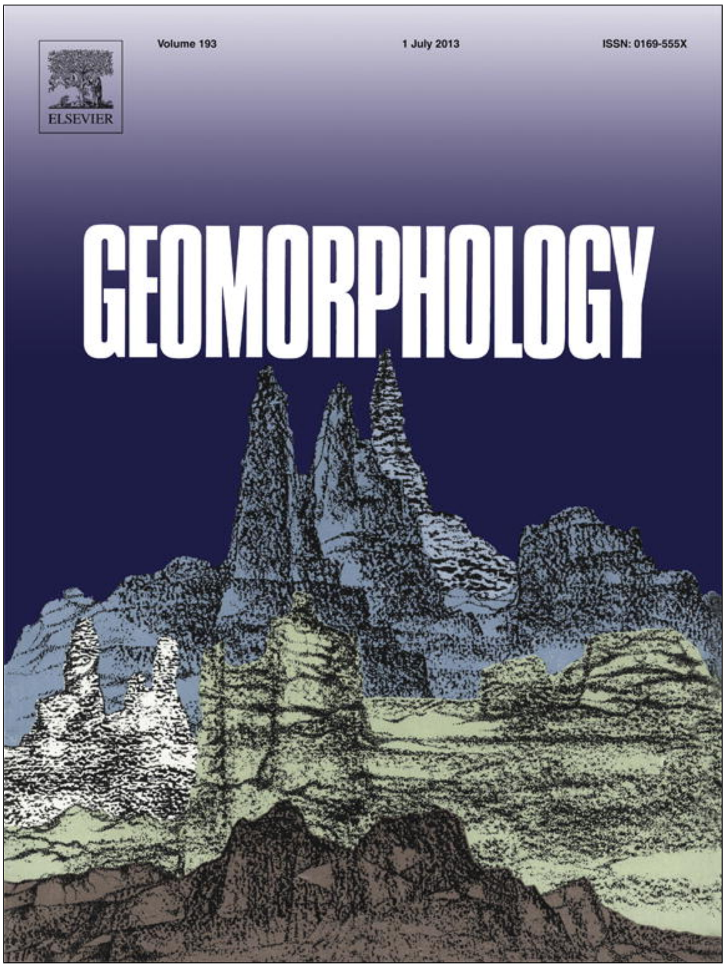
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Gravity tectonics of topographic ridges: Halokinesis and gravitational spreading in the western Ogaden, Ethiopia

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ABSTRACT

The Cenozoic history of the western Ogaden region of Ethiopia, between the Ethiopian rift and the South Afar margin, is marked by uplift and incision of the Ogaden plateau down to the Gorrahei Formation, an upper Cretaceous evaporite formation. Debuttressing of this and the overlying sedimentary formations resulted in widespread and spectacular gravitational spreading landforms over a minimum surface area of 15,000 km^2, most of which remains unstudied. After clearing up some misconceptions about the surface geology of the study area, the Kebenawa Ridge in the Audo Range, observations are reported that point to a tectonic style controlled by halokinesis and subsequently, gravitational spreading. The role of diapirism and karstification in the observed halokinesis is discussed, as well as the influence of halokinesis on gravitational spreading. Spreading is in part akin to sackung, in that ridge deformation features include a crestal graben and basal ridge topography extrusion, and deformation was triggered by lateral ridge debuttressing. Ridge spreading also presents analogy with gravitational spreading of the Canyonlands grabens in the Needles District, Canyonlands National Park, Utah. The scale and the mechanisms are found to be basically similar, but two differences are noted. First, incision by the drainage network in response to plateau uplift in Ethiopia has debuttressed the topography along two parallel rivers, instead of a single river (the Colorado River) in Utah. Secondly, incision proceeded to the base of the evaporite layer in the Ogaden, whereas incision has not exceeded the top of the evaporite layer in Utah. These differences may have influenced the details of the spreading mechanisms in ways that remain to be investigated. Overall, in Ethiopia, association of halokinesis and a transitional mode of gravitational spreading at the interface between narrow ridge spreading (sackung) and plateau spreading (Canyonlands-type), illustrates a fascinating and unusual ridge evolution style.

1. Introduction

Topographic spreading occurs at all scales, including high orogens and plateaus such as the Andes and Tibet (e.g., Froidevaux and Ricard, 1987; Mercier, 1987), volcanic edifices (e.g., Borgia et al., 2000; Van Wyk de Vries et al., 2001), low elevation plateaus such as the Canyonlands grabens in the Needles District, Utah (e.g., McGill and Stromquist, 1979; Trudgill and Cartwright, 1994), and topographic ridges, in which case gravitational spreading produces sackung features (e.g., Hippolyte et al., 2006; Jarman, 2006). This paper reports a gravitationally spreading ridge in southeast Ethiopia for which sackung has been influenced by the presence of a ductile layer at depth. Development of sackung features by flow of a basal ductile layer has been popularised by interpretations of three examples in Colorado in a well-known article by Radbrush-Hall et al. (1976), but more recent studies indicate that this mechanism is marginal at a global scale. Most deciphered sackung examples on Earth do not show such causal relationships, and the massively dominant factor for sackung to operate is glacial valley buttressing followed by postglacial debuttressing and/or uplift (Mège and Bourgeois, 2011, who also provide a review of alternative geologic contexts). The example reported here is therefore unusual; it is, however, distinct from the Colorado examples analysed by Radbrush-Hall et al. (1976) in that (1) sackung in Colorado is postglacial, in contrast to the study area; and (2) the ductile level is made of evaporites in southeast Ethiopia, whereas it is made of shale in Colorado. Because of the presence of the evaporite level, halokinesis could take place prior to sackung in southeast Ethiopia; therefore, the finite deformation is more complex than in common sackung cases. The processes involved in ridge spreading in the studied example present similarities to the processes involved in the triggering and evolution of the "gravity syncline" studied by Carena et al. (2000) in the northern Apennines, and also with spreading of the Canyonlands grabens of the

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Needles district, Utah (e.g., Moore and Schultz, 1999), a comparison with which is provided at the end of this article.

2. Kebenawa ridge: geological framework

The Kebenawa ridge is part of the northern Audo Range (Figs. 1 and 2), a series of mesas in western Ogaden separated by the river Shebele and its tributaries that had never been studied before. A stratigraphic framework and a geologic map of the Kebenawa ridge (Figs. 3 and 4) have been established from (1) field data in the Kebenawa ridge collected in 2006, and along a new road between Imi and El Kere in 2005, (2) the known regional and local stratigraphy (Elwerath, 1960, 1965, 1967; Bauduin et al., 1972; Purcell, 1979; Bosellini, 1989), (3) the relevant 1:50,000 topographic map (Ethiopian Mapping Authority, 2001), (4) SRTM (Farr et al., 2007) and ASTER digital elevation models, and (5) satellite imagery including the Geocover 1990 Landsat TM mosaic, ETM+ images made available by the Global Land Cover Facility, ASTER visible and infrared coverage, and ALOS/Palsar radar imagery (band L). Interpretations have been eventually refined, when necessary, using the Spot image coverage made available through Google Earth ©.

2.1. Stratigraphy

Extrapolating from surrounding areas known in greater details, the basement in the study area is made of peneplained Archean to Panafrican rocks. It might have been disrupted by the Karoo rift system which developed from the Late Paleozoic to Jurassic and fragmented the Gondwana during the Jurassic–Cretaceous (Bosellini, 1989). Pre-rift Adigrat fluviatile sandstone deposition was followed by a basin sequence starting with the transgressive formation of Hamanlei, followed by the Uarandab and Gabredarre formations, whose top is assigned to the Tithonian (Purcell, 1979; Bosellini, 1989).

The Gabredarre Formation is followed by the thick evaporitic Gorrahei Formation (Neocomian), the base of which is made of a peculiarly resistant carbonate layer (Fig. 4). The carbonates are being incised by the Shebele river, and form the stratigraphic and topographic base level of the Audo mesas. They crop out in places around the Kebenawa ridge, where it is observed to be horizontal, but it does not crop out within the ridge. The evaporites, mainly gypsum (Fig. 5a), are overlain by the transgressive upper Aptian–Albian Mustahil carbonates (Fig. 5d), and the Paleocene Jessoma sandstones (Fig. 6). The Mustahil Formation is occasionally brecciated with angular carbonate fragments. The Jessoma Formation is observed to be unconformable in most settings in the Ogaden and Somalia (e.g., Bosellini, 1989), but this unconformity could not be demonstrated in the Kebenawa ridge. In the Audo Range, the Mustahil and Jessoma formations constitute a resistant cap that has protected the evaporitic formation from rapid erosion by the Shebele river tributaries. An oligomictic conglomerate (Fig. 5e,f), in which carbonates (grainstone, dolostone, and calcrete), are dominant, gypsum is frequent, sandstone is occasional, and basalt is rare, covers some of the ridge slopes. It has also been observed at the summit of the ridge at the top of the Mustahil and the Jessoma formations (Fig. 5f).

Unrecognized on the earliest geological maps of Ethiopia, where it appears as Jurassic ("Antalo") limestone (Dainelli, 1943; Mohr, 1963), the Jessoma Formation had been correctly identified on the first official edition of the geological map of Ethiopia (Kazmin, 1972) and a hydrogeological survey of the Shebele drainage basin by ORSTOM (Bauduin et al., 1972). Probably because the rocks had been mapped as volcanics of unknown age by Merla et al. (1973), the geological map of Ogaden by BEICIP (1985) reported them as either the Jessoma sandstone or volcanics, and they have been identified as volcanics of

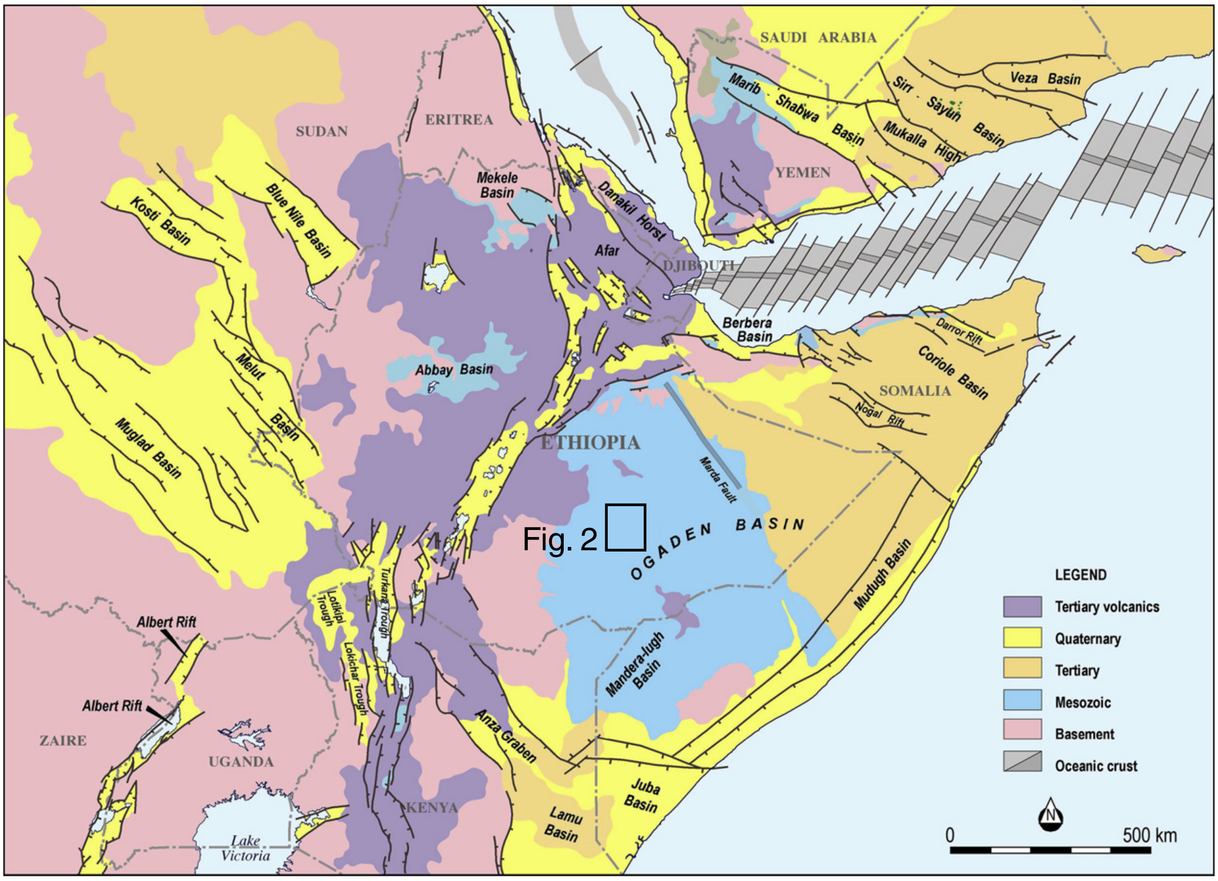

Fig. 1. Geologic map of the African Horn (by courtesy of P.G. Purcell) and location of the study area.

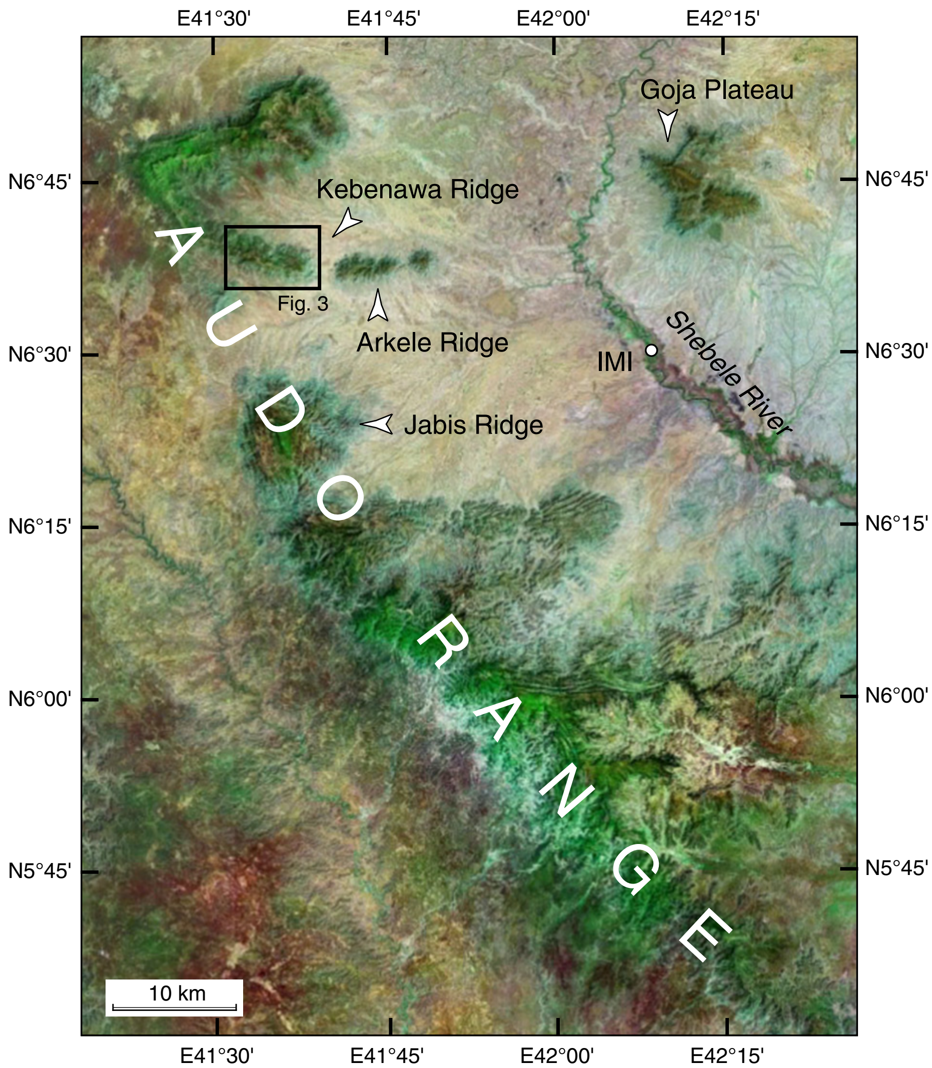

Fig. 2. Location of the Audo Range, the Kebenawa Ridge, and other places mentioned in the text.

Eocene age in the second edition of the geological map of Ethiopia (Tefera et al., 1996). Our field work has revealed that the sedimentary Jessoma Formation occurs on all the Audo range mesas, and all the Eocene volcanics displayed on the second geological map of Ethiopia should be replaced by the sedimentary Jessoma Formation.

2.2. Post-depositional events

Jessoma times correspond to the onset of a regression throughout the Ogaden and Somalia. Meandering basaltic flows fossilizing paleo-river beds throughout the Ogaden and dated upper Oligocene (Mège et al., 2010) indicate that this drainage network was already operating in the Ogaden during the Oligocene. The Jessoma depositional period was consequently followed by a period of incision of the western Ogaden topography, which is still at work nowadays, where the Shebele river tributaries are observed to have eroded the Audo Range down to the base of the Gorrahei Formation. The observed conglomerate is polygenetic, with small fragments cemented within rounded cobbles (Fig. 5f). This suggests at least two distinct episodes of transportation. Identification of the conglomerate on the Mustahil Formation at the summit of the ridge implies early ridge fluvial erosion. Evidence of mass movements is abundant on slopes, with frequent olistolites and debris avalanche deposits (Fig. 5d–f).

The origin and timing of the Ogaden uplift is poorly constrained; however, from the regional context, potential uplift causes include: (1) the thermal effect and magmatic underplating associated with the impingement of the Ethiopian plume on the base of the lithosphere during the Oligocene (Pik et al., 2003). The orientation of Oligocene lava flows in the Ogaden supports this interpretation (Mège et al., 2010); (2) rift shouldering associated with the opening of the Gulf of Aden, also during the Oligocene (Hughes et al., 1991); and (3) northward propagation of the East-African rift from Kenya to Ethiopia (Ebinger et al., 2000; Wolfenden et al., 2004), producing rift shoulder uplift since 20 Ma (Pik et al., 2008).

3. Deformation of the Kebenawa ridge

The Kebenawa ridge can be subdivided into seven almost symmetric zones that parallel the ridge trend, two Mustahil–Jessoma plateau zones surrounded by unstable piedmont zones dominantly of Gorrahei evaporites in which fallen Mustahil and Jessoma blocks are common, and a central graben (Figs. 3 and 7). Geologic mapping of the northern half of the ridge was conducted using satellite imagery and topographic data with the help of field surveys in the southern part of the ridge. Each of the formations has its own deformation style and we treat them separately.

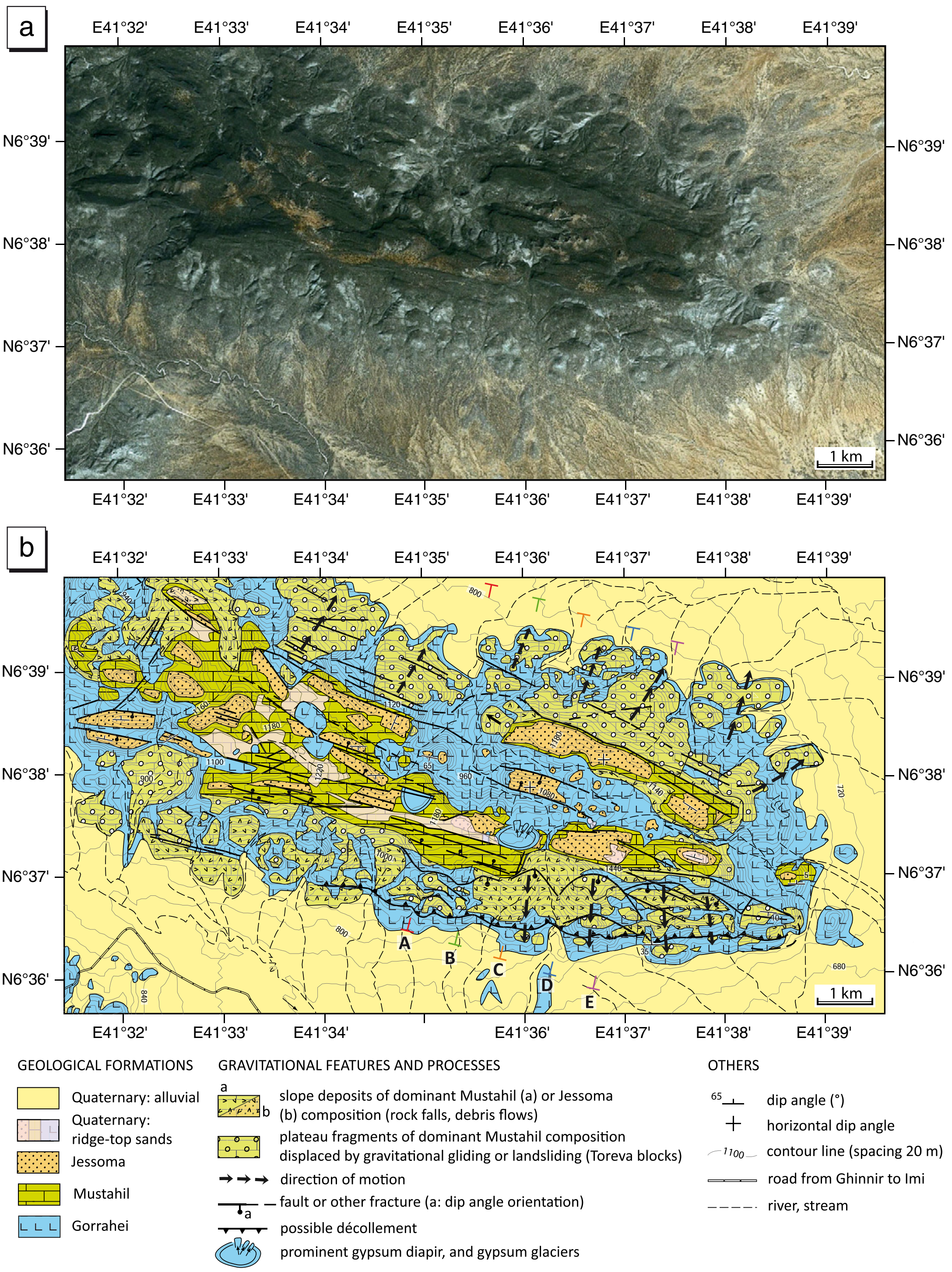

Fig. 3. Spot image (a) and geologic map (b) of the Kebenawa Ridge. Contour interval is 20 m.

3.1. The Gorrahei Formation

Two types of deformations are observed in the Gorrahei Formation. Circular and ovoid structures piercing the Mustahil and Jessoma formations are interpreted as possible diapirs. Two of them are prominent and mapped in Fig. 3. One of them displays tongues similar to salt glaciers (e.g., Ala, 1974) and are interpreted as gypsum glaciers. Folding and fracturing within the evaporites is observed outside the plateau areas shown in Fig. 7. The fractures are filled in by satin spar (Warren, 2006). The fractures are widespread within the ridge, but absent on the piedmont. They are observed to postdate all the other tectonic structures. The ridge can be longitudinally subdivided into three domains based on the dip angle of the evaporite stratification planes (Fig. 8). In the eastern part of the ridge, the gypsum is inward-dipping, as illustrated in Fig. 5a. Because of gypsum recrystallization (Schreiber and Helman, 2005) and limited outcrop continuity, field observations could not succeed in unambiguously determining whether inward-dipping results from downward ridge flexure, probably under its own load, or to slip along fracture planes following stratification planes. In spite of the absence of kinematic indicators, the latter interpretation is favoured because of the pervasive oblique jointing connecting the stratification planes suggestive of fracture displacement. The sense of displacement, however, could not be determined. The

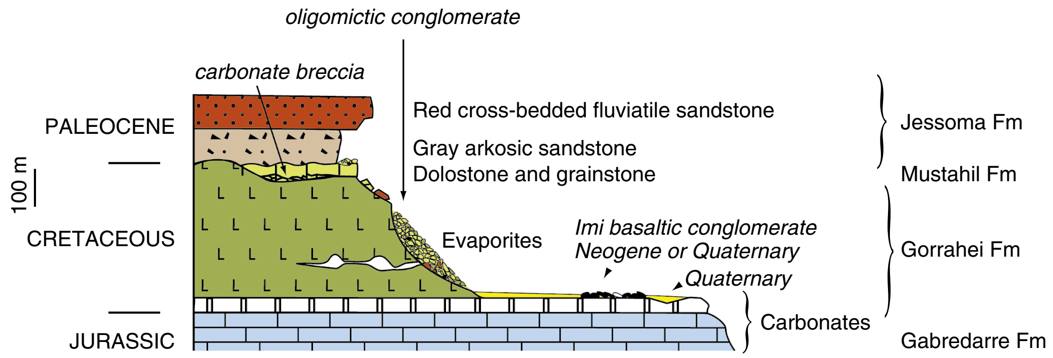

Fig. 4. Stratigraphy of the Kebenawa ridge and neighbouring areas from field observations by the authors. The Mustahil Formation denotes a lagoonal environment within a carbonate platform; at the Kebenawa Ridge it contains dissolved debris of bivalves, echinoderms, dasycladales, and rudists to which a Barremian–Albian age can be assigned. This lithology is similar to the second half of the Mustahil shoaling-up parasequence identified by Russo et al. (1991). A basalt cobble from the Imi basaltic conglomerate has been dated 14.4 ± 0.1 Ma. Carbonate incision on the lower right symbolises the activity the Shebele river and tributaries. The cave system is drawn at its approximate height of observation in the Gorrahei Formation.

central domain is characterised by shallow dip angles usually to the west. Dip angles in the western domain are parallel to the ridge topographic axis. It may be inferred from the observations in the three domains that some, but not all, of the measured stratigraphic planes, may have rotated from horizontal to the present dip in response to gravity forces associated with a topography oriented similarly to that of the present-day ridge.

The orientation of the satin spar veins (Fig. 5b,c) is not correlated with the attitude of the gypsum layers. The orientation of the fibres that crystallised in the fractures (dots in Fig. 8b) can be used to determine the orientation of the direction of dilation and even the direction of the minimum principal stress (Phillips, 1974; Cosgrove, 1995). The crystallization direction, N019°E ± 12° for 95% of the dataset, is perpendicular to the ridge (Fig. 8c). Tension was, therefore, perpendicular to the topographic gradient and suggests that fracturing and gypsum infilling occurred in response to gravity forces operating when the ridge topography had already developed, with geometry close to its present form. Fracture orientation is not always perpendicular to the fibres and indicates a significant component of shearing in addition to opening for the fractures displaying oblique fibre crystallization (Phillips, 1974).

3.2. The Mustahil Formation

The Mustahil Formation occurs as a subhorizontal cap overlying the Gorrahei Formation. The Mustahil breccia facies is observed either *in situ* or in olistolites resedimented within the Gorrahei evaporites on the ridge slopes. Gypsum olistolites are also observed to be mixed with the breccias (Fig. 5d). It is, thus, appropriate to describe the contact zone between the two formations as a mixed zone in which fragments of various sizes from both formations coexist.

3.3. The Jessoma Formation

Most Jessoma Formation outcrops form the top of horizontal or gently tilted plateaus and overlie the Mustahil Formation. A number of peaks near the centre of the ridge are made up of blocks of grey arkosic sandstone or the red sandstone directly overlying the Gorrahei Formation. These blocks are estimated to range in volume from 10 to 500,000 m^3. Bedding in them may be horizontal or inclined in any direction; the maximum dip angle measured in the field study area is 65°.

The Jessoma Formation displays two major normal fault scarps parallel to the ridge trend, located on both sides of the central plateau. The southern fault dips north, and could be accessed in the field, and the northern fault, dipping south, is inferred from the ridge topography and geomorphological symmetry. The southern normal fault juxtaposes the Jessoma sandstone and the Gorrahei gypsum. Because of the contrasting erosional resistance of the units, the fault plane is observed in the sandstone and makes a remarkable overhanging topography (Fig. 6). The master fault is associated with secondary antithetic faults. The normal sense of displacement is inferred from slickensides. Locally, curved striae suggest that some blocks, located between the master and the associated faults, have rotated (Fig. 6d). The vertical displacement along the master fault cannot be accurately determined because of the absence of stratigraphic markers. Using a conservative approach and hypothesizing that evaporite deformation by halokinesis along the fault played a negligible role, the minimum normal fault vertical throw required to offset the Mustahil Formation gives a minimum displacement of 50–100 m. The maximum vertical throw corresponds to the cumulative thickness of the Gorrahei, Mustahil, and Jessoma formations (300–550 m) minus the height of the present fault scarp and the locally observed Gorrahei Formation thickness (200–220 m), corrected for the evaporite diapiric rise along the normal fault, which is hard to determine. Simply, provided that the hypothesis (which geomorphologically appears reasonable) that the present elevation of the plateau surfaces (Fig. 7) corresponds to the stratigraphic level that crops out at the top of the central graben, and the vertical throw is ~100 m (Fig. 3b).

The Mustahil and Jessoma formations in the plateau areas are also fractured to large blocks oriented parallel to the ridge trend (Fig. 3). In most cases, the poor outcrops did not permit dip angle measurement. Geologic mapping from satellite imagery suggests that many large fractures are nearly vertical. The faults located on the ridge piedmonts commonly dip outward.

In the southern plateau, and arguably the northern plateau, the Gorrahei Formation does not appear to be internally deformed; the evaporite layers are observed to be conformably overlain by the Mustahil and Jessoma formations.

4. Origin of the observed deformation

To synthesize the observations reported above, the observed structures include (1) Gorrahei evaporite diapirs, intra-formational tilting and folding, and probable bed-parallel, inward-dipping shearing along the outer part of the ridge; (2) gypsum fracturing and satin spar crystallization, (3) brecciation of the Mustahil Formation, with rare inclusions of basalt fragments, (4) resedimentation of Mustahil olistolites within the Gorrahei evaporite on the ridge outer slopes, (5) normal faulting of the Jessoma Formation, especially through development of a ridge crestal graben, and other faults mostly sub-parallel to the ridge trend; and (6) Jessoma sandstone resedimentation on top of the Gorrahei

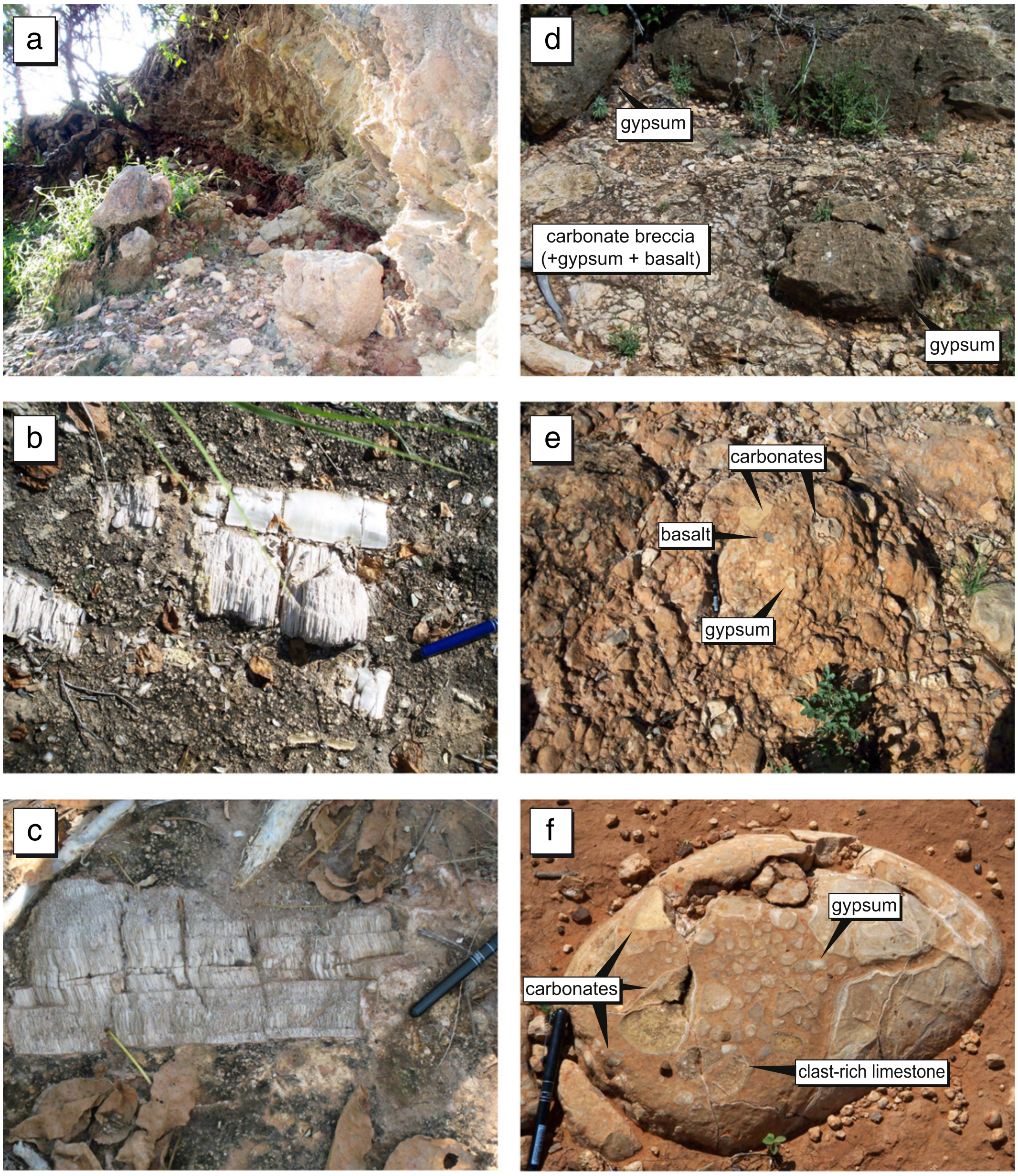

Fig. 5. Field photographs: Gorrahei Formation (a–c) and Mustahil Formation (d–f). (a) Anti-slope tilting and intense deformation of gypsum layers at the southern edge of the Kebenawa ridge (located in the southwestern corner of the eastern domain box in Fig. 8). North is to the right. Because of dissolution–recrystallization cycles, no kinematic indicators could be found to be associated to this deformation. (b) and (c) Gypsum fibre-filled fractures. In (c) two stages of displacement at least are observed along the central fracture. Fibre orientation gives the orientation of the minimum principal stress trajectory, which in this case is approximately normal to the fracture margins, denoting roughly pure (mode-I) opening. (d) Typical carbonate breccia outcrop (Mustahil Formation) containing small gypsum olistolites from the underlying Gorrahei Formation. Brecciation and the presence of these olistolites are suggestive of gypsum diapirism or karstification. (e) Oligomictic conglomerate, here in an avalanche debris on the ridge slope, contains carbonates, gypsum, sandstone (not seen in this photograph), and scarce basalt fragments. (f) Breccia boulder and rounded breccia fragments, indicating two episodes of transportation separated by a period of fragment cementation.

evaporites. The region has not undergone any orogeny since the Precambrian, nor rifting contemporaneous or subsequent to the deposition of the Kebenawa ridge sediments. As a consequence, we advocate that two local deformation mechanisms, halokinesis and gravitational spreading, may explain the observed deformations.

4.1. Halokinesis

Halokinesis refers to salt tectonics; here this term is used in the broader sense of evaporite tectonics. Evaporite deformation may result from either diapirism or evaporite dissolution and karstification, or a combination of both.

4.1.1. Diapirism

Gypsum diapirism has been debated because unlike halite, which is buoyant in other rocks, the density of gypsum is on average significantly higher than the density of halite (e.g., Telford et al., 1976). Nevertheless, gypsum diapirism has been documented in various settings (the Coahuila Marginal Fold province in northeastern Mexico — Weidie and Martinez, 1970; the Provence Alpine foreland in France — Dardeau and de Graciansky, 1990; the Zechstein Basin — Williams-Stroud and Paul, 1997; and the Messinian gypsum of the Mediterranean Sea — Dela Pierre et al., 2007). The observations reported in Fig. 3 indicate that the conditions for gypsum diapirism (Price and Cosgrove, 1990, pp. 90–96; Edgell, 1996) were met in the Gorrahei Formation too. Diapirism

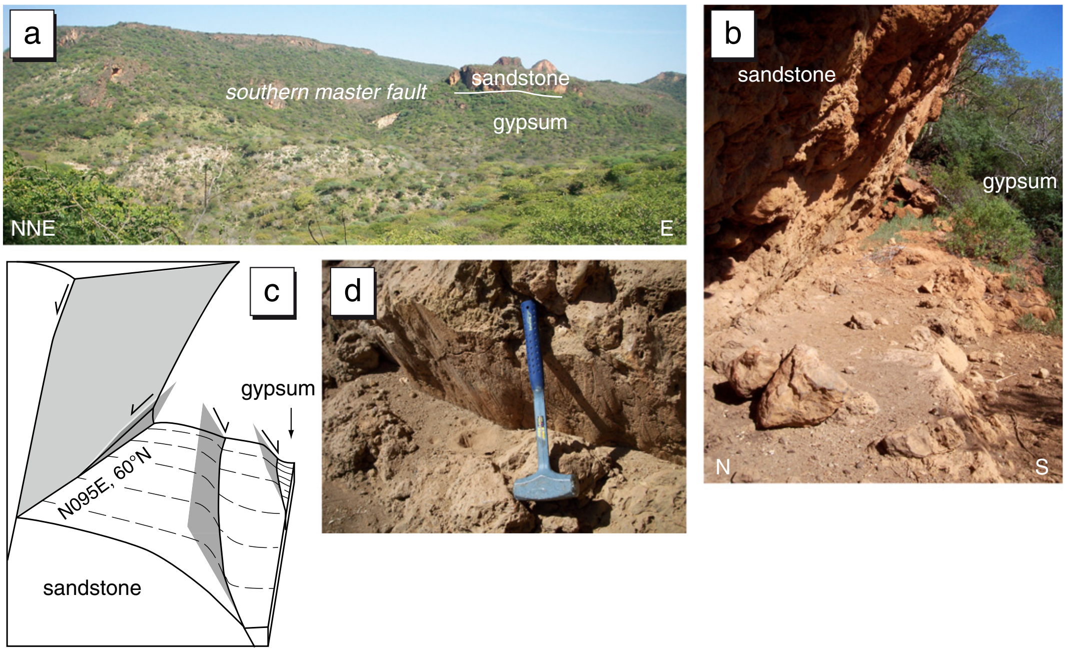

Fig. 6. Jessoma Formation. (a) View of the southern master normal fault from the SW. (b) Close view (looking East) of the southern master fault and associated faults. (c) Interpretation of b. (d) Detailed view of the southern master fault plane, showing fluting, striae indicating vertical displacement, and striae indicative of block rotation within the fault zone.

initiation requires a trigger, typically fracturing (even limited) of the overlying rock (Vendeville and Jackson, 1992). Diapirism is made easier for thick evaporite sequences, increases with evaporite purity (which also influences evaporite strength; Bell, 1994), and also depends on moisture content and temperature conditions. The two latter influence diapirism in a complicated way: on the one hand, high temperature transforms gypsum to anhydrite, a mineral of density higher than the density of many other sedimentary rocks, which significantly decreases (or suppresses) evaporite buoyancy. On the other hand, if gypsum is associated with halite, the released water enhances evaporite creep, and may also lubricate the existing fracture planes, which enhances diapirism and may even drive partly dehydrated gypsum upwards. Water percolation through anhydrite readily transforms anhydrite back to gypsum, which was suggested to trigger gypsum diapirism even at surface (Hoyos et al., 1996).

Diapirism generates upwarping of the evaporite roof and results in gravity gliding of the overlying units and aberrant stratigraphic superpositions (e.g., Vendeville and Jackson, 1992) that would appropriately explain the oblique resedimentation of the Jessoma blocks at the top of the Gorrahei gypsum in the absence of nappe tectonics. Diapirism is also appropriate to explain brecciation of the overlying Mustahil carbonates. Observation of carbonate breccias on top of an

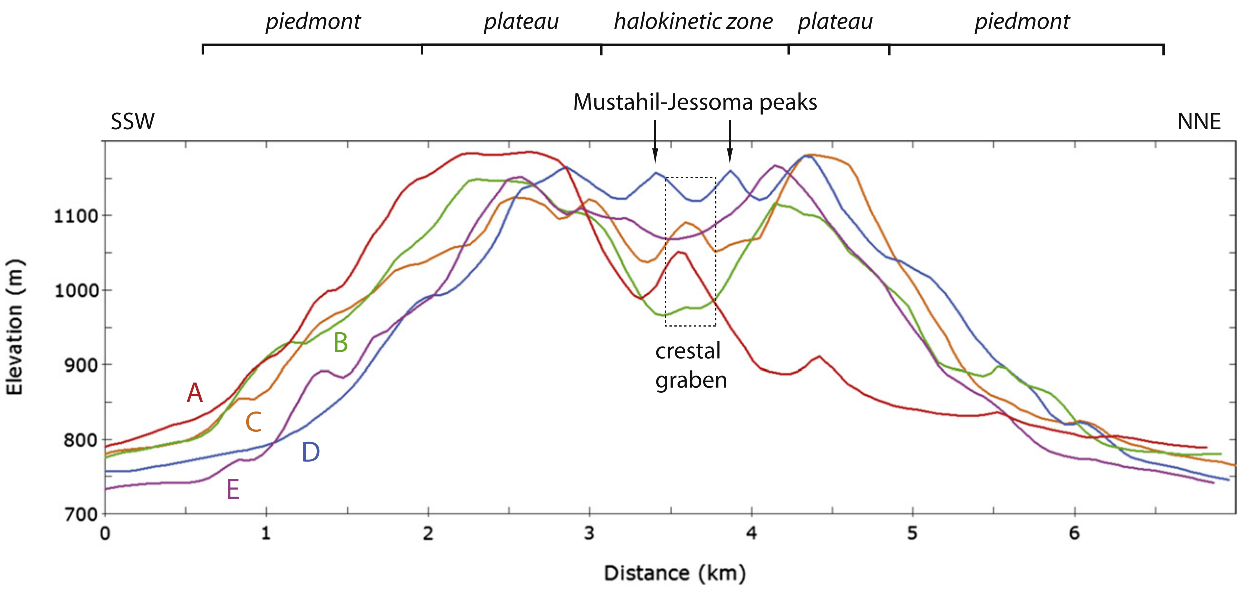

Fig. 7. Topographic cross-sections obtained from the SRTM-3 dataset (pixel spacing ~86 m). Location in Fig. 3b. Vertical exaggeration is ×5. Profile thickness increases from West to East. The salient topographic features are interpreted. The Mustahil and Jessoma peaks were displaced by diapirism of the underlying gypsum. From measurements (not shown) of SRTM topography using a profile along the Shebele river 40 km east of the Kebenawa ridge, the relative vertical accuracy of the SRTM dataset in the study area is ±2.5 m for most data points, in agreement with theoretical computations (Farr et al., 2007), with a few pixel clusters of slightly lower accuracy (±6 m).

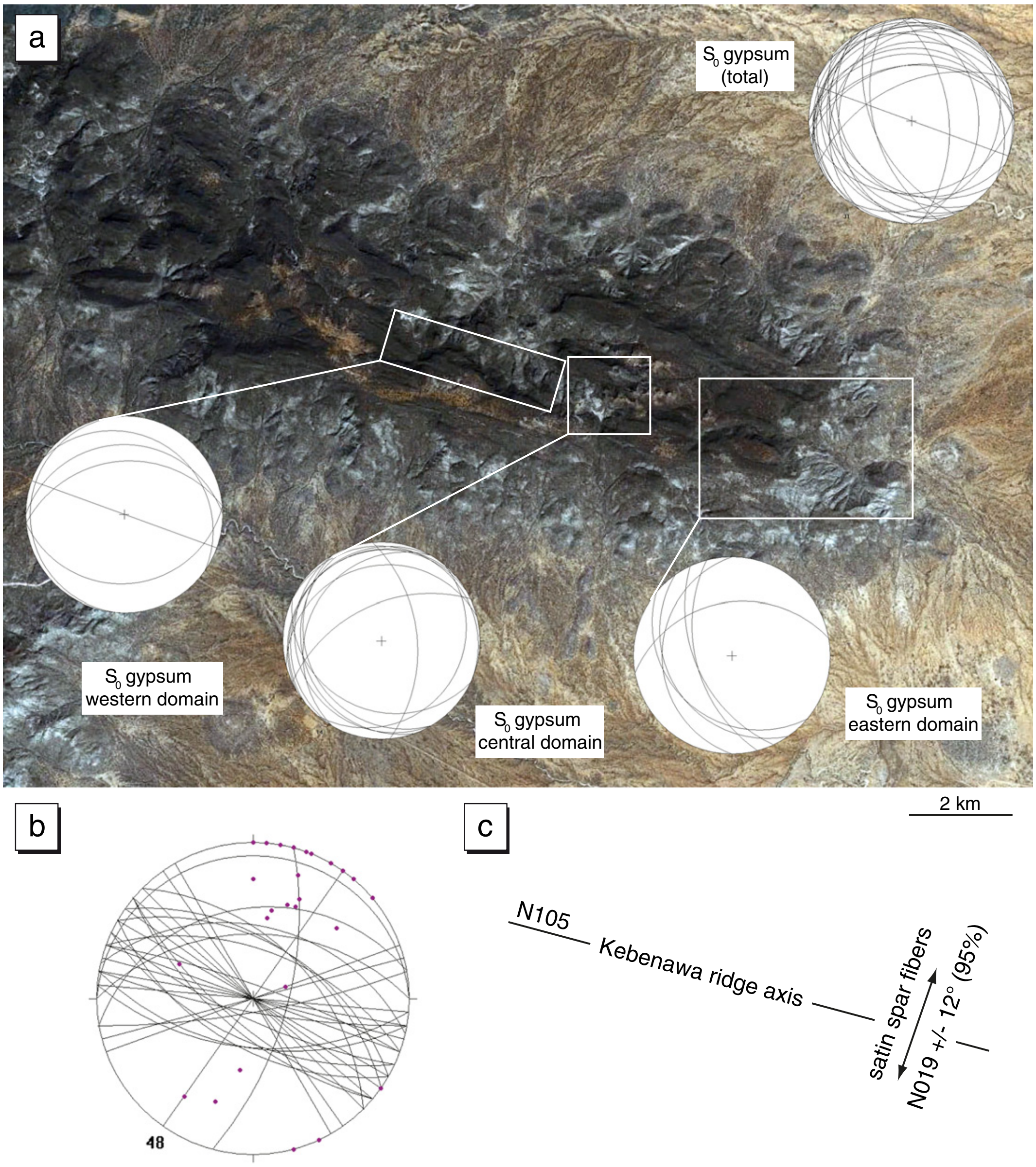

Fig. 8. Analysis of structural patterns in the Gorrahei evaporite formation. (a) Stratification planes (S_0) in areas where the overlying sedimentary cover has been eroded (projection on lower hemisphere). On the eastern domain, dip angles are uphill-facing; in the central domain, there is no preferred dip orientation, maybe resulting from diapirism. The gypsum usually dips horizontally or is gently tilted in areas where it is covered by the Mustahil Formation. (b) Orientation of fracture planes (lines) and direction of crystallization of gypsum fibres (satin spar) in these fractures (dots). (c) Diagram showing fibres perpendicular to the topographic axis.

evaporite formation is commonly interpreted as a consequence of fragmentation of roof rocks and collapse accompanying the diapiric rise of the underlying gypsum (e.g., Speed, 1975; Williams-Stroud and Paul, 1997; Dela Pierre et al., 2007). Although diagnostic diapiric structures were sought for in the field, because of the vegetation cover, too few observations preventing that goal from being achieved. Observations made in several places of gypsum, at elevations where the Mustahil or Jessoma formations are commonly observed, indicates either diapirism or normal faulting.

4.1.2. Karstification

Gypsum dissolution and karstification is a complementary or alternative process that may also explain Mustahil carbonate brecciation (Johnson, 1997; Warren, 1997; Clark et al., 1999), and also the observed unconformity between the Gorrahei evaporites and the Jessoma Formation. The observations in the Iberian Range of Spain, reported by Gutiérrez (1996), present similarities with the observed displacement of the Jessoma blocks at the Kebenawa ridge.

4.1.3. Pros and cons

Diapirism and karstification may contribute to the observed halokinesis (e.g., Calaforra and Pulido-Bosch, 1999). Apart from the diapiric structures mapped in Fig. 3, field observations could usually not help in distinguishing between the effects of these processes, due to the blurring effect of the continuous dissolution/recrystallization processes in the outcropping gypsum under the present morphogenetic conditions. How much these two types of mechanisms are widespread at the Kebenawa ridge, and implications, are discussed below.

4.1.3.1. Diapirism. Diapirism can explain the formation of the observed tectonic structures in the Gorrahei Formation and the overlying rocks. Apart from the diapirs mapped in Fig. 3b, diapiric rise of gypsum is supported by topographic comparison with the nearby Arkele ridge.

The highest elevation of the gypsum on both sides of the crestal graben is ~1000 m above sea level, which is significantly more than in areas not (or much less) affected by diapirism, such as the Arkele Ridge (800–850 m, Ethiopian Mapping Authority, 2001), which is only a few kilometres east of the Kebenawa Ridge (location shown in Fig. 2). This suggests the existence of truly diapiric areas on both sides of the crestal graben. The absence of evaporite deformation below the central graben suggests that the Gorrahei Formation rose diapirically along the normal fault footwalls as a "falling diapir" (Fig. 51 of Vendeville and Jackson, 1992). Observation of arcuate striations on one of the central graben normal fault scarps (Fig. 6d) is also elegantly explained by diapiric motions. Gypsum dehydration–rehydration cycles, which require only very small differential stress and low temperatures to occur (e.g., Schreiber and Helman, 2005), would have facilitated slip along the graben faults (Milsch and Scholz, 2005) and concomitant diapiric rise on the footwall side.

An implication of diapirism is that during the diapiric events the base level is located above the Jessoma Formation. Erosion down to the present level would have consequently occurred between the diapiric stage and ridge spreading. Diapirism requires earlier fracturing parallel to the present ridge topography. Field and experimental evidence show indeed that diapirism cannot initiate if it has not been preceded by active stretching (reactive diapirism in the terminology of Vendeville and Jackson, 1992; Jackson and Vendeville, 1994), except if the overlying rocks are thin and of uneven thickness (Vendeville and Jackson, 1992). Satellite imagery shows that the Mustahil and Jessoma formations have constant thickness over the Kebenawa Ridge, and can be considered of constant thickness over the Audo Range area. Diapirism would thus be expected to have been made possible by regional (far-field) extension after the deposition of the Jessoma Formation. This fracturing event must have triggered diapirism parallel to the present ridge trend given that the Gorrahei Formation is not internally deformed in areas where it is still covered by the more recent sediments. The fracture zone must, therefore, have been parallel to the present ridge trend.

4.1.3.2. Karstification. Karst networks make use of earlier fracturing. Similar to diapirism, the absence of evaporite deformation in areas where the Gorrahei Formation is still overlain by other sediments requires that the main dissolution paths followed brittle tectonic structures parallel to the present ridge trend. Although a cave has been observed in the southern ridge piedmont, diagnostic karst features, such as sinkholes and collapse structures, which appear to be the most common surface expression of evaporitic karsts (e.g., Johnson, 1997; Clark et al., 1999; Benito et al., 2000), have not been observed.

The relative role of diapirism and karstification in the halokinetic processes that have affected the Kebenawa ridge remains difficult to assess. The top of the Gorrahei Formation is higher at the Kebenawa ridge than on a nearby ridge where evaporite deformation is weak or null, suggesting that diapirism did take place, contributing to part or the whole of the halokinetic processes. Similarly, observation of a cave in the evaporite is evidence that karstic activity took place, though perhaps limited.

Diapirism requires that the topography be above the Jessoma sandstone level for Rayleigh–Taylor instability to exist; for this reason it is thought to be inoperative nowadays. On the contrary, karstification may still be active during the seasonal heavy rains.

4.1.4. Timing

Because of the presence of basaltic pebbles in the Mustahil breccia, halokinesis needs to postdate a basaltic volcanic event. New $^{40}Ar/^{39}Ar$ ages of volcanic events in the Ogaden (Mège and Purcell, 2010; Mège et al., 2010) indicate a rich volcanic history during a time span covering the middle Oligocene to the late Miocene. Neogene is, therefore, considered to be the most probable period of halokinesis. Identification of the oligomictic conglomerate at the top of the Mustahil Formation (Fig. 4), which contains Gorrahei evaporite fragments, suggests that incision of the Mustahil Formation locally occurred while Gorrahei diapirism may have already started. A basalt fragment of a basaltic-rich conglomerate (basalt $\geq$ 90%) deposited along the Shebele river near Imi (location shown in Fig. 2) has yielded a well-defined $^{40}Ar/^{39}Ar$ 70% plateau age of 14.4 $\pm$ 0.1 Ma (Mège et al., 2010, 2011). If the volcanic fragments of the conglomerate are similar, Gorrahei diapirism would have started after this time.

4.2. Regional extension

Whatever the halokinetic processes, a fracturing event is required after the deposition of the Jessoma Formation during Paleocene and prior to halokinesis. This event may be the opening of the east-African rift system to the west, stretching of the southern Afar margin and opening of the Gulf of Aden to the north (in both cases during the Miocene or later), or plume uplift during the Oligocene (Pik et al., 2003). No field evidence of extension predating halokinesis has been found though.

4.3. Gravitational spreading

Satin spar crystallization parallel to the ridge, and cross-cutting relationships with other tectonic patterns indicate that they formed as a consequence of building ridge topography and expansion after halokinesis, whatever the relative role of diapirism and karstification. Inward tilting of the gypsum layers and shearing in ridge piedmont area are interpreted to be contemporaneous to satin spar vein formation and accommodate ridge spreading as well. The extensional kinematics of the master fault of the large crestal graben in the central part of the ridge is also consistent with ridge spreading.

4.4. Inferred succession and timing of events

By synthesizing the information above, the succession and timing of tectonic events (Fig. 9) are interpreted to be (1) regional though limited extension in response to regional geodynamic processes during the Neogene; (2) halokinesis, including evaporite ductile deformation, brecciation and gliding of the overlying rock units; and (3) river incision on both ridge sides and gradual emergence of the ridge topography, triggering gravitational spreading by normal faulting in the carbonates and sandstones, and satin spar vein opening in the underlying evaporites.

5. Other mass wasting processes

In addition to large-scale gravitational spreading of the ridge, a variety of local mass wasting processes are observed along the ridge slopes (Fig. 3). Many ridge slopes, especially the outer slopes, are extensively covered by rock debris attributed to landslides, debris flows, and rockfalls, at such a point that *in situ* outcrops are seldom observed in some areas. The rock debris are usually carbonates or sandstones from the Mustahil and Jessoma formations and are observed in the Gorrahei Formation. Distinction between rockfalls and landslide deposits is usually hard to establish because pristine landforms such as landslide scarps are rapidly removed by gypsum flow and dissolution/recrystallization under the past and present climate conditions and because of superimposition of slope processes through time. The outer ridge slopes (especially on the northern side of the ridge) also display huge deformed plateau fragments displaced by gravitational gliding of the competent formations over the Gorrahei gypsum. Instead of identifying mass wasting processes, Fig. 3b separates the plateau fragments that have been displaced over gypsum from their *in situ* location by gravitational gliding or landsliding (Toreva blocks), and the slope deposits produced by rockfalls, rock avalanches, and other debris flows.

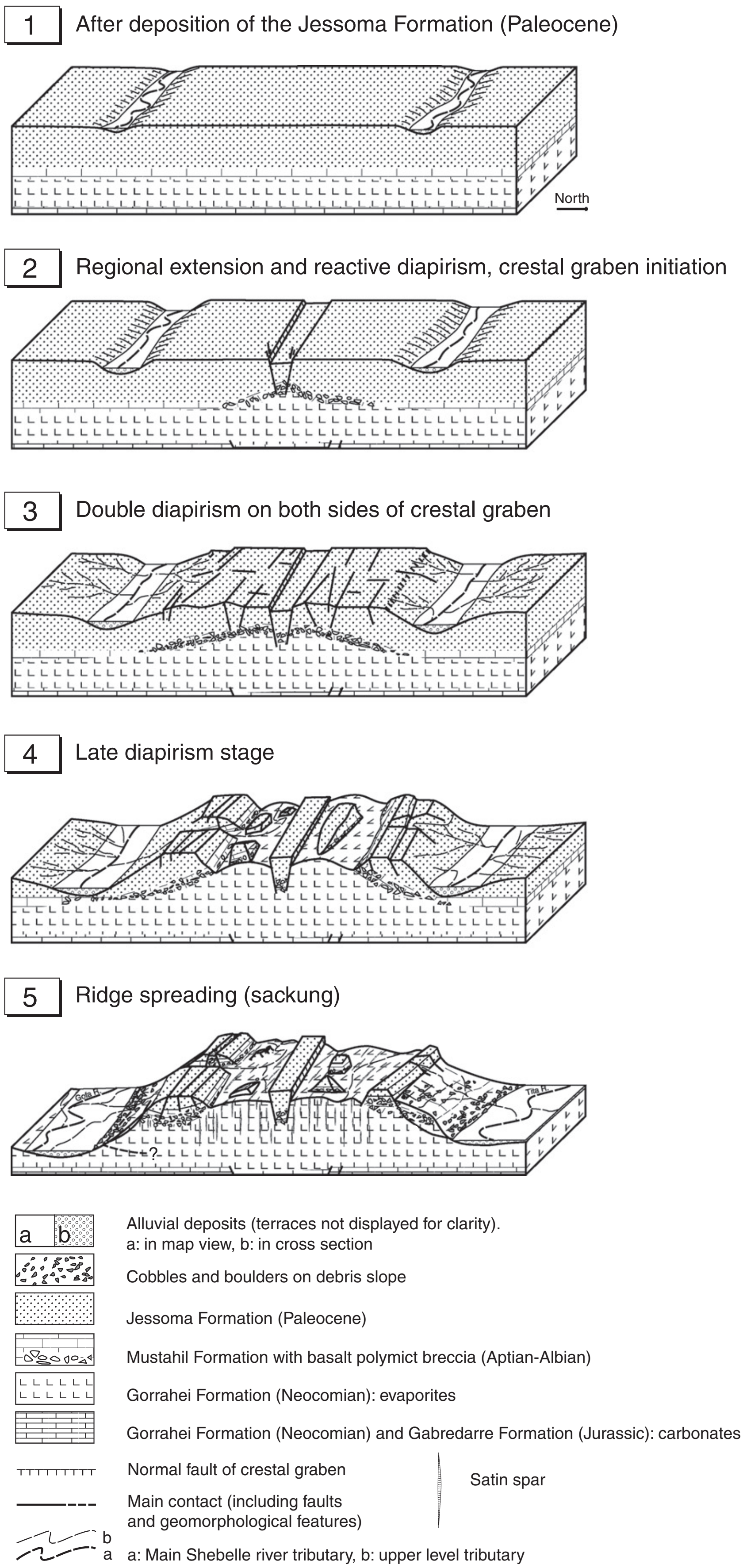

Fig. 9. Reconstruction of Kebenawa ridge evolution. The displayed faulting and vertical offsets in the Gorrahei and Gabredarre carbonates (stages 2 to 5) have not been observed and may not reflect true faulting geometry, but are shown for model self-consistency.

6. Discussion

6.1. Perspective from the Canyonlands grabens, Utah

Spreading of brittle layers above a ductile layer has been well documented at the grabens from the Needles District, Canyonlands National Park, Utah (McGill and Stromquist, 1979; Trudgill and Cartwright, 1994; review in Schultz et al., 2007). Carbonate and sandstones from the Honaker Trail Formation and the overlying Cutler Group are underlain by the evaporitic sequence of the Paradox Formation, all of which being horizontal prior to spreading of the Paradox Formation and its entire cover. The upper part of the Paradox Formation is made of contorted gypsum, shale and minor limestone; the lower part is not fully exposed but is dominantly made of halite, carnallite and sylvite (Doelling, 2004). The stratigraphy is, therefore, similar to the succession in the Kebenawa ridge, with sandstone on top, carbonates in the middle, and dominantly evaporites at the base. Uplift and incision by the Colorado River has resulted in the debuttressing of the Paradox Formation, evaporite flow, and overlying rock spreading by the development of periodically spaced grabens associated with reactive diapirism of the formation. Diapirism has not been described in detail in the field in the Canyonlands grabens from the Needles District but is predicted by structural and numerical models (Moore and Schultz, 1999; Schultz-Ela and Walsh, 2002). Evaporite flow toward the Colorado free boundary has resulted in the development of the Meander anticline within the Paradox Formation along the Colorado River, associated with many low-angle thrust faults (Huntoon, 1982). A *décollement* has developed at a lithologic interface (salt/gypsum) in the upper part of the Paradox formation. Brittle spreading of the Honaker Trail Formation and the Cutler Group, evaporite inward tilting, and development of a *décollement* at the free boundary are all suggestive of processes that have also been found to operate at the Kebenawa ridge (Fig. 10).

A difference with the Kebenawa ridge is the geometry of the surrounding rivers. The Kebenawa ridge is surrounded by two closely spaced parallel river networks, Tita on the North and Lebu/Gofa on the South, whereas the Canyonlands grabens are debuttressed on the western side by the Colorado River but buttressed on the East (Fig. 10). Thus, the stratigraphic succession is the same and also spreading at the Canyonlands grabens and the Kebenawa ridge results from similar mechanisms, the boundary conditions provided by the geometry of the nearby rivers being one of the main reasons that explains the difference in tectonic style. The length and height above base level of the Kebenawa ridge and the area covered by the Canyonlands grabens are similar, 15–20 km and 300 m respectively. The width of the Kebenawa ridge, 3.5–4 km, is twice less, however, than the width of the spreading area in the Canyonlands.

A second difference is that only the uppermost of the Paradox evaporites is outcropping at the Colorado River level (Doelling, 2004), while the base level at the Kebenawa ridge is closer to the base of the Gorrahei evaporites. This difference should have influenced the details of the spreading mechanisms, a feature that remains to be evaluated using models of the type used for studying spreading of volcanoes (e.g., Merle and Borgia, 1996; Van Wyk de Vries and Matela, 1998; Borgia et al., 2000). Other spreading mesas in western Ogaden, such as the Jabis mesa, also present similarities with the Canyonlands grabens (Lopez Gonzalez, 2006; Mège et al., 2011).

6.2. Sackung

Formation of crestal grabens is typical of structures formed at the apex of evaporite domes during early stages of diapirism (Vendeville and Jackson, 1992). In the Kebenawa ridge the crestal graben may have initiated this way; however, most of its development is expected to postdate diapirism and result from gravitational spreading. Crestal graben is equally the most spectacular and distinctive expression of sackung (Kobayashi, 1956; Jahn, 1964; Beck, 1968; Tabor, 1971; Jarman and Ballantyne, 2002; Hippolyte et al., 2006; Reitner and Linner, 2009). Other similarities with sackung include extrusion of the basal topography and ridge flank normal faulting parallel to the crestal graben (Fig. 3b). Sackung and deformation of the Kebenawa ridge also share topographic debuttressing as a common trigger (Mège and Bourgeois, 2011). A difference is that the normal faults on ridge flank in typical sackung instances are uphill-facing, in contrary to the observations made in the Kebenawa ridge. Most sackung examples identified on Earth

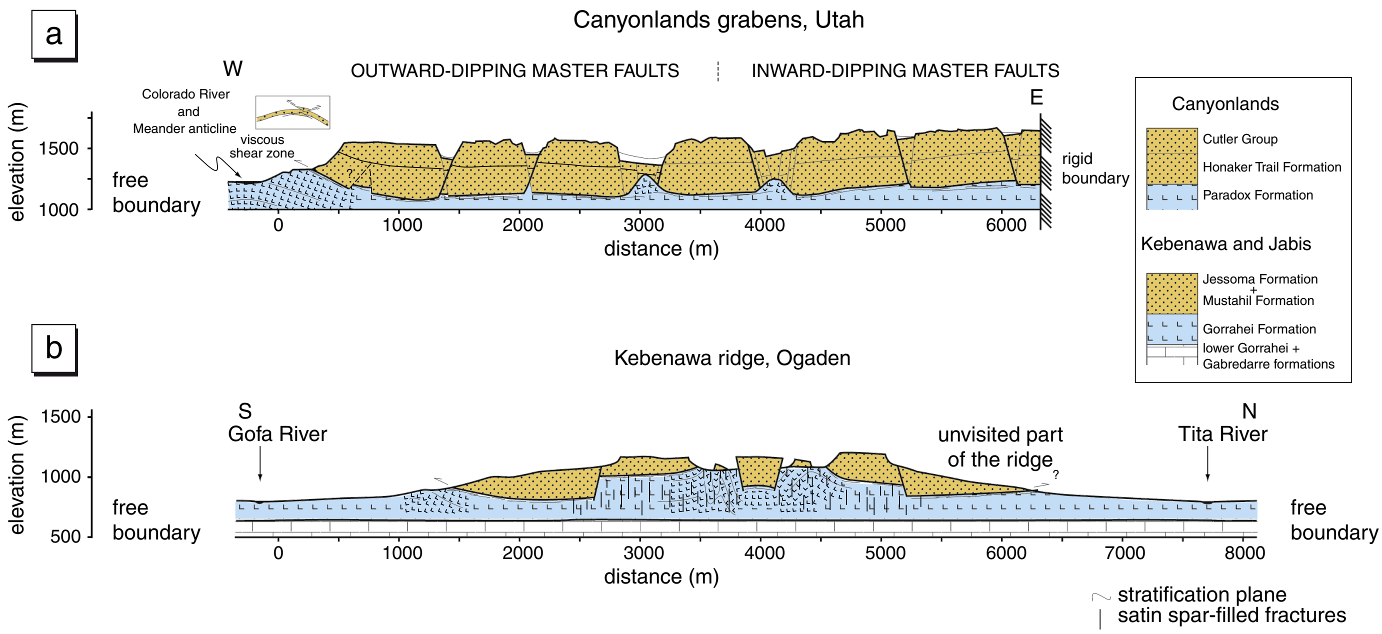

Fig. 10. Comparison between (a) spreading at the Canyonlands grabens, Needles district, Utah, redrawn from Moore and Schultz (1999) with incorporation of the Meander anticline after Huntoon (1982), and (b) that at the Kebenawa ridge. The essential difference in spreading tectonics lies in boundary conditions. The inset in (a) gives the deformation style in the sediments overlying the Paradox Formation in the Colorado River gorge in response to evaporite rise in the Meander anticline core (after Huntoon, 1982). The grabens are interpreted to have induced passive diapirism of the Paradox Formation (Moore and Schultz, 1999); dissolution collapse has been alternatively advocated in a nearby area (Gutiérrez, 2004).

are postglacial features in which sackung was triggered by glacial debuttressing and/or postglacial uplift (Mège and Bourgeois, 2011), with the exception of three debated cases (Ponti and Wells, 1991; Harp and Jibson, 1996; Rizzo and Leggeri, 2004). In three postglacial cases: Dolores Peak, Sepulcher Mountain, and Crested Butte, Colorado (Radbrush-Hall et al., 1976), sackung was found to have been influenced by ductile flow of an underlying weak layer, similar to the Kebenawa ridge. In these Colorado examples, uphill-facing scarps are, however, observed. The basal ductile layer is made of shale, not evaporites. Therefore, the reason for the absence of uphill-facing scarps in the Kebenawa ridge has to be found in processes that are unrelated to flow of an underlying ductile formation, or are related but in addition requires evaporite properties specifically.

Factors that may have played a role in the absence of uphill-facing scarps include (1) evaporite thickness, which is expected to enhance downward flexuring over lateral spreading of the overlying brittle rocks, as suggested by Merle and Borgia (1996) as well as Van Wyk de Vries and Matela (1998) on volcanic spreading; (2) modification of overlying rock rheology by water release from gypsum, either by rock corrosion or pore pressure increase; (3) mechanically atypical ridge structure gained by halokinetic-ridge reworking prior to sackung; and (4) absence of strong ridge confinement followed by rapid ridge deconfinement and expansion, as observed in the postglacial sackung instances (Cossart et al., 2008) in which ridge confinement by valley glaciers was followed by rapid valley deglaciation.

7. Conclusions

The Kebenawa ridge in western Ogaden presents spectacular and unusual characteristics of gravitational spreading. A field study combined with remote sensing analysis enabled us to provide a first detailed structural and geological study of this area, and a better constraint of the Cenozoic history of the western Ogaden region.

The Kebenawa ridge consists of a ~400 m high ridge composed of three main formations (from the base to the top): the ~300 m thick Neocomian evaporitic Gorrahei Formation, the ~20 m thick Aptian–Albian Mustahil carbonates Formation, and the 100–150 m thick Paleocene Jessoma sandstone Formation.

The present structure of the Kebenawa ridge results from a complex mix of halokinesis and gravitational spreading. Diapirism and karstification may have played a role in halokinesis. Like in many other regions in which halokinetic processes took place, estimating the relative importance of diapirism and karstification is not straightforward; nevertheless, the top of the Gorrahei Formation, higher at the Kebenawa ridge than on a nearby ridge where evaporite deformation is weak or null, suggests that diapirism significantly contributed to the halokinetic processes. Gravitational spreading presents mixed characteristics of sackung and spreading of low elevation plateaus as the grabens in the Needles District, Canyonlands National Park, Utah. The scale and mechanisms are broadly similar, in both regions; however, a difference exists in the incision style that debuttressed the topography. At the Kebenawa ridge, the drainage network consists of two parallel rivers that incised the topography to the base of the evaporite layer, whereas in the Canyonlands a single river incised the Colorado plateau, and incision has only attained the top of the evaporite layer. The Scurano-Vetto-Carpineti gravity syncline in the Apennines (Carena et al., 2000) shares some common characteristics with both the Kebenawa ridge and Canyonlands grabens. A detailed comparison between these three localities should provide new insights into the factors and mechanisms of gravitational spreading in response to lateral topographic debuttressing by river incision.

The Kebenawa ridge exemplifies a category of gravitational spreading that had been rarely investigated. It may be described as atypical sackung, with suppression of uphill-facing scarps because of processes that may be related to the absence of lateral elastic stress release subsequent to ridge debuttressing as observed in postglacial sackung instances. The Ogaden region of Ethiopia displays a much broader variety of spreading topographies in various states of evolution, probably covering a surface area that makes it the largest (15,000 km^2 or more) and best exposed spreading domain on Earth. Most of this region remains unstudied.

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