CONSERVATION AND THE GEOLOGY OF GIBRALTAR.

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Resumen

Como resultado de trabajos publicados a partir de 1990 y continuados, aún está claro que el Peñón de Gibraltar no es una secuencia monótona de roca caliza como se creía. La Formación Caliza de Gibraltar que forma la masa principal de la Roca, ha sido cartografiada geológicamente como teniendo cuatro formaciones distinguidas por su litografía bruta y características de desgaste, y se ha reconocido un ciclo de 1-3 m. en los carbonatos perimareales que constituyen los 200 m. inferiores de una sucesión de 600 m. de grosor. Otras formaciones sedimentarias expuestas en la ladera oeste del Peñón se han distinguido de aquellas expuestas en el norte y este. Fósiles distribuidos en el siglo pasado a instituciones en Francia e Inglaterra han sido reinterpretados como del bajo Jurásico para parte al menos de la caliza de Gibraltar y su semejanza a otros carbonatos del margen del Tethys.

La secuencia en la cresta del Peñón se ha visto que está invertida, contrastando con la secuencia sin invertir del plateau del sur de la Roca. Estructuralmente el Peñón se interpreta como un klippe, una reliquia desgastada de una lámina, fracturada por un complejo de fallos en dirección NW-SE como consecuencia de la colisión continente-continente del Cenozoico que creó las montañas béticas del SE de España.

La Roca está penetrada de numerosas cuevas y su superficie marcada por una serie de plataformas formadas por acción de olas en la época Cenozoica. Los sedimentos de la era Cuaternaria se preservan en algunas de las cuevas, y como depósitos incluidos los eólicos y antiguas playas. Estos son un catálogo importante de cambios climáticos, eustáticos y tectónicos del Pleistoceno. En el pasado la explotación de la piedra autóctona de Gibraltar en ocasiones ha expuesto beneficiosamente aspectos de la geología al estudio científico. Tal explotación en el futuro debe tener en cuenta los aspectos de conservación.

Abstract

Largely through studies published since 1990 and still continuing it has become clear that the Rock of Gibraltar is not as monotonous a limestone sequence as previously commonly believed. The Gibraltar Limestone Formation which forms the main mass of the Rock has been mapped geologically as four members, distinguished on the basis of gross lithology and weathering characteristics, and a 1-3m scale depositional cyclicity has been recorded in the peritidal carbonates which constitute at least the lower 200m of the 600m thick succession. So-called «shales» intermittently exposed along the western flank of the Rock have been distinguished from those which crop out along the north and east. Rare fossil brachiopods collected and dispersed to institutions within England and France during the last century have been re-interpreted to confirm an Early Jurassic (Sinemurian) age for at least part of the Gibraltar Limestone and its similarity with other platform carbonates of the marginal Tethys. The sequence in the main ridge of the Rock has been shown to be inverted, contrasting with an uninverted sequence in Gibraltar's southern plateaux. Structurally the Rock is interpreted as a klippe, an eroded remnant of a thrust sheet, fractured by a dominantly NW-SE complex of faults and emplaced as a consequence of the Cenozoic continent-continent collision that generated the Betic mountains of SE Spain. The bedrock is penetrated by numerous caves, and its surface is notched by a series of wave-cut platforms of late Cenozoic age. Sediments of Quaternary age are preserved in several of the caves, and as screes, windblown sands, and raised beaches flanking the Rock. These provide an important record of climatic, eustatic, and tectonic events for the Pleistocene epoch. Past development of Gibraltar's natural stone resources has often beneficially exposed aspects of its geology to scientific study. Future development needs continually to appraise the conservation aspects.

INTRODUCTION

It is appropriate that the Second Conference on the Study and Conservation of the Flora and Fauna of Gibraltar and the Campo de Gibraltar should be held during 1995 - European Nature Conservation Year. Appropriate too that a conference on flora and fauna should include a presentation on geology, for landscape and its geological foundation provide the essential framework upon which all conservation issues are built, controlling such critical features as topography, microclimate, water distribution and soil type (O'Halloran, Green, Harley, Stanley & Knill, 1994). And although public awareness of conservation issues has in the past largely been focused on the biological realm, the importance of earth science conservation is being increasingly recognized throughout Europe - as indicated by recent publications (Stanley, 1995; Robinson, 1995; Green, 1995; Carson, 1995; Prosser, 1995). Earth heritage conservation ensures that future generations can continue to learn about the geological history of their planet and enjoy the beauty of its natural physical features (Wilson, 1995).

The Rock of Gibraltar, one of the two «Pillars of Hercules» to the ancient classical world and Tariq's Mountain to the invading moors of North Africa, has long been famous as a feature of the western Mediterranean landscape (Fig. 1). Aspects of its geology, too, received attention early in the history of the development of geology as a distinct scientific discipline. James (1771) published brief geological observations in his *History of the Herculean Straits*, based upon six years residence on Gibraltar in the mid 18th century. More detailed, specifically geological accounts were given later by Imrie (1798) and Smith (1846), and supplemented by several mid 19th century articles which focused on particular rather than more general aspects of Gibraltar geology (as discussed by Rose, in review). These formed the background to the first geological survey, culminating in the first geological map of the peninsula, completed by A.C. Ramsay and J. Geikie in 1876. Their published account (Ramsay & Geikie, 1878) remained the definitive work on Gibraltar geology until it was largely superseded by

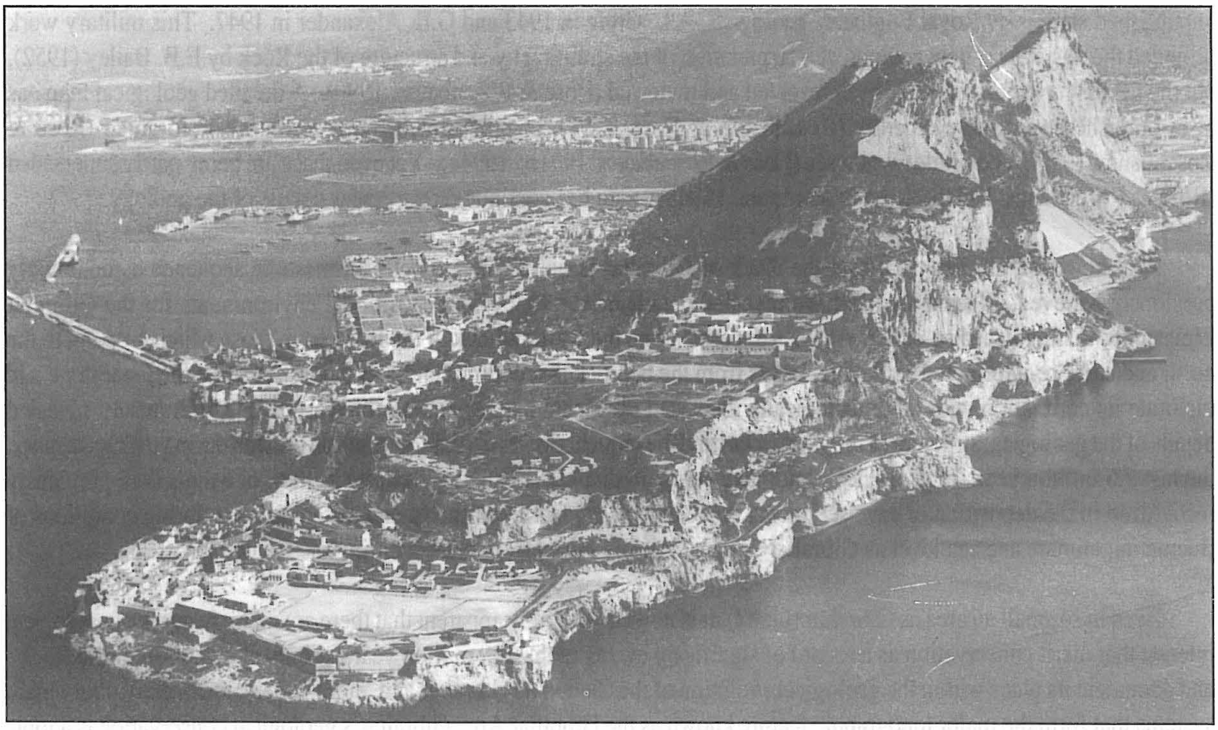

Fig. 1. Aerial view of Gibraltar, from the southeast. (From Rose & Rosenbaum, 1990)

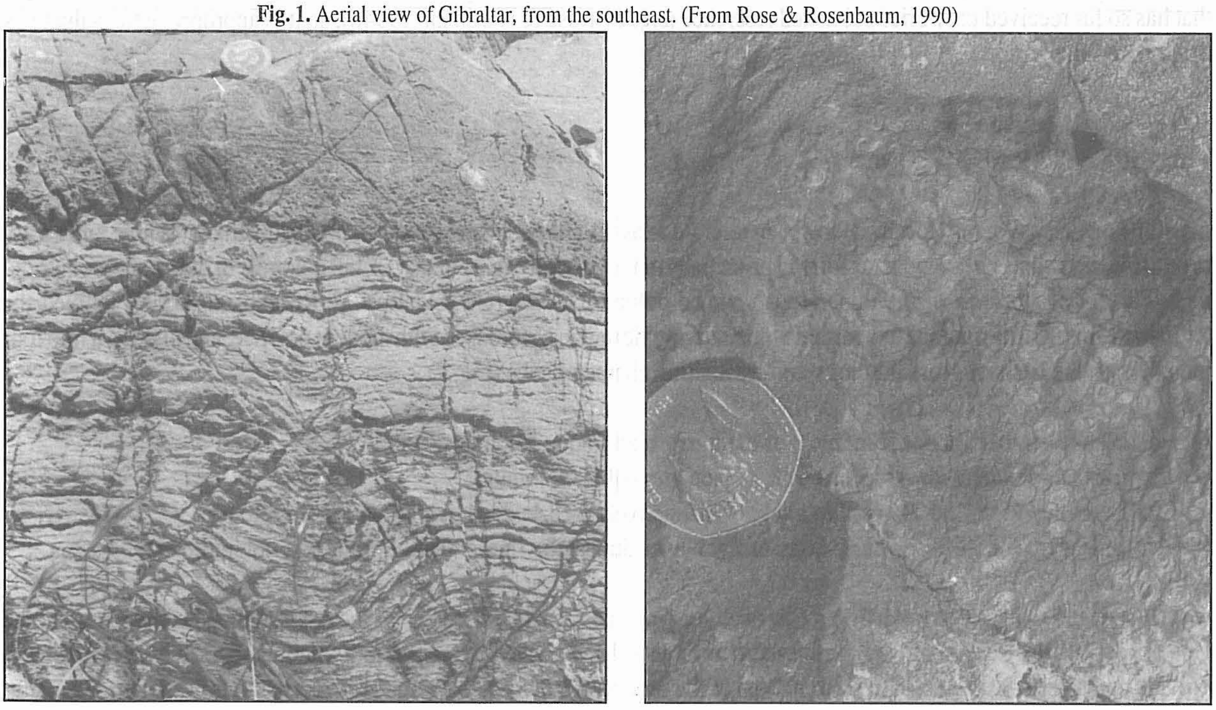

Fig. 2. Fossil marine algae within the Gibraltar Limestone, with 50 pence coin for scale: a. (left) stromatolites; b. (right) oncoids.

unpublished studies by Royal Engineers geologists, A.L. Greig in 1943 and G.B. Alexander in 1947. This military work provided the basis for a new geological interpretation of the stratigraphy and structure of the Rock by E.B. Bailey (1952), but the details have only recently been revealed and reviewed (Rose & Rosenbaum, 1990). A detailed geological map has been published even more recently (Rosenbaum & Rose, 1991), complemented by an extensive field guide (Rose & Rosenbaum, 1991a) and briefer syntheses (Rose & Rosenbaum, 1991b; 1994a). Yet even these are being partly superseded (Rose & Rosenbaum, 1994b; Rose & Hardman, 1994a) as studies continue on particular details of the geology.

It is, however, already clear that the Rock of Gibraltar is not as monotonous a limestone sequence as commonly previously believed. Recent studies have revealed details of varied, cyclic depositional environments for the Gibraltar Limestone; distinguished so-called «shales» exposed along the western flank of the Rock from those which crop out to the north and east; re-interpreted some rare fossils from the bedrock that confirm an Early Jurassic age for the Limestone and facilitate its correlation with other tectonically displaced carbonate masses around the western Mediterranean; revealed details of the geological structure of the Rock; clarified the sequence of its partial solution and erosion during the Quaternary, the last 2.6 million years of geological time; and begun to distinguish a more complex pattern of events than previously recognized in the deposition of cave sediments, scree breccias, windblown sands, and raised beaches during conditions of fluctuating climate and sea level as Gibraltar was tectonically raised from the sea during the Quaternary.

Even in so small an area as Gibraltar (6km2), it is now increasingly apparent that there are many features of geological interest that merit conservation as a record of significant events in the 200 million year geological evolution of the Rock - and document its place within the geological evolution of the Campo de Gibraltar and, more widely, the Betic-Rif mountain systems that form the major topographic feature known as the Gibraltar Arc. Gibraltar's geological conservation is a topic that has so far received only brief published reference (*e.g.* by Rose & Hardman, 1994b), so it is appropriate to evaluate its need more fully here.

THE GIBRALTAR LIMESTONE

The main mass of the Rock has long been referred to as the Gibraltar Limestone, although much of it is now known not to be a true limestone, its components formed principally of the mineral calcite ($CaCO_3$), but dolomite or dolostone, composed in significant proportions of the mineral also named dolomite ($CaMg(CO_3)_2$). Rose & Rosenbaum (1990) defined the Gibraltar Limestone Formation as a formal lithostratigraphic unit in accordance with modern practice, and divided it into four members on the basis of gross lithology and weathering characteristics (Fig. 2).

a. Bleak Member: about 55m thick, of dark grey bituminous dolomites;
b. Europa Member: about 120m thick, of pale grey-white dolomites;
c. Keightley Member: about 35m thick, of distinctively well-bedded dolomites and limestones;
d. Buffadero Member: at least 400m, of light or medium-grey fine-grained limestones, dolomitic at the base.

A sequence which exposes parts at least of all four members can be traced beside the roads within the boundaries of the Upper Rock Nature Reserve, so is already within a conserved area. The type areas for all four members, however, currently provide much better exposure of the lower 200m of the sequence, and these are spread across localities in southern Gibraltar some potentially vulnerable to building development.

Comparative detailed sedimentary logging in both the main ridge of the Rock and the southern plateaux has revealed facies in the lower three members that are typical of a supratidal setting within peritidal carbonates (J.L. Wood, in Rose & Rosenbaum, 1994b). Fenestral and peloidal mudstones/wackestones, stromatolitic algal laminites, and carbonate conglomerate lenses with scoured bases occur in shallowing and fining upward cycles of 1-3m thickness. These are common features of tropical/subtropical tidal flats traversed by migrating channels, such as may be seen at present in the Bahamas or the Persian Gulf. The most obvious cycles are those exposed near Bleak Beach on the western shore of southern Gibraltar, but they are also visible to the trained eye higher in the succession, and within the Upper Rock Nature Reserve. Cycles similarly characteristic of intertidal channels also occur high in the succession, in the Buffadero Member, but have more frequent horizons of coated grains (oncoids, pisoids and ooids), fewer stromatolites, and more common invertebrate fossils - indicating a change to a less restricted depositional environment. The Upper Rock Nature Reserve preserves many horizons within the Buffadero Member that reveal the fossil content of the rock: bivalve and gastropod molluscs may be seen in cross section, and horizons of stromatolitic or oncoidal marine algae (Fig. 3). Few visitors are aware of the existence and significance of these remains, but any attempt to increase public awareness by mounting of explanatory plaques at key localities or publishing a simplified field guide would increase the risk of vandalism, and defacement by those who try to chip away attractive souvenirs.

SHALES

Rocks commonly called «shales» on Gibraltar have now (Rose & Rosenbaum, 1990; 1991a,b) been described and mapped in terms of two separate formations (Fig. 2).

a. Little Bay Shale Formation. In Little Bay, on the west coast of southern Gibraltar, 15m of red and green fissile clastic mudstones with thin beds of fine sandstone and pebble conglomerate, together with thicker beds of dark grey dolomite, crop out at the base of the cliffs. Sheared red and green mudstones, with thin chert bands and some sandstones, can be traced as faulted outcrops at the base of cliffs northwards through Camp Bay. Quarrying to create a car park has recently beneficially exposed more of this unit in Camp Bay. However, the more extensive outcrops mapped by Ramsay & Geikie (1878) have long been quarried away or overbuilt so are no longer accessible to study - a misfortune in geological terms since this unit seemingly represents the oldest bedrock currently exposed on Gibraltar. Although the remaining outcrops do not seem very spectacular they should be conserved as the only remaining evidence for this part of Gibraltar's geological history.

b. Catalan Bay Shale Formation. This unit crops out at the base of the North Face, at the type locality of Catalan Bay Quarry (Fig. 4), as a small exposure at the south end of Sandy Bay and an even smaller one further south, and at Ammunition Jetty even further south along the east coast. The rocks are medium-bedded grey cherty carbonates alternating with thinner beds of reddish-grey fissile clastic mudstones, originally overlain by thinly-bedded cherts. Former quarrying has revealed the North Face and Catalan Bay outcrops, and tunnelling provided access to the Ammunition Jetty locality. Rare fossil ammonites from the North Face and Catalan Bay quarries indicated that these Catalan Bay Shales are younger in Jurassic age than the Gibraltar Limestone (Pliensbachian rather than Sinemurian), and that the rock sequence in the main ridge has been overturned. Potentially, further quarrying in these two localities might beneficially reveal even more of the shale sequence and its fossils to geological study, but measures to stabilize the existing quarry faces would tend to obscure the rock. A case could be made for conservation of Catalan Bay Quarry as a regionally important geological site: it is the only locality on Gibraltar which conveniently exposes conveniently both the medium-bedded carbonates and the cherts, and it reveals a prominent fault. However, the quarried face in the cherts has low stability, so the site is too dangerous to permit public access. The geology must be viewed from a safe distance.

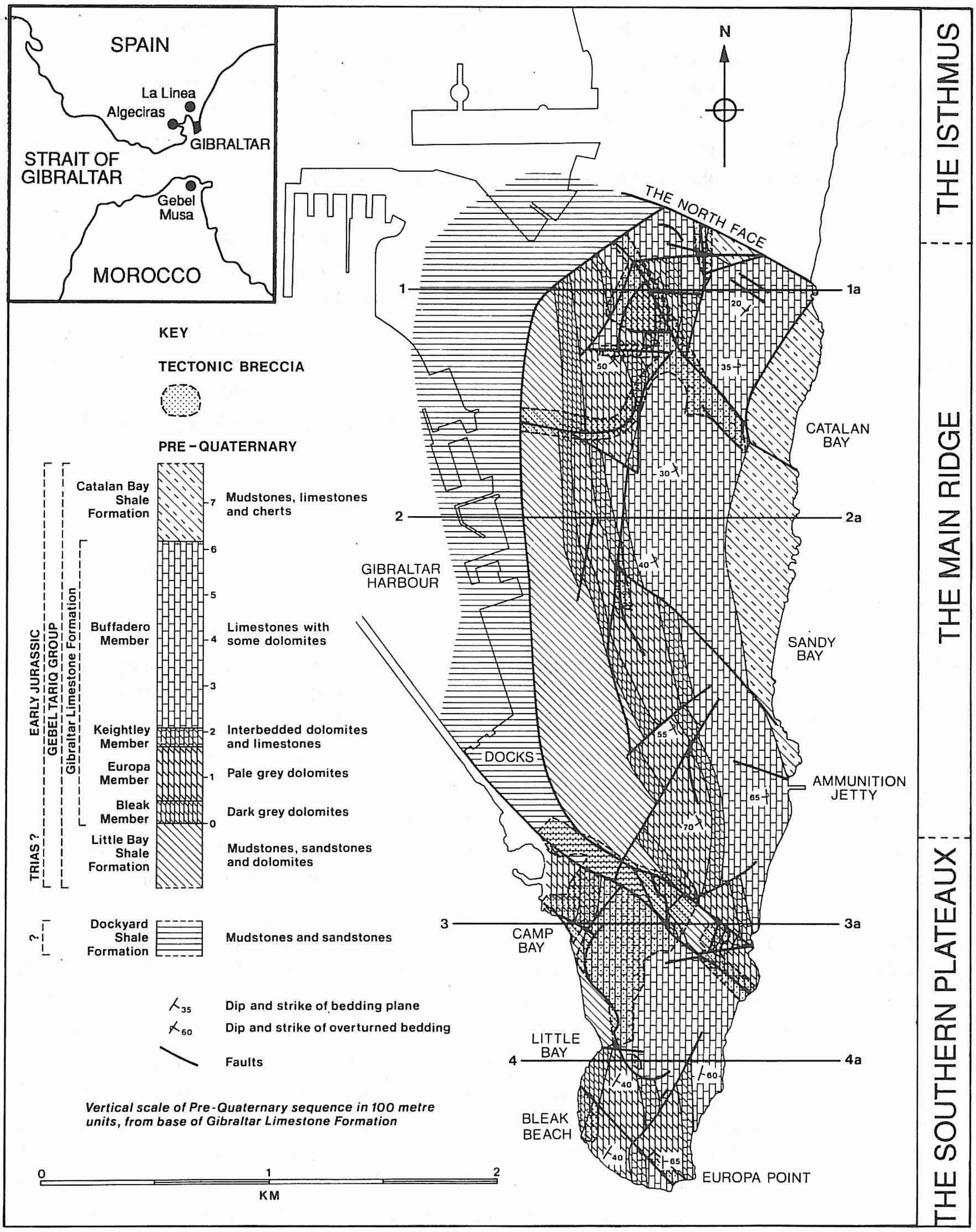

Fig. 3. Map of Pre-Quaternary Geology of Gibraltar. (From Rose & Rosenbaum, 1990; see original publication of cross-sections drawn along lines of section shown on the map).

«Shales» were formerly exposed during construction of the Gibraltar dockyards, at the beginning of the 20th century. These appeared to have a contrary dip to the Limestone in the main ridge, so their relationship to the sequence as currently exposed is uncertain. Moreover, the dockyard construction records do not give details of the rock excavated in geological terms. They have been designated the Dockyard Shale Formation on recent maps (Rose & Rosenbaum, 1990), but their nature and age are as yet uncertain.

JURASSIC FOSSILS

In the last two years the film «Jurassic Park» has excited public interest in fossils of Jurassic age (208-145 million years before present) - but Gibraltar rocks have yielded (and are only likely to yield) rare invertebrates and marine algae rather than spectacular vertebrates such as dinosaurs. The ammonites from the North Face and Catalan Bay quarries identified by L.F. Spath (in Bailey, 1952) were small and poorly preserved and have apparently all been lost. Brachiopods (Fig. 5) collected by James Smith of Jordanhill early in the 19th century have fortunately been preserved first in the collections of the Geological Society of London, later at the Natural History Museum, London. Three additional brachiopods, hitherto wrongly catalogued, have also now been located in the Department of Palaeontology at the Natural History Museum. Three other Gibraltar brachiopods were sent in the last century to E. de Verneuil in France for identification, donated to the Ecole des Mines in Paris, and subsequently transferred to the Université Claude-Bernard, at Villeurbanne, Lyon. The number of specimens in total is small (only 32), as is the number of species represented (five), but studies currently nearing completion indicate that they include representatives of one new genus and one new species - for which Gibraltar will become the type area.

The brachiopods are similar to species from Morocco and Sicily to which a Lower Jurassic (Sinemurian) age has been assigned. They are the only evidence known for such precise correlation of part (at least) of the Gibraltar Limestone - which therefore appears to have been part of the shallow water carbonate platform widely developed along the margins of the Mediterranean Tethys at this time (Bernoulli & Jenkyns, 1974), and fragmented by subsequent tectonic plate movements.

These specimens were all collected during former quarrying operations on the Rock. Conservation within institutions of international scientific repute has ensured their accessibility to generations of scholars. No Gibraltar specimens are known from private collections. The Gibraltar Museum has only one specimen of possible Mesozoic age: a cast of a large pleurotomariid gastropod, designated as from Little Bay but otherwise of uncertain provenance. Sadly, at the time it was collected it was not realized locally that good conservation preserves not only the specimen, but also precise details of where, when and how it was discovered. Without detailed knowledge of its geological context, the significance of the specimen cannot be confidently evaluated.

GEOLOGICAL STRUCTURE

The Rock of Gibraltar has been fractured by numerous faults. The most obvious can be seen in Catalan Bay Quarry (Fig. 4), where Gibraltar Limestone to the north is apparently downthrown against thin-bedded cherts of the Catalan Bay Shale Formation exposed to the south. Faulting within the Gibraltar Limestone is also clearly visible in the cliffs separating Windmill Hill Flats from Europa Flats, best viewed by looking north from Harding's Battery Observation Post at Europa Point at the southern tip of Gibraltar. The most important fault is the «Great Main Fault» of Ramsay & Geikie (1878), which trends NW-SE across Gibraltar separating the westward dipping Gibraltar Limestone of the main ridge from the eastward dipping sequence in the southern plateaux. The fracture pattern within this zone is complex and not generally spectacular except for an outcrop of «shales» near Devil's Bellows, whose vertical orientation (a consequence of fault movement) is exceptional.

Ramsay & Geikie (1878) assumed that the succession in the main ridge of the Rock was the «right way up», and inferred that the sequence in the southern plateaux had been overturned. Bailey (1952) inferred that the succession in the main ridge (and presumably the whole of the Rock) had been inverted. In contrast, Rose & Rosenbaum (1990, 1991a) have demonstrated that whereas the rock sequence in the main ridge is indeed overturned, that of the southern plateaux is the «right way up». Evidence for the inversion of the main ridge is largely conserved within the Upper Rock Nature Reserve: especially gastropod geopetal infills, and upward growth directions discernable in stromatolitic algae. Convincing evidence for the «right way up» of the southern plateaux is visible as a distinctive horizon of rip-up clasts within the Limestone exposed beside Europa New Road, and several localities across Europa that reveal upward growth directions of stromatolitic algae. Such localities ought to be conserved in place if ever threatened by construction works - or photographed, and the rock specimens removed for permanent conservation elsewhere on Gibraltar under the auspices of the Gibraltar Heritage Trust.

Convincing evidence for the geological structure of Gibraltar is relevant to formulation and assessment of models for the geological evolution of the general Straits region (Rose & Rosenbaum, 1994a) - still a topic of considerable controversy. Most interpretations favour radial thrusting of nappes from a centre within the Alboran Sea as a consequence of African-European continent-continent collision following plate tectonic movements in the Cenozoic. These movements generated the Rif mountains of Morocco as well as the Betics of southeastern Spain. A major thrust plane is inferred to dip eastwards at shallow depth beneath Gibraltar (Bailey, 1952; Rose & Rosenbaum, 1994a) but has not knowingly been observed. The Rock is interpreted as a "klippe", the eroded remnant of the overlying nappe.

CAVES

Gibraltar is honeycombed by caves: 143 have been named above sea level, and more are known from below it. Most appear phreatic in origin, formed by solution of the Gibraltar Limestone at or above the prevailing water table. Cave position is controlled by: (1) stratigraphy, since caves appear to be more commonly developed in the lower, more soluble dolomitic members of the Limestone than its upper, calcitic member; (2) tectonism, since cave orientation often follows prevailing fault or joint directions in the Rock; and (3) former groundwater levels, since cave systems are developed in more or less horizontal series, and individual passages vertically as a response to deepening base levels, cross-cutting the steeply dipping bedrock. High level cave systems are inferred to be older than those at low level, since groundwater level is closely related to sea level and the high level caves indicate considerable tectonic uplift since their formation. Almost all of the caves are now dry; solution must have taken place at times when the climate was more humid than that of the present day.

Many of the caves are empty of sedimentary deposits except for speleothem, sometimes impressively developed as stalactite and stalagmite formations (Fig. 6). The St. Michael's Cave system, conserved as a tourist attraction within the Upper Rock Nature Reserve, falls in this category - as does the New St. Michael's system, discovered at lower levels in 1942, but with more difficult access so not open to the general public. The speleothem deposits preserved in these caves have considerable potential for future study, for example by uranium series analysis, thermoluminescence (TL) or electron spin resonance (ESR), to reveal their age(s) and fluctuations in climate (especially humidity) during the time of their deposition (cf. Smart *et al.*, 1988; Bluszcz *et al.*, 1988; Gordon et al., 1989; Proctor & Smart, 1991; Baker *et al.*, 1995). Tratman (1971) has inferred at least two phases of solution in Gibraltar caves on the basis of cave morphology.

Other caves contain deposits such as cave earth, cave breccia, and fluvial or windblown sand, occasionally punctuated by layers of speleothem marking successive floor levels (cf. Cooper, this volume). Such sedimentary successions preserve

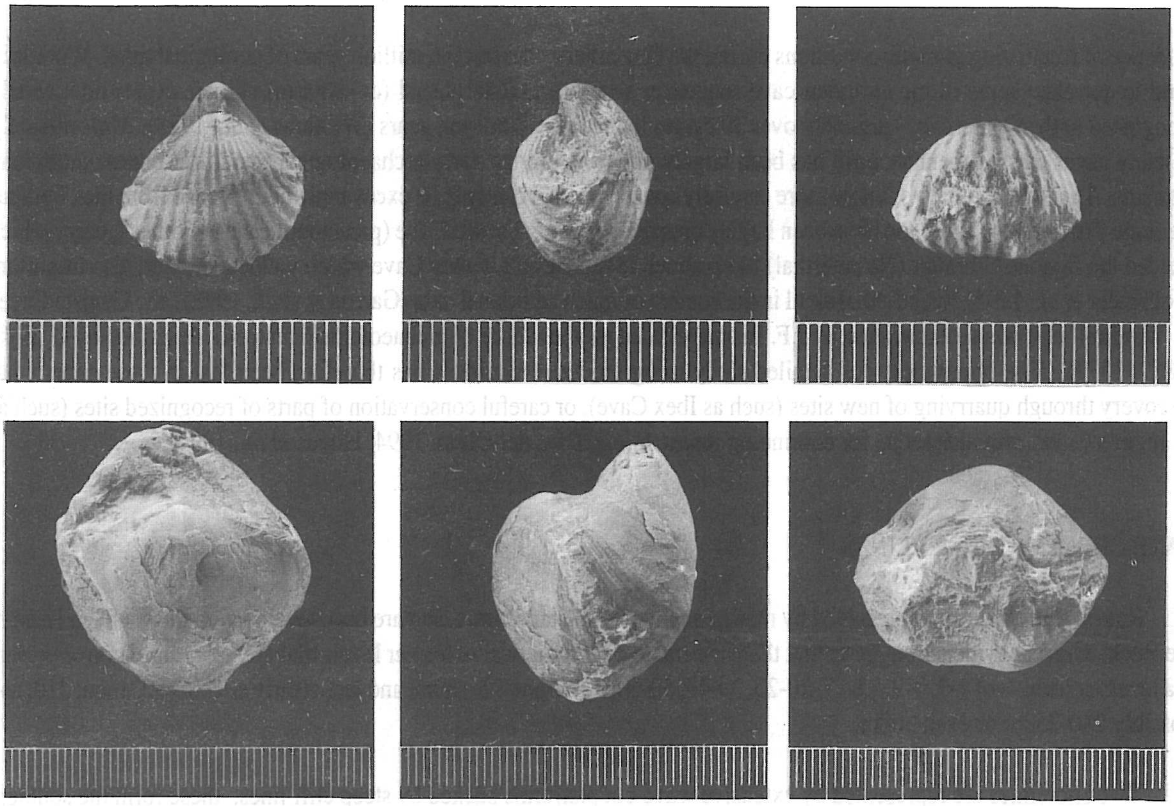

Fig. 4. Fossil brachiopods from the Gibraltar limestone, with scale in millimetres: **a.** (top) *Gibbirhynchia* (brachial, lateral, and anteriors views); **b.** (bottom) *Spiriferina* (brachial, lateral, and anterior views) Photographs courtesy of Dr. E. F. Owen, the Natural History Museum, London.

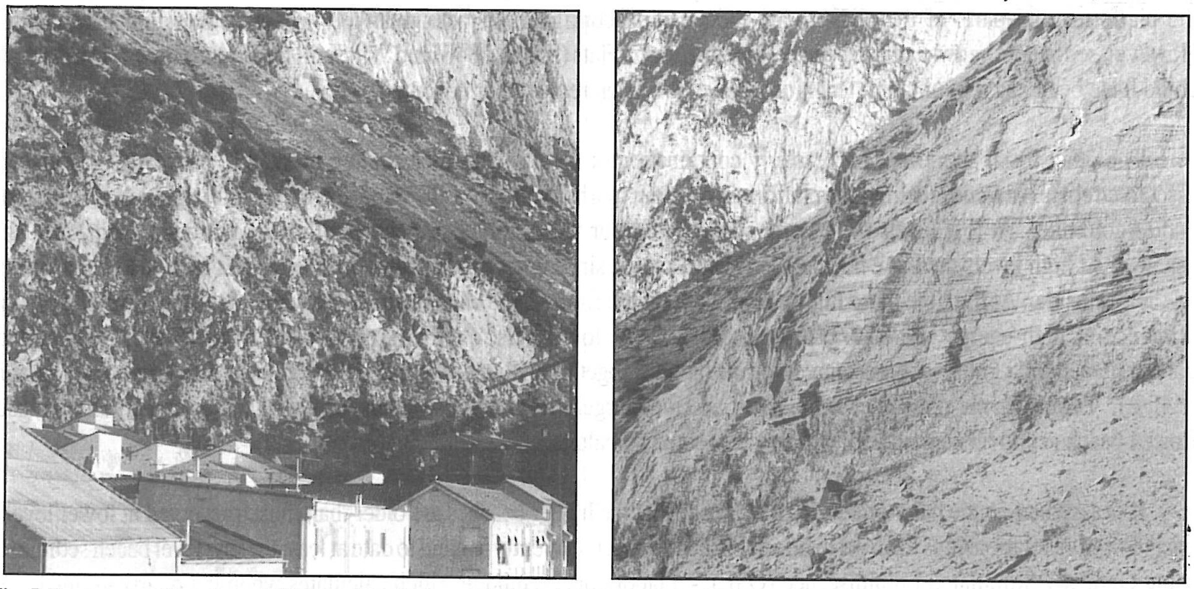

Fig. 5. Quaternary sediments: **a.** (left) Scree breccia, in quarried face behind Catalan Bay village; **b.** (right) Catalan Sands, in quarried face at toe of water catchment slope, showing large scale cross-bedding.

evidence of fluctuating climatic conditions during the Quaternary - the last 2.6 million years of geological time. Work is in hand to correlate some of the Gibraltar cave sequences with glacial/interglacial (cold/warm) climate cycles now widely recognised in the Quaternary - arguably over 30 cycles in the last 1.8 million years (Williams *et al.*, 1988). Unfortunately in many caves the sedimentary infill has been largely dug away during early archaeological search for bones and human artefacts. That which remains is now more carefully conserved, and can only be excavated under licence from the Gibraltar Heritage Trust. Some caves too have been largely quarried away or obscured: the (presumed) cave at Forbes Quarry which yielded the famous Gibraltar (Neanderthal) Skull about 1848; Devil's Tower Cave which yielded another, also important (Zollikofer *et al.*, 1995) Neanderthal skull in the context of much additional data (Garrod & *et al.*, 1928); the Genista Caves on Windmill Hill whose excavation by J.F. Brome yielded an abundance of archaeological material, described by G. Busk (1869, 1877). The opportunity for detailed study using modern techniques has therefore been lost in these cases - but discovery through quarrying of new sites (such as Ibex Cave), or careful conservation of parts of recognized sites (such as Gorham's Cave) provides scope for continuing research (*e.g.* Díaz del Olmo, 1994; Hoyos *et al.*, 1994).

LATE CENOZOIC SHORELINES

Raised shorelines are represented by marine sediments and landforms, and are best developed to the south and east of the Rock. Current evidence suggests that there are traces of at least twelve former levels that are now raised above present sea level: at heights of 1-3, 7-9, 15-17, 20-25, 30-40, 50-60, 80-86 and 90-130m, and less clearly at 180-190, about 210, and possibly 240-250m or even 300m.

Two shorelines are represented by extensive wave-cut platforms backed by steep cliff lines: these form the southern plateaux of the Rock (Fig. 1). Windmill Hill Flats slopes south from 130 to 90m above present sea level, and is succeeded further south by Europa Flats sloping from 40 down to 30m. From maps and models made in the last century it appears that the platforms and parts of the cliffs retain their natural configuration with relatively minor engineering landscaping. However, sediments known to have been present on Europa Flats (Smith, 1846) and Windmill Hill Flats (Brown, 1867) which could have been dated by modern techniques have now been removed or obscured.

The other fossil shorelines and easterly continuation of the southern plateaux are marked by narrow platforms and associated cliffs. In some localities the platform is overlain by a basal unit of well-rounded cobbles and/or gravels of limestone and/or dolomite. At low levels these carbonate clasts occur with cobbles or pebbles of chert, quartzite, sandstones and «shale». At high levels there are no chert or «shale» clasts, since appropriate source rocks crop out only at lower altitudes on the peninsula. At the time these high level beaches were formed, the cherts and shales would have been well below the influence of high-energy shoreline erosive processes. At low levels, overlying or associated sands are poorly sorted, comprising angular grains of limestone/dolomite (*c.*40%) together with more rounded fragments of schist and quartz grains (*c.*40%). Typically, the remainder is bioclastic, derived largely from mollusc shells, echinoid spines and coralline algae. Raised beach sediments are now all variably cemented by calcite.

It is assumed on the basis of landform evidence that the higher beaches are older than those preserved at lower levels, but precise age relationships have yet to be established. Work is currently in hand to date at least the low level beach sediments using Optically Stimulated Luminiscence (OSL) - a laboratory technique which calculates when the quartz grains in the sediment were last exposed to sunlight (*i.e.* the time of their deposition).

The sediment being analysed is the quartz-rich sand free of large clasts which overlies the low-level basal conglomerates. The high beach levels visible on the Rock are more difficult to date by OSL, since they appear to contain at least two generations of quartz, one as large clasts and the other as matrix, which cannot be completely separated for analysis. High level beach sands are essentially of carbonate with very little quartz, and the preserved sediments are largely conglomeratic - not only is there little quartz in the matrix, there is little matrix between the clasts. However, these beaches are clearly indicative of tectonic uplift since the time of their deposition. Although global sea level is estimated to have fluctuated over a range of about 100m during the Quaternary as a consequence of glacio-eustacy (Shackleton, 1987), with low sea levels characteristic of cold climates and high global ice volumes, and high sea levels indicative of warmer climates and the melting of glacier ice, it seems that sea level would never have risen more than a few metres above that of the present day. The tectonic uplift is interpreted as a consequence of plate convergence, consistent with African-European continent-continent collision in the late Cenozoic. Dating of the beach levels would allow interpretation of the rate of uplift, and comparison with movement in other plate-boundary areas in the Straits region (*cf.* Zazo & Goy, 1989).

Raised beach sediments are far weaker than the Gibraltar Limestone, so more easily worked, and the wave-cut platforms make convenient foundation sites. In some areas geological evidence of Gibraltar's Quaternary palaeoenvironmental history has already been quarried away or overbuilt. For example, low-level shoreline features around Europa Point have been militarily scarped to make the region less accessible to attack; and the town of Gibraltar has been developed over features formerly visible along the western flanks of the Rock (*e.g.* South Barracks, built on one of the platforms distinguished by Ramsay and Geikie, 1878). Fortunately many still remain, but some low level features are currently being obscured by reclamation of land from the sea, and others are threatened as former military land is released for potential building development.

QUATERNARY SCREE BRECCIAS

Scree breccia occurs widely on the flanks of the Rock (Fig. 7), most obviously forming large scree slopes at the base of the North Face, and to the north and south of the sandy slope surfaced by water catchments along the eastern Rock (Fig. 8a). It occurs to lesser extent south of the main dockyard area adjacent to the west coast, but less obviously in many other areas - even beneath the sands which surface the water catchment slope.

These breccias are largely composed of very poorly-sorted angular fragments of Gibraltar Limestone which may be up to several metres in diameter. The angularity, size and form have long been recognised as evidence for formation in a climate significantly colder or more extreme than that of present day Gibraltar - an interpretation first argued by Ramsay & Geikie (1878), and maintained by Rose & Rosenbaum (1990). Scree breccia is most extensively developed where the Limestone cliffs are underlain by weaker «shales», whose erosion in the past has facilitated slope instability and collapse. The breccias are inferred to be cryoclastic in origin. Fragmentation of the cliffs is believed to have produced the large angular blocks as the result of freeze-thaw action on water within the already well-jointed Limestone. The fragments then accumulated under gravity. Beneath the larger cliffs, slopes developed with a surface angle of about 30-35o - the natural angle for loose coarse fragments - and were later weakly cemented by precipitation of calcium carbonate from pore waters.

The breccias are more easily quarried than the massive Gibraltar Limestone as a source of fill for land reclamation. Breccias formerly at the base of cliffs between Little Bay and Camp Bay were almost completely removed by quarrying in 1895-1905 to provide material for the construction of the dockyard. Other quarries were developed at other times inland of

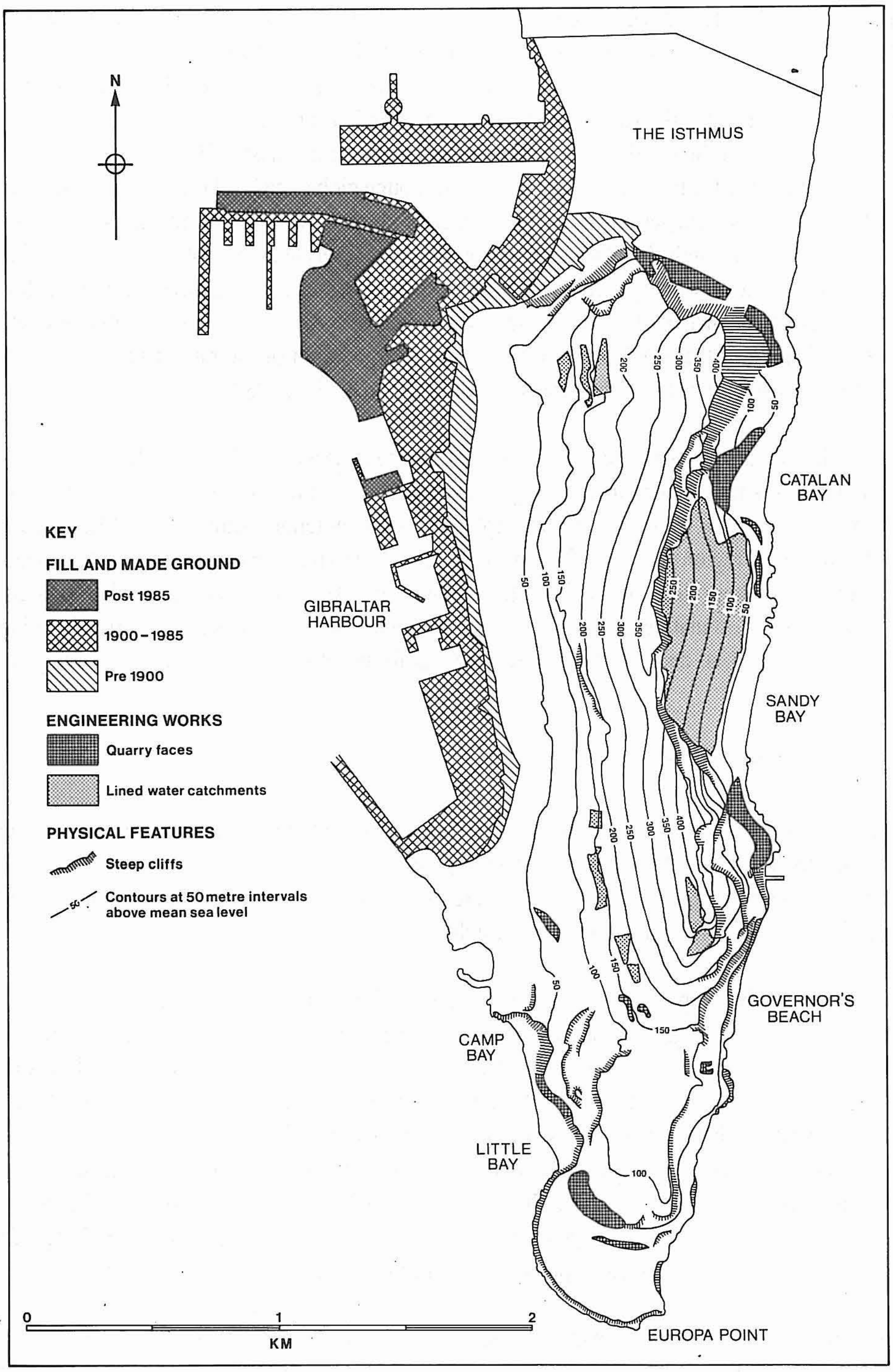

Fig. 6. Map of Quaternary geology of Gibraltar. (From Rose & Rosenbaum, 1990).

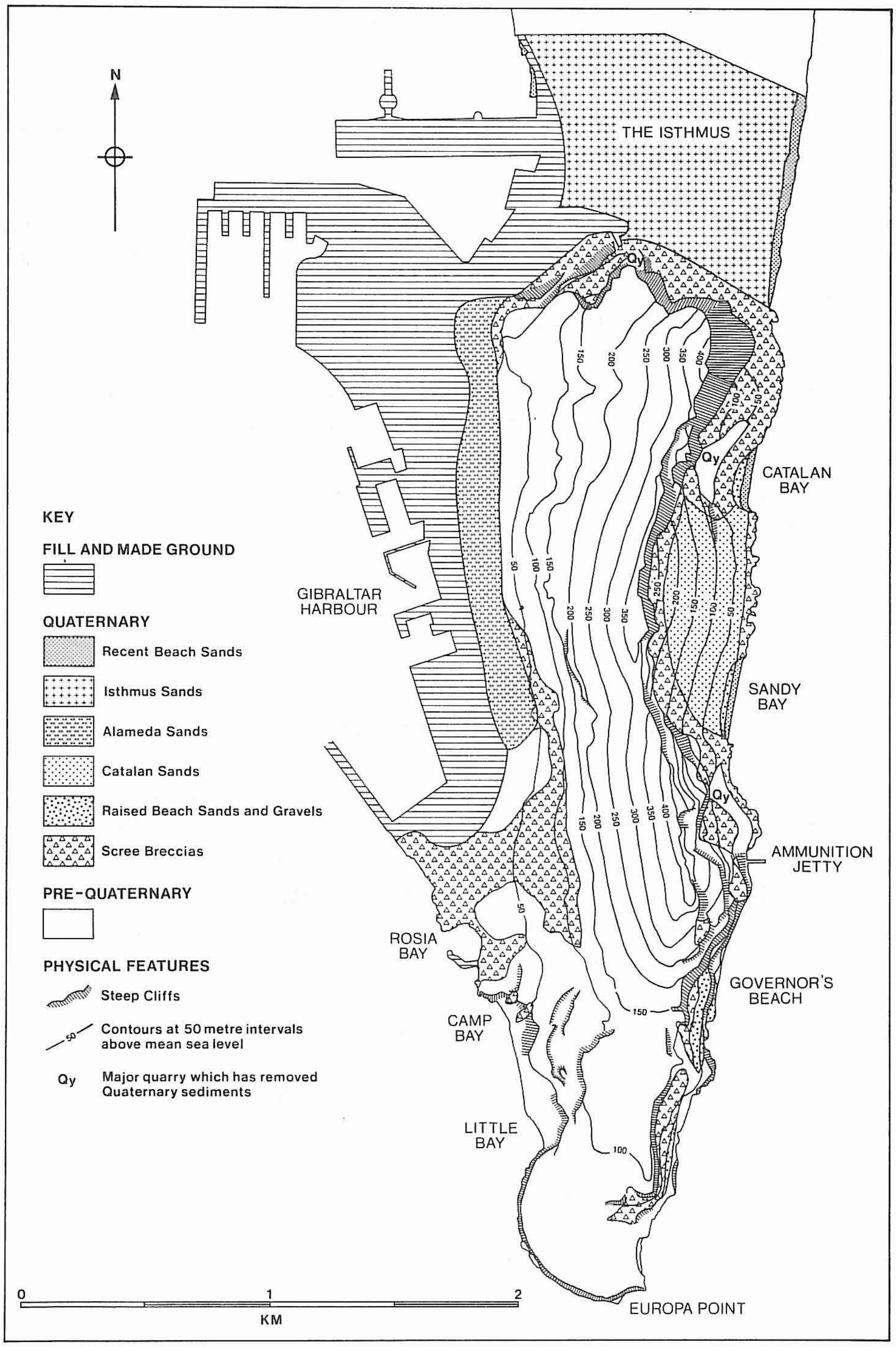

Fig. 7. Map showing areas of fill and made ground and major engineering works based on geological features (From Rose & Rosenbaum, 1990).

Catalan Bay, Sandy Bay, and at the base of the North Face. These have left enough of the original scree slope to reveal its internal structure - especially in the relatively stable, near-vertical cut faces in the east coast areas. These are so spectacular, especially near Catalan Bay, that it is hoped that they will long remain in their present form.

Most breccias appear to have accumulated under terrestrial conditions. Trechmann (1943) described a fauna of land snails from sand lenses within the screes of both the North Face and the east coast. However, we have recently reported (Rose & Hardman, 1994a) that along part of the shore at Camp Bay on the southwest coast there are outcrops of breccia which was clearly deposited in marine waters. The clasts, although still quite large and angular, show surface borings characteristic of marine organisms. Moreover, the intervening matrix is rich in marine bioclastic debris, notably thalli of coralline algae and spines of echinoids. These outcrops are clear evidence of deposition at a time of higher relative sea level than at present. The site, however, may be vulnerable if there is further development of the recreational facilities built along this part of the coast.

Ramsay & Geikie (1878) distinguished two periods of breccia formation on Gibraltar. Present investigations indicate from observed stratigraphic relationships that deposits of this kind formed on a number of occasions. In the Camp Bay area, it is already possible to distinguish features of coastline evolution from the pattern of breccia sedimentation. Breccias in Catalan Bay have a sandy matrix near the base, but their exact relationship with the overlying and therefore younger windblown Catalan Sands is not currently visible.

WINDBLOWN SANDS

As recently documented by Rose & Hardman (1994a), extensive deposits of Quaternary windblown sand flank the Rock: the Catalan Sands to the east, and the Alameda Sands to the west (Fig. 7).

The Catalan Sands (Fig. 8b) form the surface layers of a slope 1km long banked against the eastern cliffs of the Rock to a maximum height of about 200m. A 10m high quarried face at the toe of the slope reveals about 30 truncated cross-bedded yellow-brown coloured sand units with overall dip to the west at between 20 and 30o. These units are moderately well-sorted, medium sand with sub-rounded, highly spherical grains. The composition of the sands is dominantly quartz (*c.*70%), with subordinate lithic fragments of schist and speleothem (each *c.*3-12%), minerals derived from the schists (such as garnet), and a few shell fragments and benthic foraminifera. Carbonate content is low, and creates a weak cement.

The high proportion of quartz and schist indicates derivation of these grains from outside the present land area of Gibraltar, since appropriate source rocks are absent from the peninsula. On the basis of form and composition these units are inferred to be aeolian sand dunes derived from the sea floor east of the Rock, during one or more periods of low sea level. Scanning Electron Microscope (SEM) studies of quartz grains from the sands reveal surface textures indicative of aeolian transport and deposition (smooth rounded surfaces with deeply-chipped depressions), and subaqueous transport, probably beach origin (surfaces with crescent-shaped cracks, and small v-shaped chips) (Krinsley & Doornkamp, 1973). Glacio-eustatic lowering of global sea level during at least the last two Quaternary glacial maxima is widely inferred to have lowered sea levels by some 100-150m, and lowering to this extent would have exposed a significant area of the present sea floor around Gibraltar to wind erosion.

A zone characterized by a bleached horizon above a reddened horizon is developed at the top of a marked unconformity in the sequence near the Caleta Palace Hotel. Preliminary analysis suggests that this is a soil profile represented by Ea and Bfe horizons above the parent material (C horizon). Formation of such a soil suggests that humid conditions accompanied its formation and indicates a period of land surface stability during which pedogenesis took place, probably under «Mediterranean» conditions very similar to those which prevail on Gibraltar at the present day.

The Alameda Sands, known locally as the «red sands», underlie much of the town area on the western side of the Rock. They occur as a narrow strop nearly 2km long, with preserved height within 50m above present sea level, and maximum reported thickness of 16m. They are well sorted, with a mode in the fine sand fraction. Grains are more rounded and have a higher sphericity than those in the Catalan Sands, but also suggesting wind transport. The Alameda Sands show a similarly high percentage of quartz grains (*c.*70%) to the Catalan Sands, but unlike the Catalan Sands they contain some (*c.*2%) grains that are lithic sandstone fragments. Potential source rocks for the fragments are the Cenozoic flysch sandstones now widely exposed to the north and west of Gibraltar. At time(s) of low sea level these would have been exposed even closer to the peninsula, within part of the area now occupied by the Bay of Gibraltar. Schist and speleothem fragments occur in the Alameds as well as the Catalan Sands, but in low proportions (<10%). The red colour also appears to be the product of well developed pedogenesis.

Sand is required on Gibraltar to sustain the construction industry, used both in cement and land reclamation. Both the Catalan and Alameda Sands have been quarried in the past as a valuable local resource. Quarrying of the Catalan Sands at the toe of the water catchment slope was abandoned only because quarry development threatened the long term stability of the slope as such. The cut faces in the former quarry now reveal the internal structure of the sand slope extremely well, but long term these exposures may be threatened either by degradation by weathering, or by slope-stabilization works. An attempt has been made more recently to initiate quarrying at the top rather than the bottom of the slope. Short term such procedures may be geologically beneficial in revealing subsurface features of scientific interest. Carried to extreme, however, removal of the sand slope would remove a major feature of Gibraltar's landscape - and evidence for the climatic events that governed its deposition.

The Alameda Sands have now been largely overbuilt, although they are intermittently exposed by digging within the Botanic Gardens which now occupy their type area. They were formerly exposed in a sandpit to the south of the Gardens, but this has now been floored by tennis courts, and the quarry faces allowed to degrade. Consideration might be given to opening a face for conservation either within the confines of the Garden, or the vicinity of the tennis courts.

CONCLUSION

As for many other areas in Europe, Gibraltar has a detailed field guide (Rose & Rosenbaum, 1991a) readily available for public purchase to route visitors and residents alike to sites of geological interest. Although information on sites and access to them was correct at the time the Guide was completed for publication in 1989, increased urban development of the Rock has rendered some data obsolete. There is continual pressure to develop sites, and consequently to restrict access and obscure rock faces whose stability is questioned.

Now that it is clear that Gibraltar has a geological heritage worth conserving, it would be timely to consider how this might be done. From a purely scientific point of view, it is clear that quarrying in some areas would be positively beneficial, in revealing new features of geology: the major present-day exposures of the Catalan Bay Shale, for example, have all been created or made accessible by engineering works in the past (Fig. 9). In other areas, quarrying would lead to an irreplaceable loss of evidence for geological events in the Gibraltar region - and much has already been lost. The same applies to the burying of natural features by fill to create new surfaces for building construction.

Gibraltar would benefit from a conservation scheme similar to that adopted in the United Kingdom, where RIGS (regionally important geological sites) are being designated as well as SSSIs (sites of special scientific interest). Sites of importance or interest should not be destroyed out of ignorance, but be conserved for the benefit of future generations. If conservation is not feasible, then an alternative site should be enhanced and made accessible, and the former site be subject to detailed study and sampling prior to destruction. Balancing of priorities between «developers» and «conservationists» is never easy, but surely necessary.

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REFERENCES

BAILEY, E.B. 1952. Notes of Gibraltar and the Northern Rif. *Quarterly Journal of the Geological Society of London,* 108, 157-175.

BAKER, A., SMART, P.L. & EDWARDS, R.L. 1995. Palaeoclimatic implications of mass spectrometric dating of a British flowstone. *Geology*, 23, 309-312.

BERNOULLI, D. & JENKYNS, H.C. 1974. Alpine, Mediterranean and central Atlantic Mesozoic facies in relation to the early evolution of the Tethys. In: DOTT, R.H. & SHAVER, R.H. (eds) Modern and Ancient Geosynclinal Sedimentation. *Special Publication, Society of Economic Palaeontologists and Mineralogists*, 19, 129-160.

BLUSZCZ, A., GOSLAR, T., HERCMAN, H., PAZDUR, M.F. & WALANUS, A. 1988. Comparison of TL, ESR and 14C dates of speleothems. *Quaternary Science Reviews* 7, 417-421.

BROWN, A.B. 1867. On the geology of Gibraltar, with especial reference to the recently explored caves and bone breccia. *Proceedings of the Royal Artillery Institution*, 5, 295-303.

BUSK, G. 1869. On the caves of Gibraltar in which human remains and works of art have been found. *Transactions of the international Congress on Anthropology and prehistoric Archaeology, 3rd session Norwich 1868*, 106-167, 12 pls.

BUSK, G. 1877. On the ancient or Quaternary fauna of Gibraltar, as exemplified in the mammalian remains of the ossiferous breccia. *Transactions of the Zoological Society of London*, 10, 53-156, pls. 1-27.

CARSON, G. 1995. Education or legislation? The role of RIGS in geological conservation. *Geoscientist*, 5, 17-18.

COOPER, J.H. (this volume) Quaternary micromammals from Gorham's Cave, Gibraltar, and their palaeoenvironmental significance.

DIAZ DEL OLMO, F. 1994. Interferencias sedimentarias y cambios climaticos en Gorham's Cave (Gibraltar). In: RODRIGUEZ VIDAL, J., DIAZ DEL OLMO, F., FINLAYSON, C. & GILES PACHECO, F. (eds) Gibraltar during the Quaternary. *AEQUA Monografías*, Seville, 2, 49-55.

GARROD, D.A.E., BUXTON, L.H.D., SMITH, G. ELLIOT & BATE, D.M.A. 1928. Excavation of a Mousterian rock-shelter at Devil's Tower, Gibraltar. *Journal of the Royal Anthropological Institute, London*, 58, 33-113.

GORDON, D., SMART, P.L., FORD, D.C., ANDREWS, J.N., ATKINSON, T.C., ROWE, P.J. & CHRISTOPHER, N.S.J. 1989. Dating of Late Pleistocene Interglacial and Interstatial Periods in the United Kingdom from speleothem growth frequency. *Quaternary Research*, 31, 14-26.

GREEN, C. 1995. The Curry Fund of the Geologist's Association: paying for earth science conservation. *Geoscientist*, 5, 15-16.

HOYOS, M., LARIO, J., GOY, J.L., ZAZO, C., DABRIO, J.C., HILAIRE-MARCEL, C., SILVA, P., SOMOZA, L. & BARDIJI, T. 1994. Sedimentacion karstica : Procesos morphosedimentarios en la zona del Estrecho de Gibraltar. In: RODRIGUEZ VIDAL, J., DIAZ DEL OLMO, F., FINLAYSON, C. & GILES PACHECO, F. (eds) Gibraltar during the Quaternary. *AEQUA Monografías*, Seville, 2, 36-48.

IMRIE, [N.]. 1798. A short mineralogical description of the mountain of Gibraltar. *Transactions of the Royal Society of Edinburgh*, 4, 191-202.

JAMES, T. 1771. *History of the Herculean Straits, commonly called the Straits of Gibraltar.* Rivington, London. 2 vols.
KRINSLEY, D.H. & DOORNKAMP, J. 1973. *Atlas of quartz sand surface textures.* Cambridge University Press, Cambridge. 99p.
O'HALLORAN, D., GREEN, C., HARLEY, M., STANLEY, M. & KNILL, J. (eds) 1994. *Geological and Landscape Conservation.* Geological Society, London. 554p.
PROCTOR, C.J. & SMART, P.L. 1991. A dated cave sediment record of Pleistocene transgressions on Berry Head, Southwest England. *Journal of Qauternary Science*, 6, 233-244.
PROSSER, C.D. 1995. Conserving our Earth heritage through Natural Areas, *Geoscientist*, **5**, 19-20
RAMSAY, A.C. & GEIKIE, J. 1878. On the geology of Gibraltar. *Quarterly Journal of the Geological Society of London*; 34, 505-541.
ROBINSON, E. 1995. The role of the voluntary sector in earth science conservation. *Geoscientist*, 5, 13-14.
ROSE, E.P.F. (in review) Geological interpretation of the Rock of Gibraltar 1749-1878: from natural history to practical geology, a case study of changing emphases in early earth sciences. *Archives of Natural History*.
ROSE, E.P.F. & HARDMAN, E.C. 1994a. Quaternary geology of Gibraltar. In: RODRIGUEZ VIDAL, J., DIAZ DEL OLMO, F., FINLAYSON, C. & GILES PACHECO, F. (eds) Gibraltar during the Quaternary. *AEQUA Monografias*, Seville, 2, 21-25.
ROSE, E.P.F. & HARDMAN, E.C. 1994b. The caves, tunnels and rocks of Gibraltar. *Sanctuary*, 23, 16-17
ROSE, E.P.F. & ROSENBAUM, M.S. 1990. *Royal Engineer Geologists and the Geology of Gibraltar.* Gibraltar Museum, Gibraltar. 55p. (Reprinted from *Royal Engineers Journal*, 103 (for 1989), 142-151, 248-259; 104 (for 1990) 61-76, 128-144).
ROSE, E.P.F. & ROSENBAUM, M.S. 1991a. *A Field Guide to the Geology of Gibraltar.* Gibraltar Museum, Gibraltar. 192p.
ROSE, E.P.F. & ROSENBAUM, M.S. 1991b. The Rock of Gibraltar. Geology Today, 7, 95-101.
ROSE, E.P.F. & ROSENBAUM, M.S. 1994a. The Rock of Gibraltar and its Neogene tectonics. Paleontologia i Evolucio, 24-25 (for 1992), 411-421.
ROSE, E.P.F. & ROSENBAUM, M.S. 1994b. The Pre-Quaternary Geological Evolution of Gibraltar. In: RODRIGUEZ VIDAL, J. , DIAZ DEL OLMO, F., FINLAYSON, C. & GILES PACHECO, F. (eds) Gibraltar during the Quaternary. *AEQUA Monografias*, Seville, 2, 6-11.
ROSENBAUM, M.S. & ROSE, E.P.F. 1991. Geology of Gibraltar. Single sheet 870 x 615mm: Side 1, cross-sections and solid (bedrock) geology map 1:10,000, Quaternary geology, geomorphology, and engineering use of geological features maps 1:20,000; Side 2, illustrated geology (combined bedrock Quaternary geology) map 1:10,000, plus 17 coloured photographs/figures and explanatory text. *School of Military Survey Miscellaneous Map 45.*
SHACKLETON, N.J. 1987. Oxygen isotopes, ice volume and sea level. *Quaternary Science Reviews*, 6, 183-190.
SMART, P.L., SMITH, B.W., CHANDRA, H., ANDREWS, J.N. & SYMONS, M.C.R. 1988. An intercomparison of ESR and uranium series ages for Quaternary speleothem calcites. *Quaternary Science Reviews*, 7, 411-416.
SMITH, J. 1846. On the geology of Gibraltar. *Quarterly Journal of the Geological Society of London*, 2, 41-51.
STANLEY, M.F. 1995. Earth science conservation. *Geoscientist*, 5, 11-12.
TRATMAN, E.K. 1971. The formation of the Gibraltar Caves. *Transactions of the Cave Research Group of Great Britain*, 13, 135-143.
TRECHMANN, C.T. 1943. Some Pleistocene land shells from Gibraltar. *Annals and Magazine of Natural History, London*, series 11, 10, 426-431.
WILLIAMS, D.F., THUNELL, R.C., TAPPA, E., RIO, D. & RAFFI, E. 1988. Chronology of the Pleistocene oxygen isotope record 0-1.88 m.y.B.P. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 64, 221-240.
WILSON, C. (ed.) 1995. *Earth Heritage Conservation.* Geological Society, London. 276 p.
ZAZO, C. & GOY, J.L. 1989. Sea-level changes in the Iberian peninsula during the last 200,000 years. In: SCOTT, D.B. *et al.* (eds) *Late Quaternary Sea-level Correlation and Applications.* Kluwer Academic Publishers, 27-39.
ZOLLIKOFOR, C.P.E., PONCE DE LEÓN, M.S., MARTIN, R.D. & STUCKI, P. 1995. Neanderthal computer skulls. *Nature*, 375, 283-285.