Samalang river, a tributary to the Liwagu River, also contain trace fossils. *Paleodictyon* is confidently identifiable from its hexagonal network A bathyal to abyssal environment is indicated. On account of the *Nereites-Zoophycos* ichnofacies other trace fossils shown in Figure 20 are provisionally labeled as (a) *Spiroraphe*? -Samalang River; (b) *Lorenzinia*? - Kaung Village; and (c) *Thalassinoides*? - Samalang River.

### **CONCLUDING REMARKS**

Outcrops of sole markings of the Crocker Formation are numerous and under-explored. Paleogeographic studies seem restricted to the pioneering work of Stauffer. The relative paucity of well-developed flute casts at the Kaung Village outcrop suggests a more proximal position. On the other hand, the Shangrila outcrop and Samalang River exposures of Crocker beds contain possess more flute casts. Stratigraphic facing of the sole markings has assisted in unraveling complex structures. The present article attempts to show the great variety of forms but also the less satisfactory kinematic interpretations derived from the markings. Is the large push cast in the lower Figure 15 properly identified? One would expect the first upcurrent crescent represented by a ridge (a depression in the cast). The extraordinary large size of sole markings shown by the outcrop near Kaung Village may not be site-restrictive as other giant groove casts over 10 m long and a couple of decimeter wide have also been noted in roadcuts between Kundasang and Ranau. River outcrops are usually too small to fully expose the grandeur of Crocker sole markings.

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central part of the figure. Other forms in Figure 16 are prod (P) casts, push cast (Pu), and smaller and usual sizes of the Crocker sole markings near Kaung Village. A prominent of usual dimensions. Sp is a spiral groove cast, with the spiral ornamentation representing groove cast occurs beneath the paleocurrent indicator. Flute (Fl) and groove casts (G) are horse shoe cast (H). the track of a counterclockwise or CCW vortex. (Lower): A large bounce cast (Bo) is in the **Figure 16:** (Upper): This 20-cm wide photograph shows a patch of the outcrop that display



sandstone near Kaung Village. sole casts at the upcurrent side of the large horse shoe cast (left half of the picture). Crocker center; tool present at its upcurrent end), and prod cast (P). Note the streamlined character of groove casts (G), flute casts (Fl), probable turbulence casts (Tu) and a push cast (Pu; bottom an arrow-pointed line; and an other upon which rests the 2-cm coin). Other markings are 20



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**Figure 19:** Load deformation may affect only part of the bed. Well-developed syndromous casts occupy the left side of the photograph, while a push cast (P) and flute casts (Fl) are still recognisable indicating the paleocurrent direction (arrow). Crocker sandstone near Kaung Village.







**Figure 20:** The Nereites - Zoophycus ichnofacies of the Crocker sandstone is also represented by (a) *Spiroraphe*? - Samalang River; (b) *Lorenzinia*? - Kaung Village; and (c) *Thalassinoides*? - Samalang River. Apatch of sole markings at the right side of figure 20 (c) indicate the direction of paleocurrent parallel to the groove casts. Width of view is 80 cm.

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