

DStretch® and Egyptian tomb paintings: A case study from Beni Hassan

Linda Evans*, Anna-Latifa Mourad

Department of Ancient History, Macquarie University, Sydney 2109, Australia

ARTICLE INFO

Keywords:

Egyptology
Egyptian art
Epigraphy
Wall paintings
Animal imagery

ABSTRACT

The advantage of using DStretch® – image enhancement software developed for rock art research – for the analysis and recording of ancient Egyptian wall paintings is demonstrated via its recent application at the cemetery site of Beni Hassan. DStretch® enhanced photographs of painted surfaces enable obscure or faded details to be viewed by artificially highlighting traces of remaining pigment. Trial use of DStretch® for the examination of wall paintings at Beni Hassan has revealed or confirmed new images of pigs and bats (animals that are rarely attested in Egyptian art), and a highly unusual depiction of a vulture, exposing features that were otherwise unavailable visually. When used in conjunction with digital epigraphy, DStretch® offers an invaluable tool for achieving a more complete record of Egypt's artistic legacy.

1. Introduction

Digital epigraphy has been a boon to archaeological practice in Egyptology. Prior to the introduction of computerised methods for recording Egyptian tomb paintings and reliefs in the 1990s, epigraphers could only rely on direct 1:1 tracing of wall imagery on-site (in which drawing paper or film is adhered to the walls) or tracing enlarged photographs. Both methods are time-consuming and, in the case of direct tracing, potentially damaging to fragile or poorly preserved wall surfaces.

Epigraphic practices began to change with the advent of vector-based image software (such as Adobe Photoshop), which, when used in conjunction with graphics tablets, allows epigraphers to trace scanned or digital photographs (Der Manuelian, 1998). This method produces high-quality, high-resolution, scalable line drawings that can also be collated digitally, avoiding misalignment problems that may be introduced with direct tracing (Vertés, 2014). Corrections are made quickly and efficiently, while the ability to magnify photographs on-screen enables minute details to be checked and traced.

Magnification is one of the primary advantages of digital epigraphy over 1:1 tracing (Der Manuelian, 1998), helping to reveal details that the human eye cannot detect. However, magnification cannot always clarify wall images that are damaged, faded or obscured by pollutants such as dirt, soot, or varnish. As many Egyptian monuments are poorly preserved, this problem is encountered frequently. If indistinct sections of wall scenes cannot be resolved visually, epigraphers must either omit them or indicate their uncertainty via dotted lines.

Indeed, the epigrapher's drawing rests ultimately on the ability to

differentiate painted or carved lines and textures, and to make informed decisions about what can be seen. Egyptology training plays an important role in the latter, however the epigrapher's visual acuity and colour discrimination are highly important. Light levels and colour pigments in objects, as well as individual differences in vision, affect our ability to ascertain details (for example, age diminishes both contrast and colour perception; e.g., Greene and Madden, 1987). Thus, despite the advantages that digital epigraphy has afforded Egyptology, the accuracy of produced line drawings is still largely dependent on human vision.

Image enhancement software can be used to improve the appearance of indistinct digital photographs by sharpening or adjusting features (e.g., by manipulating lighting or contrast). Adobe Photoshop®, for example, is the industry standard for digital imaging. However, recent advances in graphic technology have resulted in the emergence of both cheaper and more specialised software to aid the interpretation of specific forms of digital media (e.g., CCTV footage) or for use in particular disciplines. One such example is DStretch®, which was developed in 2005 by rock art specialist Jon Harman to help define elements in faded rock paintings that are virtually invisible to the naked eye. The application of DStretch® has since broadened to include other research areas that similarly require the analysis of painted surfaces. Despite growing use of DStretch® in archaeology (see below), the Egyptology community is largely unaware of the software as, to date, few researchers have published findings based on its application. The potential for this simple tool to aid the analysis of Egyptian wall paintings is thus not generally known or appreciated. The following overview will therefore explain the technique, describe how it has been

* Corresponding author.

E-mail address: linda.evans@mq.edu.au (L. Evans).

applied in archaeological contexts, and share epigraphic case studies from an Egyptian context that have benefitted from the use of DStretch®.

1.1. DStretch®

Colour Decorrelation Stretching or DStretch® is a plug-in for the free, open-source image processing and analysis program ImageJ®. Colour Decorrelation Stretching, which was developed by California's Jet-Propulsion Laboratory (Soha and Schwartz, 1979), was subsequently used in remote sensing to enhance multispectral images and, in 2004, it was employed by NASA to analyse photographs taken by the Mars Rover (NASA News Release, 2004). DStretch® was developed the following year and is now available online as a free download (a minimal fee of 50 USD is requested from professional researchers, however; see www.dstretch.com).

DStretch® analyses the three bands of RGB colour (red, green, and blue) embedded in an image, improving the intensity and saturation of each. The software applies a data transformation technique known as a 'Karhunen-Loeve transformation' to the colourspace, which derives its transformation vectors from the covariance or correlation matrix of the original data (Harman, 2005). In essence, the contrast for each colour is amplified to adjust colour variances (Harman, 2005). Lincoln provides the useful analogy of treating each of the three bands of RGB colour as a coordinate in a colourspace, the transformation process afterwards stretching these coordinates so that they are further apart, making it easier to see the differences between them (Lincoln, 2011). Once stretching has taken place, the program maps the colours back to their near-original form in RGB, enhancing their intensity and saturation and allowing for a greater distinction of colours in an image.

The application and effectiveness of DStretch® may vary according to the quality of the original photograph (e.g., its resolution, perspective or whether it was taken in uneven illumination), its distribution of colours, and the colourspace chosen for analysis (Harman, 2005). Consequently, DStretch® will enhance each image differently. Colours that are particularly well enhanced by the plug-in are red, yellow, black, and white. However, rather than cycling through several filters and modifications in image enhancing programs such as Adobe Photoshop®, DStretch® provides a number of custom colourspaces or pre-settings that can be used to bring out or suppress different colours and shades. The resulting enhancements produce artificial colours. This is because they are intended to show specific hues in great intensity and saturation. Further modifications are often required to increase contrast between elements, boost sharpness, or select particular colours for emphasis by greying out surrounding noise. These can easily be accomplished using DStretch®'s expert mode and Adobe Photoshop® (see Le Quellec et al., 2015). The software also includes the option to save a transformation matrix calculated on one image for later application on others. This allows for quick, efficient and easily reproducible results that can be applied consistently to images of a particular detail, scene or room.

Unlike other image enhancement protocols, very little training is required to use DStretch®. Furthermore, an inexpensive DStretch® app for tablets and mobile phones is now available, enabling the software to be used on-site to immediately clarify ambiguous painted details, while tablet and desktop applications can be used for later recording, tracing, and interpretation.

1.2. Archaeological applications

DStretch® has been widely utilised for the analysis of rock art in many parts of the world, including Africa, Europe, North America, and Australia. The software has sharpened and made more visible the features of faded, eroded and/or overlapping painted images, as well as pictographs (e.g., Cassen et al., 2014; Defrasne, 2014; Defrasne and Bailly, 2014; Gunn et al., 2014; Harman, 2014; Le Quellec et al., 2013,

2015; Tomášková, 2015). It has frequently uncovered previously undocumented images and has also allowed painted features to be differentiated from natural rock stains (Dodd, 2013) or imperfections (Le Quellec et al., 2013, 2015). DStretch® has been especially beneficial for the analysis of problematic paintings. For example, a curious figure, one of many painted images at the World Heritage site of Tassili-n'Ajjer in Algeria, appears to have a drum-like head. However, after a photograph of the image was processed via DStretch® (Le Quellec et al., 2013, 2015), the figure's actual head could be seen inside the drum, the arrangement of the lines also revealing clearly that it was painted after the circular feature, but with the pigment failing to adhere properly inside the sphere.

Although designed primarily for rock art research, DStretch® applications have begun to vary recently, with archaeologists now utilising the plug-in to evaluate a range of painted surfaces. For example, it has been used to study faded wall paintings in the temple of Angkor Wat in Cambodia (Tan et al., 2014) and frescoes in an early seventeenth century church in Bulgaria (Raykovska et al., 2016), soot-obscured imagery (Miller and Thompson, 2015) and paint layers on ancient pottery from the southwestern United States (Shepard and Wright, 2016), as well as crackle patterns on Chinese ceramics (Lahlil et al., 2013).

We are aware of only two published reports in which DStretch® has been applied to ancient Egyptian material. It has aided the interpretation of faded inscriptions at the quarry site of Hatnub, where it has helped to reveal many previously unknown images and texts (Enmarch, 2015), while at Gebelein the technique has been combined with Reflectance Transformation Imaging to yield clear images of otherwise invisible painted and inscribed graffiti and dipinti (Witkowski et al., 2016; see also Witkowski, 2015). To our knowledge, however, the benefits of DStretch® for the analysis of pharaonic wall paintings is not yet widely known among Egyptologists, despite Gebelein scholars noting that 'It would appear that the same approach can provide good results during research on the decoration of temple walls' (Witkowski et al., 2016: 944). We therefore offer the following case study as a practical demonstration of the software's feasibility and potential use with digital epigraphy.

2. Method

2.1. The site

The Middle Kingdom cemetery at Beni Hassan (c. 2050–1650 BC) is well known for the exceptional quality of its artwork (Kanawati and Evans, 2014, 2016; Kanawati and Woods, 2010; Shedid, 1994). Each of the 12 decorated rock-cut tombs at the site display highly detailed scenes of daily life (e.g., agricultural tasks, hunting and fishing, workshop activities, funerary rites, etc.), painted directly onto the wall surfaces in a range of vivid colours. First recorded by Percy Newberry in the 1890s (Newberry, 1893, 1894; Griffith, 1896; Carter et al., 1900), re-assessment of these unique images is currently underway as part of a federally funded project by the Australian Centre for Egyptology, Macquarie University, which has the long-term goal of publishing all of the decorated tombs at the site.

During fieldwork, wall scenes are photographed and traced using a combination of 1:1 tracing and digital epigraphy. While the paintings are largely well preserved, some sections are damaged. That is, the combined effects of age, human intervention, pollutants, and exposure to the elements have resulted in faded or eroded scenes that are difficult to reconstruct and thus trace, either manually or digitally. DStretch® was consequently employed to check the validity of tracings following their production on site.

2.2. Approach

The procedure implemented was largely based on Gary Hein's

'DStretch Suggested Workflow', available on the DStretch® website. Hein's workflow also includes an online 'Guide to Selecting Colourspace', which can be used to decide which enhancement is best for an image. For our trial of DStretch®, we used high resolution, digital photographs of animal imagery taken at the site during fieldwork in June 2015. Each photograph was processed by first opening it in ImageJ© and then initiating DStretch®. Simple keystrokes enabled the saturation, colour (Adj Col) and contrast to be quickly adjusted before passing the photograph through the software's pre-set colourspaces (Cycle), visually assessing the effectiveness of each. The most suitable colourspaces were then selected and modified for further analysis by, for instance, reducing background noise through the Colour Balance (CB) option, and amending the illumination via the Flat option. If the result was particularly effective, the entire process was saved using the Matrix feature for use on other images of the same detail, scene, or context. This not only reduced the time taken in selecting optimal colourspaces, it also ensured that details observed in one colourspace could be checked in others. If ineffective, the original photo could be accessed via the Reset option, after which other colour enhancements could be trialled utilising the same sequence.

The artwork at Beni Hassan is multi-coloured, occurring in various shades of red, brown, blue and green, as well as black and white; as such, a number of colourspaces had to be applied to ensure that the most detail could be extracted. We have found that the CRGB colour-space is especially good for red to brown paint, including outlines and original guidelines; LAB is useful for black paint; LDS enhances all colours but especially yellow; and YBK is best for green paint. Once the colour enhanced images were created in DStretch® and saved, further modifications and adjustments of contrast, sharpness and colour selection were made in Photoshop©, where necessary.

Most of the processed images retained sufficient clarity to allow subsequent tracing. To achieve this, the original RGB photograph, its auto-contrasted version, and its best DStretch® enhanced images were each placed in a separate layer in Adobe Illustrator©. Another layer was then created, upon which a line drawing of the image was made. While tracing, the different images were 'cycled' through, each illuminating particular details that were added to the drawing. Indistinct details in the original RGB photo were often sharper in one of the selected colour-enhanced layers, reducing the chance of misinterpreting elements or drawing them based on subjective analysis. Details could also be compared between different colour-enhanced images to ensure that they were not simply dirt, wall cracks, or other secondary elements. The resulting line drawings were consequently based on a highly objective evaluation of the painted imagery, ensuring a more accurate reproduction.

3. Results and discussion

We have found DStretch® to be very effective in adding extra details to otherwise clear images, revealing obscured images, and for resolving puzzling images, as the following examples illustrate.

3.1. Pigs

The Beni Hassan cemetery has yielded a number of animal images that are rarely encountered in Egyptian art (Osborn and Osbornová, 1998, 142–3). To date, the only known representation of pigs (*Sus scrofa*) from the Middle Kingdom period is a small herd found in the Eleventh Dynasty Beni Hassan tomb of Khety (no. 17) (Newberry, 1894, pl. xi). We can now report, however, that a second group has been identified in the contemporary tomb of Baqet III (no. 15), at the northern end of the west wall of the chapel. Newberry was unable to trace this section of the wall, but recent re-recording by our drafting team has shown that it displays an extensive marshland scene, similar to that found on the corresponding wall of the tomb of Khety, in which a series of papyrus thickets extend across the wall surface. The original

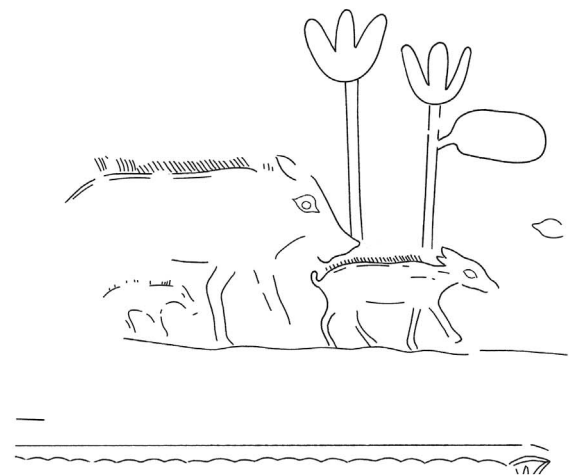
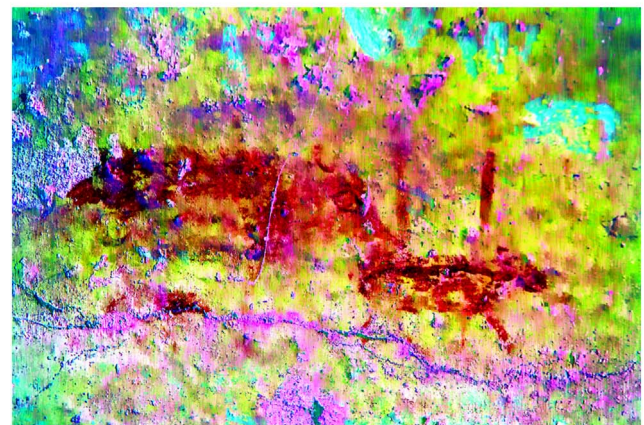


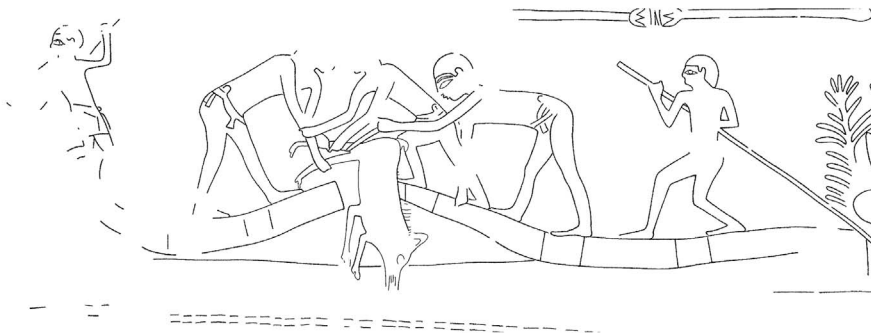
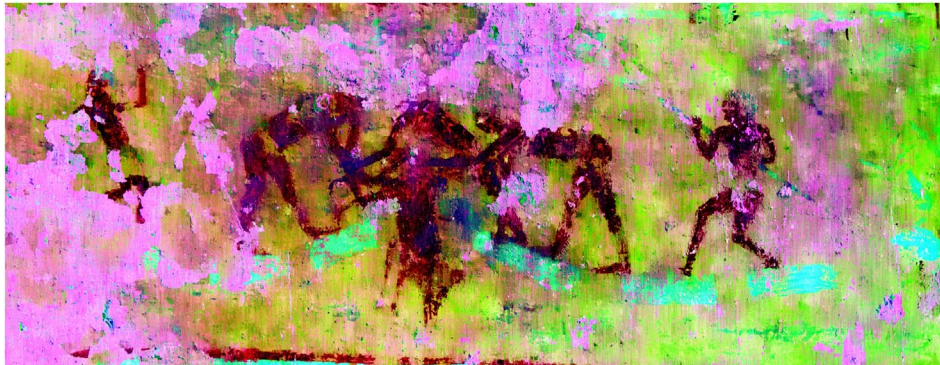
Fig. 1. Herd of pigs, tomb of Baqet III. DStretch® enhancement with CRGB matrix.

1:1 tracing of the scene made on site showed a juvenile pig that accompanies a large boar as they travel to the right (Evans, 2017). The animals, each painted reddish-brown, have large ears, large eyes, long snouts, and bristled backs, the latter two features confirming that they are swine (Fig. 1). When digital photographs of the scene were processed using DStretch®, however, the enhanced images showed the presence of a third animal – a piglet, standing under the large boar – which had hitherto been overlooked. The new animal was subsequently traced using Adobe Illustrator© and inserted into the scene (Fig. 1).

Similarly, on the same wall in the tomb of Baqet III, our drafting team traced a curious image of a reddish-brown animal suspended between two papyrus skiffs (Fig. 2). Three workmen grasp the creature's hind legs, holding it in such a way that its head is immersed in the water below. Its stocky body, cloven hooves, elongated snout, and upturned



Fig. 2. Pig overboard, tomb of Baqet III. DStretch® enhancement with CRGB matrix.



tail suggested the presence of yet another pig, despite the unique composition, but this is now confirmed following processing via DStretch®, which has revealed obvious bristles on its back (Fig. 2), diagnostic features that were previously invisible (Evans, 2017).

This highly unusual scene is echoed in the nearby tomb of Khety. At the northern end of the west wall of the chapel, two male bearers advance to the left towards a larger figure who wields a whip. The first of the smaller figures carries a grey, four-legged object upside-down on his shoulders, reaching up to hold it with both hands (Fig. 3). Few details can be seen in Newberry's diminutive line drawing, but processing of the original wall scene via DStretch® (Fig. 3) quickly revealed that the object is an animal, with legs extended and its head hanging down to be supported by the second bearer (Fig. 3). The image is poorly rendered or possibly unfinished, as one of the animal's hind legs erupts from the bearer's forehead. Nevertheless, although no bristles are apparent, the distinctive shape of the animal's snout combined with its cloven hooves seems to indicate that it is another representation of a pig, which, like that in the tomb of Baqet III, is inverted. The meaning of this somewhat humorous motif remains to be determined.

3.2. Bats

Elsewhere in the tomb of Khety, an indistinct, tapering block of yellow-brown pigment was noticed on a badly damaged section of the

northern wall (Fig. 4), while a hook-shaped sliver of paint in the same colour was observed nearby (Fig. 5). Subsequent processing of photographs by DStretch® revealed further details associated with each motif in the surrounding areas, confirming our suspicion that each represents a bat (Order Chiroptera), one with its wings outstretched (Fig. 4) and another with its wings folded (Fig. 5), very similar to known images of bats on the north wall of the tomb of Baqet III (Davies, 1949, pl. III; Newberry, 1894, pl. iv). The traced images of both bats (Figs. 4 and 5) can now be added to the very meagre records for these creatures in pharaonic art (see Audouit, 2016; Houlihan, 1986; Osborn and Osbornová, 1998; Vandier d'Abbadie, 1936–37).

3.3. Vulture

DStretch® has also illuminated the meaning of a curious image of a bird, again in the tomb of Khety (Fig. 6). The raptor-like creature is represented at the eastern end of the north wall, with its body and booted legs in profile and its large wings outstretched. The bird's feathers are rendered in red and bluish-green paint, with scalloping on the body and bands of colour separated by individual plumes on its unfurled wings. Its beak is short and sturdy. A spherical object dangles from its talons. Newberry originally described this motif as 'a conventionalized hawk carrying an egg(?) in its claws' (Newberry, 1894: 59). To our surprise, however, image enhancement (Fig. 6) quickly revealed



Fig. 3. Pig carried, tomb of Khety. DStretch® enhancement with YBL matrix and contrast.

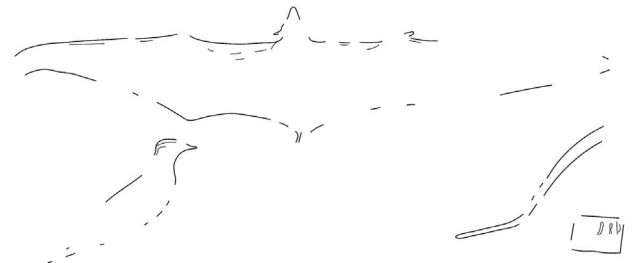
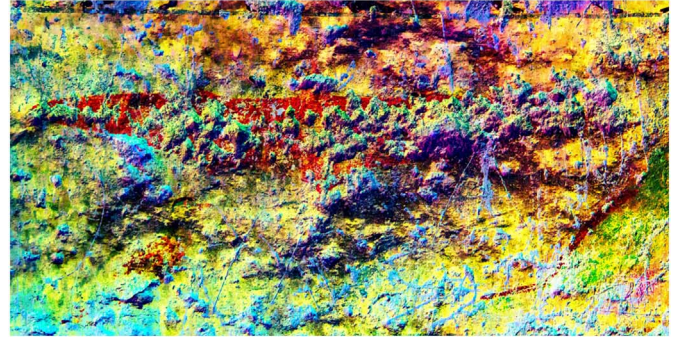
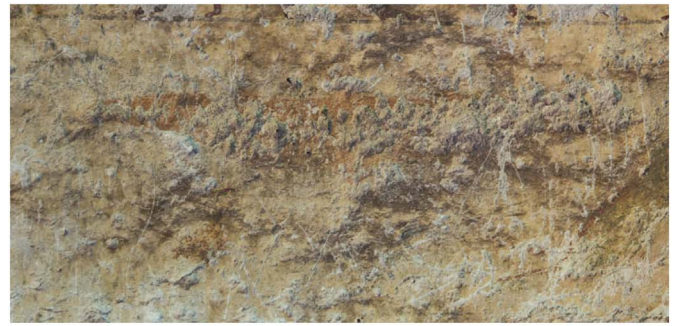
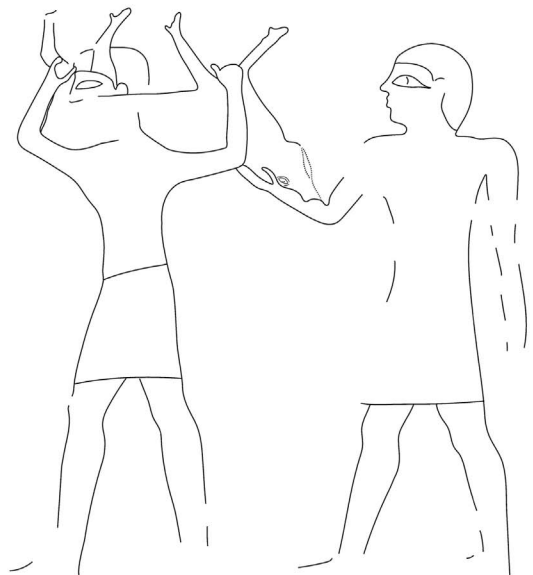


Fig. 4. Bat, outstretched wings, tomb of Khety. DStretch® enhancement with LDS matrix.



that the ‘hawk’ is in fact a vulture (either a Griffin vulture (*Gyps fulvus*) or a Lappet-faced vulture (*Aegypius tracheliotus*); Houlihan, 1986) and that the ‘egg’ appears to be the upper half of an *ankh*-sign (Fig. 6). The vulture’s distinctive neck is now clearly visible while a section previously thought to be part of the nape is seen to form part of the bird’s upper body. So too, the apparent egg reveals a point at its lower end, which rests upon a horizontal bar with flared extremities and marked with a series of diagonal lines (there is no clear evidence of the sign’s vertical post, however).

Representations of the vulture goddess, Nekhbet, hovering above the king while clasping a *shen*-ring in her talons, are well known from the Early Dynastic period onwards (Klop, 2008), however, the bird depicted in the tomb of Khety clearly holds an *ankh*-sign. The latter composition is attested intermittently. Identified examples include: falcons holding *ankh*-signs: Step Pyramid of Djoser, Third Dynasty, Saqqara (Friedman, 1995, fig. 2b); a vulture holding an *ankh*-sign(?): Sun Temple of Niuserre, Fifth Dynasty, Abu Ghurob (Borchardt, 1907, fig. 67); a falcon holding an *ankh*-sign: relief block from the reign of Userkaf, Fifth Dynasty, found at Lisht (Oppenheim, 1999, fig. 121) vultures holding *ankh*-signs: Gateway (Bubastite Portal) of Osorkon/ Shoshenq I, Karnak, Twenty-second Dynasty (The Epigraphic Survey, 1954, pl. 11B and possibly pl. 14); vultures holding *ankh*-signs: Gateway of the palace of King Apries, Memphis, Twenty-sixth Dynasty (Petrie, 1909, pls. 5–6); and vultures holding *ankh*-signs: Kiosk of Nectanebo, Temple of Isis, and Gate of Philadelphos, Philae, Ptolemaic

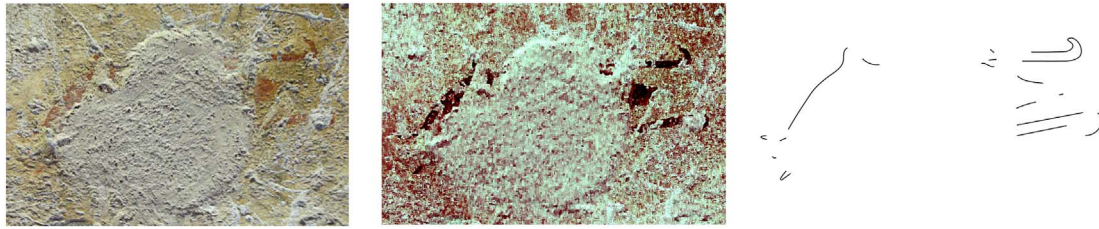


Fig. 5. Bat, folded wings, tomb of Khety. DStretch® enhancement with YRE matrix, and other filters.

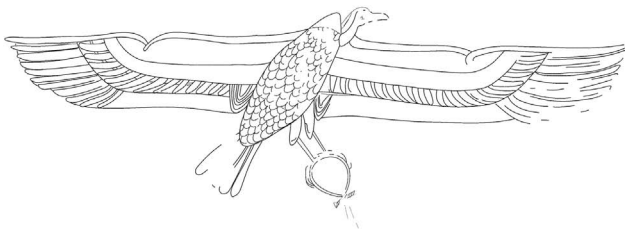


Fig. 6. Falcon grasping an ankh sign, tomb of Khety. DStretch® enhancement with LAB matrix, and other filters.

Period (Vassilika, 1989, 395, cat. V1–V2).

A brief survey has nevertheless indicated that the motif of a raptor with a single *ankh*-sign was more prevalent during the Middle Kingdom compared to other periods. For example, a falcon grasping an *ankh* can be seen hovering before the king on a First Intermediate Period relief from the *ka*-chapel of Nebhepetra Mentuhotep at Dendera (JE 46048, Cairo Museum) (Robins, 1997, fig. 87). A number of pillars in king Senusret I's White Chapel at Karnak display opposed images of Nekhbet as a vulture and Horus as a falcon, in which each holds a single *ankh*-

sign in their claws (Chevrier, 1943, fig. 3; Lacau and Chevrier, 1956, pls 13–16, 25, 28, 30–31, 40). A pectoral belonging to Mereret, daughter of Senusret III (JE 30875 = CG 52003), shows a vulture in face view dangling an *ankh*-sign from each foot to which *djed* columns have also been attached (Craig Patch, 2015, 113, fig. 66; see also Klop, 2008, 12–13). Curiously, representations of vultures with *ankh*-signs have also been reported on Syrian cylinder seals dated to the Middle Bronze Age (c. 1850–1620 BC) (see Teissier, 1996, 56 [37], 93–94 [176], 96 [179–180]). One, for example, has its wings outstretched while holding an *ankh* in each foot (AO 10.865, Louvre Museum) (Schaeffer-Forrer, 1983, 21, fig. e) and another is in profile while grasping a single *ankh* (Teissier, 1984, 528–9 [no. 514]).

We have yet to determine why such an unconventional motif was included in a private tomb (see Shonkwiler, 2012), but its now unambiguous identification is further testament to the success of DStretch®.

4. Conclusion

This brief summary has highlighted the value of DStretch® for the analysis of wall paintings at Beni Hassan, showing how it has provided new insights and improved the accuracy of our record of this remarkable site. It is an indispensable tool for both field and lab work, enabling painted details that are otherwise invisible to be viewed quickly on-site and elsewhere, and subsequently recorded. We therefore recommend that for the purposes of reaching a more complete and objective record of ancient Egyptian wall paintings similar to those found at Beni Hassan, the best method is to combine 1:1 epigraphic tracing or digital epigraphy with DStretch® enhanced photographs.

Acknowledgements

Funding for this work was provided by a Macquarie University Research Development Grant awarded to the first author – Beasts and Beliefs at Beni Hassan: Identifying New Religious Functions for Ancient Egyptian Tomb Art (2015–16).

References

- Audouit, C., 2016. La chauve-souris et ses usages en Égypte ancienne. *CdE* 91 (181), 14–40.
- Borchardt, L., 1907. Das Grabdenkmal des Königs Ne-user-re'. J.C. Hinrichs, Leipzig.
- Carter, H., Blackden, M.W., Brown, P., Buckman, P., 1900. Beni Hasan Part IV: Zoological and Other Details. Egypt Exploration Fund, London.
- Cassen, S., Lescop, L., Grimaud, V., Robin, G., 2014. Complementarity of acquisition techniques for the documentation of neolithic engravings: Lasergrammetric and photographic recording in Gavrinis Passage Tomb (Brittany, France). *JAS* 45, 126–140.
- Chevrier, H., 1943. Une chapelle de Sésostris Ier à Karnak. *CRAI* 87 (2), 221–234.
- Craig Patch, D., 2015. Excursus: considering Middle Kingdom pectorals. In: Oppenheim, A., Arnold, D., Arnold, D., Yamamoto, K. (Eds.), *Ancient Egypt Transformed: The Middle Kingdom*. Metropolitan Museum of Art, New York, pp. 112–114.
- Davies, N.M., 1949. Birds and bats at Beni Hasan. *JEA* 35, 13–20.
- Defrasne, C., 2014. Digital image enhancement for recording rupestrian engravings: applications to an alpine shelter. *JAS* 50, 31–38.
- Defrasne, C., Bailly, M., 2014. Les Oullas: an image bearing rockshelter on a neolithic alpine path? In: Besse, M. (Ed.), *Around the Petit-Chasseur Site in Sion (Valais, Switzerland) and New Approaches to the Bell Beaker Culture*. Proceedings of the International Conference held at Sion, Switzerland October 27th–30th, 2011.

- Archaeopress, Oxford, pp. 101–110.
- Der Manuelian, P., 1998. Digital epigraphy: an approach to streamlining Egyptological epigraphic method. *JARCE* 35, 97–113.
- Dodd, J., 2013. Petroglyphs as paintings: the application of digital image enhancement to the study of Årsand 1, Hordaland, Western Norway. *Adoranten* 2013, 116–124.
- Enmarch, R., 2015. Writing in the 'Mansion of Gold': texts from the Hatnub quarries. *EA* 47, 10–12.
- Epigraphic Survey, 1954. Reliefs and Inscriptions at Karnak 3. The Bubastite Portal (OIP 74). University of Chicago Press, Chicago.
- Evans, L., 2017. Pig overboard? An enigmatic tomb scene from Beni Hassan. In: Di Biase-Dyson, C., Donovan, L. (Eds.), *The Cultural Manifestations of Religious Experience. Studies in Honour of Boyo G. Ockinga (ÄAT 85)*. Ugarit Verlag, Münster, pp. 153–165.
- Friedman, F.D., 1995. The underground relief panels of king Djoser at the Step Pyramid Complex. *J. Am. Res. Cent. Egypt* 32, 1–42.
- Greene, H.A., Madden, D.J., 1987. Adult age differences in visual acuity, stereopsis, and contrast sensitivity. *Am. J. Optom. Physiol. Optic* 64 (10), 749–753.
- Griffith, F.L., 1896. Beni Hasan, Part III. Egypt Exploration Fund, London.
- Gunn, R.G., Douglas, L.C., Whear, R.L., 2014. 'Interpreting' polychrome paintings using DStretch. *Rock Art Res.* 31 (1), 1–4.
- Harman, J., 2005. Using decorrelation stretch to enhance rock art images, DStretch*. <http://www.dstretch.com/AlgorithmDescription.html>, Accessed date: 1 October 2017.
- Harman, J., 2014. A tale of two Cañadas: the most northerly great mural site yet discovered. *Proc. Soc. Calif. Arch.* 28, 206–218.
- Houlihan, P., 1986. The Birds of Ancient Egypt. Aris and Phillips, Warminster.
- Kanawati, N., Evans, L., 2014. Beni Hassan, I: The Tomb of Khnumhotep II (ACE Reports 36). Aris and Phillips, Oxford.
- Kanawati, N., Evans, L., 2016. Beni Hassan, III: The Tomb of Amenemhat (ACE Reports 40). Aris and Phillips, Oxford.
- Kanawati, N., Woods, A., 2010. Beni Hassan. Art and Daily Life in an Egyptian Province. Supreme Council of Antiquities, Cairo.
- Klop, D.J.O., 2008. Beneath the Raptor's Wings: The Avian Composition Grasping the Symbol for Eternity in Egypt. Stellenbosch University, Stellenbosch (Unpublished MPhil thesis).
- Lacau, P., Chevrier, H., 1956. Une chapelle de Sésostris Ier à Karnak. Planches. L'Institut Français d'Archéologie Orientale, Le Caire.
- Lahlil, S., Weidong, L., Xu, J.M., 2013. Crack patterns morphology of ancient Chinese wares. *The Old Potter's Almanack* 18 (1), 1–9.
- Le Quellec, J.-L., Harman, J., Defrasne, C., Duquesnoy, F., 2013. DStretch* et l'amélioration des images numériques: Applications à l'archéologie des images rupestres. *Les Cahiers de l'AARS* 16, 177–198.
- Le Quellec, J.-L., Duquesnoy, F., Defrasne, C., 2015. Digital image enhancement with DStretch*: is complexity always necessary for efficiency? *DAACH* 2, 55–67.
- Lincoln, B., 2011. Decorrelation stretch images, Beneath the Waves. https://www.beneaththewaves.net/Photography/Decorrelation_Stretch_Images.html, Accessed date: 1 October 2017.
- Miller, M.R., Thompson, M., 2015. Knife-wing imagery on El Paso polychrome: using DStretch to reveal obscured ceramic designs. *Pottery Southwest* 31 (3), 18–26.
- NASA News Release, 2004. <http://mars.nasa.gov/mer/gallery/press/opportunity/20040701a.html>, Accessed date: 1 March 2017.
- Newberry, P.E., 1893. Beni Hasan, Part I. Egypt Exploration Fund, London.
- Newberry, P.E., 1894. Beni Hasan, Part II. Egypt Exploration Fund, London.
- Oppenheim, A., 1999. Cat. 103. Cast of a block with running troops and an inscription with the names and titles of King Userkaf. In: Arnold, D., Ziegler, C., Allen, J.P. (Eds.), *Egyptian Art in the Age of the Pyramids*. Metropolitan Museum of Art, New York, pp. 318–319.
- Osborn, D., Osbornová, J., 1998. The Mammals of Ancient Egypt. Aris and Phillips, Warminster.
- Petrie, W.M.F., 1909. The Palace of Apries (Memphis II). B. Quaritch, London.
- Raykovska, M., Bevan, G., Vasilev, I., Tenekedjiev, V., 2016. An Application of Colour Decorrelation Stretching to Faded Frescoes in a Late Medieval Church, Poster Presented at the 36th Symposium on Byzantine and Post-Byzantine Art and Archaeology, Byzantine and Christian Museum, Athens, 20–22 May.
- Robins, G., 1997. The Art of Ancient Egypt. Harvard University Press, Cambridge, MA.
- Schaeffer-Forrer, C.F.-A., 1983. Corpus des cylindres-sceaux de Ras Shamra-Ugarit et d'Enkomi-Alasia, I. Editions Recherche sur les civilisations, Paris.
- Shedid, A.G., 1994. Die Felsgräber von Beni Hassan in Mittelägypten. Verlag Phillip von Zabern, Mainz am Rhein.
- Shepard, L., Wright, A., 2016. Using Non-invasive Technologies to Identify Multiple Paint Recipes on Hohokam Pottery, Poster Presented at the Southwest Symposium, Tucson, Arizona, 14–16 January.
- Shonkwiler, R., 2012. Sheltering wings: birds as symbols of protection in ancient Egypt. In: Baillet-LeSuer, R. (Ed.), *Between Heaven & Earth: Birds in Ancient Egypt (OIMP 35)*. Oriental Institute of the University of Chicago, Chicago, pp. 49–57.
- Soha, J.M., Schwartz, A.A., 1979. Multispectral histogram normalization contrast enhancement. In: *Proceedings of the 5th Canadian Symposium on Remote Sensing*, Victoria, British Columbia, Canada, August 28–31, 1978. Canadian Aeronautics and Space Institute, Ottawa, pp. 86–93.
- Tan, H.T., Sokrihy, I., Than, H., Chan, K., 2014. The hidden paintings of Angkor Wat. *Antiquity* 88, 549–565.
- Teissier, B., 1984. Ancient Near Eastern Cylinder Seals From the Marcopoli Collection. University of California, Berkeley.
- Teissier, B., 1996. Egyptian Iconography on Syro-Palestinian Cylinder Seals of the Middle Bronze Age (OBO 11). University Press Fribourg, Fribourg.
- Tomášková, S., 2015. Digital technologies in context: prehistoric engravings in Northern Cape, South Africa. *DAACH* 2, 222–232.
- Vandier d'Abbadie, J., 1936–37. A propos d'une chauve-souris sur un ostracon du musée du Caire. *BIFAO* 36, 117–123.
- Vassilika, E., 1989. Ptolemaic Philae (OLA 34). Peeters, Leuven.
- Vertés, K., 2014. Digital Epigraphy. Epigraphic Survey at the Oriental Institute of the University of Chicago, Chicago.
- Witkowski, P., 2015. Reflectance transformation imaging. *EA* 47, 9.
- Witkowski, P., Chyla, J.M., Ejsmond, W., 2016. Combination of RTI and decorrelation: an application to the examination of badly preserved rock inscriptions and rock art at Gebelein (Egypt). In: Campana, S., Scopigno, R., Carpentiero, G. (Eds.), *CAA2015. Keep the Revolution Going, Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*. Archaeopress, Oxford, pp. 939–944.