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Biokarst Development: Contrasting Cases from Dwarka Coast, Gujarat, India

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Abstract

Biokarst development is a characteristic feature of tropical, biogenic coasts, including coral reefs and rocky carbonate (limestone) coasts. Development of biokarst is considered as an important driver of Holocene coastal evolution and the same is considered as a geomorphic indicator of present tidal regime. Bio-eroding organisms play an important role in the ecosystem dynamics and geomorphological development of micro-topography in these coasts. Biokarst features developed on beach rock exposures from Indian coral reef coasts have so far been reported in geological and paleontological studies. A detailed appraisal of their origin and evolution remains rather unexplored in the context of coastal geomorphology of Indian reefs. This paper documents the differences observed in biokarst features in two sites from Dwarka coast of Saurashtra peninsula of Gujarat and tries to correlate these variations with coastal, weathering and ecological processes (bio-erosion) that are shaping their development. This study is based on extensive field observations and morphometric measurements. Individual biokarst forms and associated molluscan fauna can be considered as indicators of tidal regime and erosional processes leading to biokarst zonation. Siphoneria sp. of limpets and Littorina sp. of periwinkles can be considered as indicators of intertidal and supratidal zones in biokarst landscape of Dwarka coast. Pan-sharpened, sub-meter resolution multi-spectral images seem to be a major requirement for detection of biokarst landscape from space.

Keywords : *Biokarst, micro-topography, Bio-erosion Dwaraka coast.*

1. Introduction

Coral reefs and rocky carbonate (limestone) coasts constitute almost a third of tropical coastlines (Birkeland 1997). Warm climate, abundance of calcareous substrates and varied marine biota lead to biokarst development: typical of these biogenic coasts. Biokarst is defined as small scale karst landform produced mainly by organic action (Thomas and Goudie 2009). Viles (1984) proposed the term 'biokarst' as an "umbrella term" for 'a landform produced largely by the direct biological erosion and/or deposition of calcium carbonate'. Biokarst features can be either erosional (abrasion and boring of carbonate rock surfaces by organisms) or constructional (certain reef forms and tufas). Bio-eroding organisms play an important role in the ecosystem dynamics and bio-geomorphological development of micro-topography in these coasts. The three main distinctive features of biokarst landscape are i) notches, ii) vertical pinnacles or lapies and iii) circular forms like pits, pools or pans. All together they produce an assemblage of small-scale (in millimeters) to large-scale (in meters), jagged, pool and pinnacle topography in calcareous beach rock outcrops: a common feature of these coasts. Biokarst development is considered as an important driver of Holocene coastal evolution (Duane 2006). Biokarst features developed on beach rock surfaces serve as eco-geomorphic indicators of present sea level variations. Biokarst landscape can also suffice as a miniaturized field laboratory to study several coastal landforms and model their development. These landscapes result from a complex interplay of coastal, weathering and ecological processes and offer excellent research area to study the complexities present in carbonate coastal environments (Spencer and Viles 2002).

Bioclastic, carbonate, Quaternary shore deposits or beach rocks associated with Indian coral reef coasts have mostly been studied from geological (Krishna Kumar et al. 2012; Bhonde and Desai, 2011; Bhatt, 2003; Khadkikar and Rajshekhar, 2003) and ecological (Rajshekhar and Reddy, 2002; Pillai and Appukuttan, 1980) perspectives. Bhatt, 2003 and Bhonde and Desai, 2011 have reported karstification of exposed beach rock surfaces from certain parts of Saurashtra coast of Gujarat which lies in close proximity to present reef formations in Gulf of Kachchh. These beach rocks lithologically comprise of bioclastic limestone and conglomerate. Bhatt, 2003 has classified these beach rocks as *calcirudites* (coarse and shell rich variety) which belong to Okha Shell Limestone Member of Chaya Formation of Middle to Late Pleistocene age (Bhonde and Desai, 2011). Trenhaile (1987) has considered parts of Saurashtra coast as one of the typical example of littoral zonation in coral limestone coasts of warm seas. However, a detailed appraisal of such karst (more precisely biokarst) features on beach rock surfaces and their geomorphic evolution from Indian reef coasts still remains unexplored.

This paper documents the differences observed in biokarst morphology in two sites from Dwarka coast of Gujarat, India and tries to account these differences in the light of site-specific, subtle variations in coastal, weathering and ecological processes that are shaping their development.

2. Study Area

Two coastal locations (Fig.1 see page 235) from Dwarka coast (a subset of Saurashtra coast of Gujarat) were selected as test cases for this study on biokarst landscape developed on beach rock exposures in Okhamandal area of coastal Saurashtra. The first site is located in the northern beach of Bet Shankhodhar or Bet Dwarka Island adjacent to coral reef area and shares the environmental characteristics of Jamnagar-Okha segment (Merh, 1995) of Saurashtra coast. The second site is located in the west-facing rock-shore platform to the south of Bhadkeshwar Temple in Dwarka. This site is representative of environmental characteristics of Dwarka-Diu segment of the Saurashtra coast. The sites were selected as ideal representations of biokarst landscape after preliminary field visits carried out in February and April, 2008.

3. Materials and Methods

3.1. Remote Sensing:

For this study, an initial attempt was made to visually identify the signatures of known biokarst landscape in Okhamandal area from high spatial resolution (5.8m), multi-spectral images as captured by Resourcesat-1 (IRS-P6) LISS-IV imaging sensor on different dates and tidal conditions. Seven LISS-IV MX scenes (precision geocoded products) of Dwarka coast pertaining to 2007 to 2009 period were analysed to locate the biokarst features on the images. It appeared from on-screen analysis that the biokarst landforms were neither spatially resolved nor spectrally detected at individual pixel level and got converged into spectrally bright signature of broad coastal form of the adjacent beach or the rock-shore platform. This can be attributed as a limitation of the spatial resolution of the sensor. However, macro-scale signatures of biokarst landscape as beach rock exposures from Bet Shankhodhar and Dwarka sites are visible in sub-meter resolution, pan-sharpened multi-spectral images from GeoEye-1 satellite data dated 20th October, 2012 and 12th May, 2010 respectively. (http://www.google.com/earth/index.html). GeoEye-1 satellite acquires panchromatic (spatial resolution: 0.41 meter) and multi-spectral images (1.65 meter) of earth from an altitude of 681 km.

3.2. Field Measurements:

Both the sites were visited for detailed field observations in July, 2011 and in December, 2012. The sites were surveyed during their low tide exposures (Survey of India Tide Tables: 2011 and 2012; reference tidal station: Okha.). Coastal profiles of biokarst landforms (from their seaward ascent to final transition under present beach material) were carried out from each site. On each profile the extents of morphological and biological zonation were marked according to the micro-form assemblages and presence of key molluscan species. The field surveys documented the frequency, size and shape of biokarst features and comments on bio-erosive actions. Extensive field photography was carried out to analyse the individual biokarst features. Major morphometric parameters: length, breadth, depth and degree of connectivity (in terms of coalescence ratio) for pools and near-vertical or slant height of pinnacles (or lapies) were measured in field to adapt the morphometric approach followed by Gómez-Pujol and Fornós (2010) and Johansson et al. (2001) for their study on coastal karren features and rock-basins. Measurements of structural controls (like joints and fractures) and algal contribution to bio-erosion have not been considered for this study.

4. Results & Discussion

Both Bet Shankhodhar and Dwarka sites show significant biokarst development on beach rocks in the intertidal and supratidal area which receives different levels of daily exposures during the low-tides. The biokarst landscape of Bet Shankhodhar (Fig.2A see page 235) and Dwarka (Fig.3A see page 236) can be separated into three distinct, geomorphic zones in its vertical, shore-zone profile with dominant micro-features as summarized in Table: 1. The micro-features in each zone reported in Table 1 are sequenced as per their frequency of occurrence.

Table: 1 Salient Characteristics of Morphological Zones identified in the Biokarst Landscape

	Morphological Zones			
Field Sites	**Dominant Micro-features**	**Zone:1**	**Zone:2**	**Zone:3**
Site: 1 Bet Shankhodhar	Circular and Elliptical Plan Forms	Elliptical Pools	Honeycombs; Bore holes; Elliptical to Circular Pools	Flat-floored Pans with irregular edges; Presence of salt crystals
	Vertical Forms	Pyramidal Lapies	Cliffs (Notches and Visors); Vertical Lapies with serrated edges	Absent
	Dominant Bio-eroders	Limpets (*Siphonaria* sp.)	Gastropods (*Nerita sp.*) and Periwinkles (*Littorina sp.*)	Periwinkles (*Littorina sp.*)
Site: 2 Dwarka	Circular and Elliptical Plan Forms	Oval Pits	Honeycombs; Circular to Elliptical Pools	Elliptical, flat-floored Pans with regular edges; Presence of salt crystals
	Vertical Forms	Inconspicuous	Pyramidal Lapies with serrated edges	Absent
	Dominant Bio-eroders	Chitons and Limpets (*Siphonaria* sp. and *Clypidina* sp.)	Chitons and Periwinkles (*Littorina sp.*)	Periwinkles (*Littorina sp.)*

4.1 Vertical Zonation and Form Assemblages:

Zone: 1

The extreme seaward zone or zone 1 in Bet Shankhodhar rises from a narrow strip of beach which separates the macroalgae dominated coral reef area from the beach rock surfaces. This zone extends over an approximate width of 7 to 9 meters dominated by elliptical to circular pools and pyramidal lapies (Figure 2B). The pools have an average length of 25 cm, breadth of 19 cm and average height of the pool walls range between a maximum of 13 cm to a minimum of 6.5 cm (Fig.4 Zone:1 see page 236). The average lapie height in this zone is 30 cm. The lithified beach material has a fine coating of silt and appears in offwhite colour in this zone. The individual pools are disconnected in the seaward side and shows coalescence with a ratio of 2:1 to 3:1 (i.e. 2 pools joining to form 1 pool) as one move inward. Structural control on pool coalescence has been noticed in this zone. Pools are filled with fine to coarse broken shells in the seaward side and the size of fill-material increases as one move inward. Round conglomerate pebbles are arrested within the pools in the rear end of this zone1. Green filamentous algae *Enteromorpha sp.* cover the lapie walls while green macro algae *Ulva sp.* is found within some of the water-filled pools. Limpets like *Siphoneria sp.* (Figure 2E) dominate this zone.

In case of Dwarka, zone 1 starts from a height of 35 to 40 cm above the rock-shore platform and extends over a shorter width of 3 to 4 meters. This zone is marked by the presence of small elliptical pits and absence of lapies (Figure 3B). The small elliptical pits are basically an extended and coalesced form of multiple, small chiton-homing scars sharing one common wall whose minimum length ranges from 7 to 9 cm. The average dimensions of these coalesced pools are 19 cm in length, 12 cm breadth and wall heights ranging from a maximum of 9 cm to a minimum of 3 cm (Figure: 4 Zone:1). In the seaward front individual pools are disconnected while coalescence starts with a ratio of 2:1 to 3:1 as one moves inward. Green (*Ulva sp.*) and brown macro-algae attached to the substrate are present within the pools mostly filled with water along with species of algae –grazing Chitons and limpets like *Siphoneria sp. and Clypidina sp.* The pools are free of beach deposits unlike Bet Shankhodhar.

Zone: 2

An extremely bio-eroded, honey-combed cliff face (average height: 80 to 90 cm) separates zone 2 from zone 1 in Bet Shankhodhar site. In certain cases the notches created in this cliff-face has extended into small caves with a maximum length of 220 cm, width of 250 cm and height of 102 cm. Sharp, serrated, vertical lapies and well-scooped pools are located above the cliff or more precisely the visor (Figure 2C) and this zone extends over a width of 3.25 meters. The pools in this zone have average length of 18 cm, breadth of 19 cm and maximum wall height of 16 cm to minimum wall height of 6 cm (Figure 4 Zone:2). Pools show a coalescence ratio of 5:1. The lapie heights range from 14 to 18 cm. The whole zone appears in a grayish brown colour. Pinkish colour of pool walls indicates presence of micro-algae while gastropods like *Nerita sp.* (Figure 2F) and periwinkles like *Littorina sp*. (Figure 2G) dominate in the cliff-wall and lapie-pools respectively. These two are considered as the major bio-eroding agents in this zone. Lapie-pools are free of any beach deposits.

In case of Dwarka, zone 1 culminates into Zone 2 and there is no exposure of cliff-face (or visor) and notch as a separating unit within the biokarst. The pool and pinnacle micro-topography remains same but differ considerably in morphometry as compared to Bet Shankhodhar site (Figure 3B). The pools have an average length of 55 cm, breadth of 49 cm and wall heights ranging from a maximum of 46 cm to a minimum of 18 cm (Figure 4 Zone:2). Pool dimensions are in fact more than double as compared to Bet Shankhodhar site. The pools here have a composite structure indicating coalescence of multiple pools into a large pool. The coalescence ratio for these large pools is 2:1

to 3:1. Pool floor is generally serrated with remnant walls of earlier pools and generally has an average water column of 3 to 5 cm. Pool floors become smooth and flat in the rear end of this zone. Pools are free of any beach deposit. The whole topography appears in an orangish brown colour indicating an oxidized environment. Water within the pools appears in greenish yellow colour indicating presence of micro-algae. In this zone Chitons (in pool floor in the front zone; Figure 3E) and periwinkles like *Littorina sp.* (pool and lapie-walls) (Figure 3F) are the dominant molluscan fauna contributing to extensive bio-erosion. Patch density of *Littorina sp.* increases as one move inward.

Zone: 3

The third and the topmost zone is featured with coalesced pans on relatively flat beach rock surface in Bet Shankhodhar and extends for a width of 2.70 meters. The flat-floored, coalesced pans with irregular edges (Figure 2E) have an average length of 66 cm, breadth of 31 cm and walls with a maximum height of 12 cm to a minimum height of 7 cm (Figure 4 Zone:3). The pans show a coalescence ratio of 3:1. Pinnacles or lapies are not present in this zone. Presence of salt crystals is noted within the pan floors and *Littorina sp.* dominates the pans mostly along joint lines.

In case of Dwarka similar micro-forms have developed on an extremely indurated, oxidized, flat, beach rock surface which extends upto the linear cliff-base for a width of 5 meters. The flat-floored pans (Figure 3D) have a characteristic balloon or elliptical shape with regular edges unlike Bet Shankhodhar. The pans have an average length of 34 cm, breadth of 32 cm and wall height ranging from maximum of 9 cm to a minimum of 5 cm. The pan-floors appear orange in colour, smooth and in certain cases serrated beneath the brown, indurated, honeycombed duricrust. Lapies are absent in this case too. Salt encrustations are noticed in the pan-floors. *Littorina sp.* is present in this zone however with a decreasing patch density.

4.2 Vertical Zonation of Bioerosion

In case of Bet Shankhodhar site, limpets like *Siphonaria sp*. dominate in zone 1 while other macro-boring gastropods like *Nerita sp.* and rock-grazing *Littorina sp.* dominate zone 2 and 3. Presence of *Littorina sp.* in the rear end of zone 2 and in zone 3 is indicative of intertidal to supratidal transition of the biokarst zones. Both limpets and the gastropods found in Bet Shankhodhar lead to "burrowing and browsing" processes of bio-erosion through mechanical rasping with their radula (Fairbridge, 1968). Limpets are however known for erosion through shell abrasion.

In case of Dwarka, Chitons (belonging to Class: Polyplacophora of phylum Mollusca) dominate in zone 1 and 2 while *Littorina sp.* in Zone 2 and 3. Chitons and limpets like *Clypidina sp.* and *Siphonaria sp*. in zone 1 and Chitons in zone 2 can be considered as indicators of inter-tidal environment while *Littorina* sp. in rear of zone 2 and in zone 3 are indicative of commencement of supratidal zone. The browsing and burrowing erosional activity through mechanical abrasion with a radula reinforced with magnetite mineral is known for chitons (Fairbridge, 1968).

Table 2 summarizes the hydrodynamic conditions and sub-aerial processes (sequenced according to their operational intensities) which can be related to these morphological zones.

Table 2 : Hydrodynamic conditions and erosional processes operating in the Morphological Zones identified in the Biokarst landscape. (+ sign denotes processes working in conjunction).

Field Sites	Hydrodynamic conditions	Morphological Zones			
		Zone:1	Zone:2		Zone:3
Site:1 Bet Shankhodhar	Tidal Zone	Intertidal	Intertidal	Supra-tidal	Supra-tidal
	Processes	Wave erosion + Bio-erosion	Wave erosion+ Splash+ Bio-erosion	Spray+ Bioerosion+ Physico-chemical weathering	Physico-chemical weathering + Bioerosion+ Spray
Site:2 Dwarka	Tidal Zone	Intertidal	Intertidal	Supratidal	Supratidal
	Processes	Bio-erosion+ Wave erosion	Wave erosion+ Splash+ Bio-erosion	Spray+ Bio-erosion+ Physico-chemical weathering	Physico-chemical weathering + Bio-erosion+ Spray

5. Conclusions

From the preceding discussion on the morphological zones, it emerges that the three morphological zones of biokarst landscape from the selected sites represent subtle variations in coastal processes at micro-scale. In both the sites zone 1 and seaward part of zone 2 are intertidal in nature while rear part of zone 2 and zone 3 represent supratidal segments (Table: 2). In fact occurrence of *Littorina sp.* can be considered as the signature of the commencement of supratidal zone. Wave erosion dominates in zone 1 for Bet Shankhodhar while the frontal part of zone 2 is affected by splash action of the waves. Rear end of zone 2 and zone 3 are sculpted by a combination of processes: spray action of sea water, biological and physico-chemical weathering. Presence of salt crystals is indicative of active physico-chemical weathering in this zone.

It is inferred that for a precise process-zonation, zone 2 needs to be further subdivided with reference to this tidal transition. Biological boring and honeycombing is present only in the cliff-face of zone 2 in Bet Shankhodhar which is completely absent in Dwarka as a biokarst feature. The large scale pool dimensions in zone 2 of Dwarka is a result of strong wave energy and surf action as compared to Bet Shankhodhar site which has a higher tidal energy but comparatively low wave energy conditions (Merh, 1995). Absence of vertical lapies in zone 1 of Dwarka in contrast to Bet Shankhodhar is indicative of high intensity bio-erosion and low-intensity wave erosion. Thus, the subtle points of contrast between the two biokarst sites lie in zone 1: absence of vertical lapies in zone 1 in Dwarka; absence of cliff-face in zone 2 in Dwarka and in terms of lapie-pool morphometry in zone 2.This point calls for further investigations in future.

From remote sensing point of view biokarst landscape demands sub-meter resolution stereo data and development of suitable photogrammetry techniques for image based morphometric analysis. In this regard utility of Cartosat data products in combination with Resourcesat LISS IV multi-spectral products can be examined in future.

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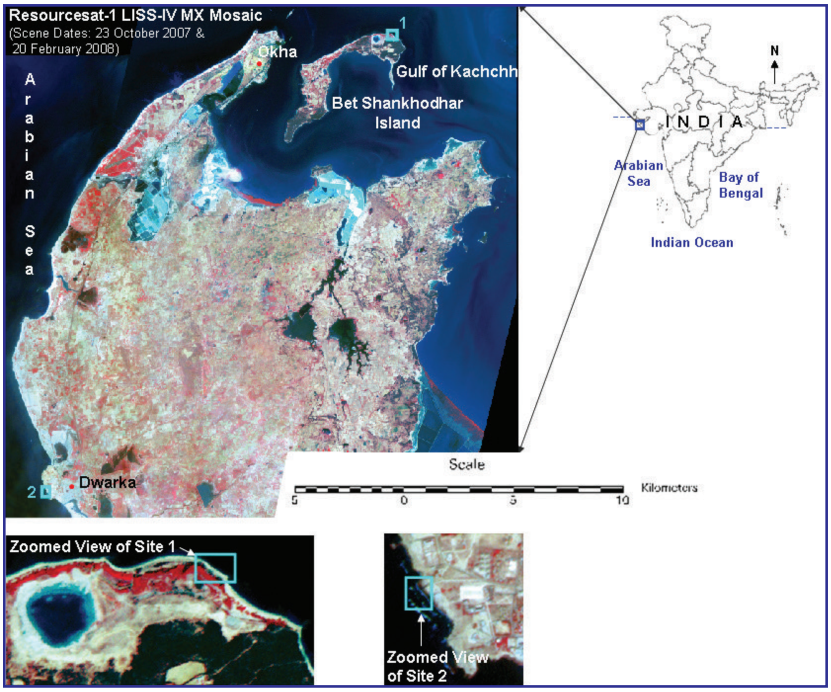

Fig.1 See page 226 for text

Fig.2 See page 226 for text

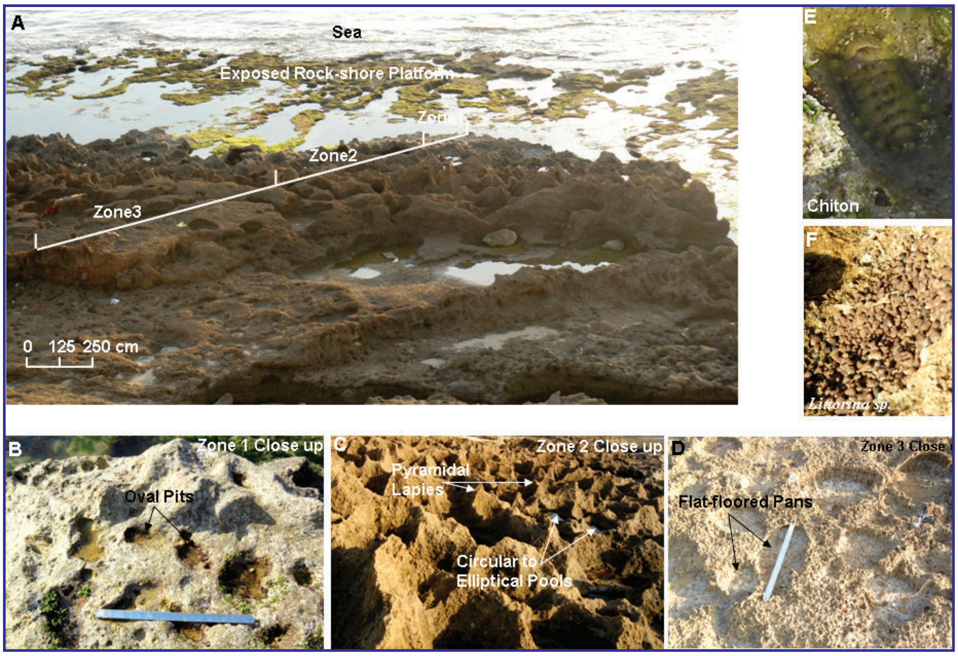

Fig.3 See page 227 for text

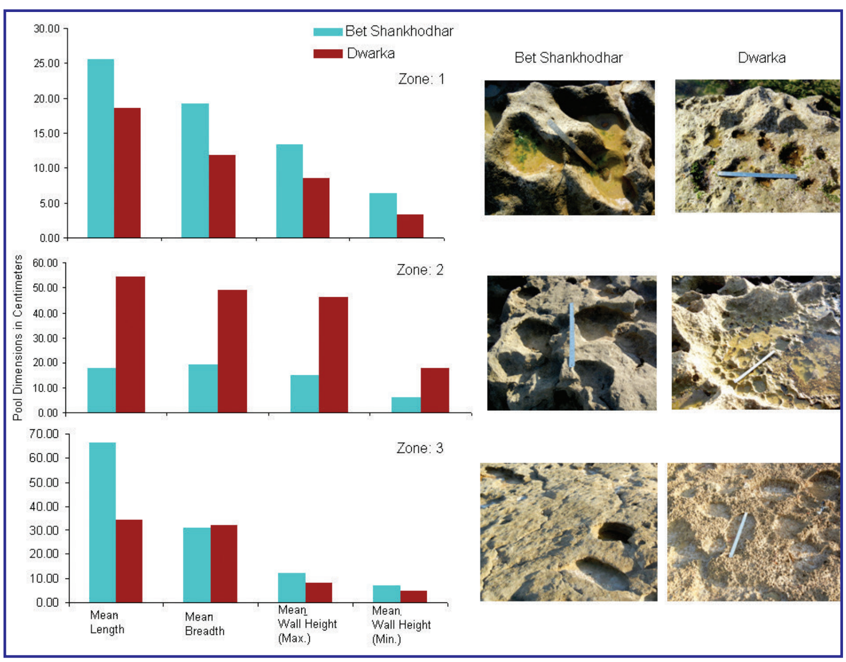

Fig.4 See page 228 for text

Plate 1 : See page 245 for text

Plate 2 : See page 245 for text

Plate 3 : See page 245 for text