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Shannon Ferguson
Louisiana State University and Agricultural and Mechanical College

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EVALUATION OF PLEISTOCENE TO HOLOCENE (MIS 5 TO 1) CLIMATIC CHANGES IN SOUTHWESTERN BLACK SEA: A PALYNOLOGICAL STUDY OF DSDP SITE 380

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in The Department of Geology and Geophysics

by

Shannon Ferguson
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ABSTRACT

Site 380 of the Deep Sea Drilling Program [DSDP] is located in the southwestern region of the Black Sea (42°05.94’, 29°36.82’E). The location of this site is important due to its proximity to the narrow Bosphorus strait, the only present-day connection between the Black Sea and the Aegean Sea. Drops in eustatic sea level during extensive Pleistocene glacial episodes disconnected the Black Sea from the Aegean Sea at the Bosphorus strait, creating a change from brackish to freshwater within the Black Sea during these intervals. Organic-walled phytoplankton (dinoflagellate cysts, acritarchs, and fresh-water algae) are investigated to better constrain these glacio-eustatic sea-level changes associated with extensive Pleistocene glacial episodes that resulted in interruption of water exchange between the Black Sea and the Aegean Sea. A combination of high-precision analysis of morphological changes seen in two of the most abundant dinoflagellate cyst species present, *Galeacysta etrusca* and *Spiniferites cruciformis*, is undertaken and is combined with dinoflagellate assemblage changes to evaluate a possible morphological response of the cysts to changes in sea-surface salinity and better quantify the impact of sea level changes on the history of the connection.

**Keywords:** Black Sea; dinoflagellates; salinity; *Spiniferites cruciformis*; *Galeacysta etrusca*; *Pyxidinopsis psilata*; DSDP Site 380; brackish; sea level.
CHAPTER 1. PRESENT-DAY PHYSIOGRAPHIC SETTINGS OF THE MODERN BLACK SEA REGION

1.1. Geography

The Black Sea (42°05.94’N, 29°36.82’E) is a large semi-enclosed basin located between southeastern Europe and Asia (Fig. 1). At present, the Black Sea has only one marine connection, through the Bosphorus strait (Fig. 1). The strait is relatively shallow, with its shallowest depth being approximately 30 meters near Istanbul, Turkey. The depth of this connection limits the salinity and oxygen provided to the Black Sea (Kerey et al., 2004). The Bosphorus Strait connects to the Marmara Sea, which then connects to Aegean and Mediterranean seas through the Dardanelles strait (Fig. 1). In addition to this marine connection, the Black Sea currently also has one non-marine connection. The narrow Straight of Kerch connects to the freshwater Sea of Azov. At a maximum depth of 14 meters, the Sea of Azov is the shallowest sea in the world. It has a constant outflow of water to the Black Sea (Kosarev et al., 2008).

1.2. Modern Hydrographic Configuration

The Black Sea’s drainage basin is extensive, covering territories of 22 countries and is approximately 1,864,000 km² (UNEP, 2009; Ross et al, 1978a). The hydrographic configuration of the Black Sea is controlled by basin bathymetry and fluvial inputs from the discharge of large
European rivers: the Danube, Bug, Dniepr, Dniestr, Don, Kuban, and the Rioni (Fig. 2) (UNEP, 2009). The Danube, the second largest river in Europe (behind the Volga River) is by far the largest of this group. It flows through ten European countries and constitutes more than 50% of the total river run-off entering the basin (Bahr et al., 2005). Average annual river runoff into Black Sea is 350 km$^3$ per y against a total Black Sea volume of 534,000 km$^3$ (Murray et al., 2005). As a whole the Black Sea’s surface area occupies approximately 423,000 km$^2$ with a maximum water depth of 2.2 km (Nikishin et al., 2003; Murray et al., 2005).

Figure 2. The modern drainage basin of the Black Sea, including the watershed and relief (blue lines represent the major rivers) (after Paleari et al., 2005).

The Black Sea’s seabed is comprised of a broad continental shelf, continental slope, and a deep basin floor. Its shelf occupies a large area in the northwestern part of the Black Sea, where it ranges between 2.2 to 200 km wide and has a depth ranging from 0 to 160 meters (Ross et al., 1978a). Deep Sea Drilling Program (DSDP) Site 380 is located near the base of the slope on the
basin apron, which is a sloping area that is similar to a continental rise (Neprochnov and Ross, 1978; Ross et al., 1978a).

The Black Sea’s circulation is of interest to many geoscientists since it represents how salt balance controls work in the oceans on a smaller scale, and how oceans function when the conveyor belt is shallower (Stanev, 2005). The eastern and western gyres, and several smaller coastal eddies currently dominate Black Sea’s surface circulation (Fig. 3) (Stanev et al., 2001). Stanev (2005) proposes that wind and winter convection are the primary controls on surface circulation and mixing (Fig. 4) based on numerical models. The influx of cold marine water from the Mediterranean Sea through the Bosphorus sill controls deep-water circulation (Mudie et al., 2002). As this water flows to the east, the geothermal heat flux slowly mixes the water at a rate of 2.5 ka (Mudie et al., 2002).

Figure 3. Sea surface circulation in the Black Sea (Stanev, 2005).
Freshwater river input keeps modern day sea surface salinity (SSS) distribution in the surface waters of the Black Sea surface salinity low (SSS= 18.0 +/- 0.5 in the central region) (Figure 5a). Seawater enters through the Bosphorus at an original average salinity of 34.9 (Murray et al., 2005). This produces a densely stratified water column due to the largely varying salinities entering the region (Murray et al., 2005). Bottom water SSS for the modern Black Sea average 22.33 ppt. A consequence of this vertical stratified sea is that the surface layer (from 0 to 50 m) is well oxygenated while the deep water (approximately 100 to 2243 m) is highly anoxic, and rich in sulfides (Murray et al., 2005). The approximate permanent location of the halocline is 50 to 200 m (Murray et al., 2005).

The modern day temperature distribution in the Black Sea is 14.5° C to 15.0° C during the summer months, and 12.5°C to 13.5°C during the winter months (Murray et al., 2005) (Figures 5b-d). The Black Sea obtains its maximum sea surface temperature (SST) of 15°C near the Bosphorus strait since this is the only source of warm water for the basin (Murray et al., 2005).
Figure 5a. Physical surface parameters of the Black Sea: Sea Surface Salinity (www.ims.metu.edu.tr/cv/oguzt/bs_res.html).

Figure 5b. Physical surface parameters of the Black Sea: Sea Surface Temperature in August (www.myocean.eu).
Figure 5c. Physical surface parameters of the Black Sea: Sea Surface Temperature in October (www.myocean.eu).

Figure 5d. Physical surface parameters of the Black Sea: Sea Surface Temperature in Spring (www.myocean.eu).
CHAPTER 2. GEOLOGICAL AND PALEOENVIRONMENTAL EVOLUTION OF THE BLACK SEA REGION

2.1. Geological and Tectonics Settings

The Black Sea is located south of the European craton and is surrounded to the north, northeast, south, and southwest by Alpine-like systems, such as the folded mountain systems of Crimea, Caucasus, Asia Minor, and the southern Balkans (Letouzey et al., 1978; Neprochnov and Ross, 1978). The structure of this region is complex due to its position on several structural zones (Letouzey et al., 1978).

In the 1978 Initial Reports of the DSDP Site 380, these authors (Neprochnov and Ross, 1978; Letouzey et al., 1978) stated that the timing and origin of the Black Sea was, at the time of the drilling, heavily debated and controversial because wells drilled previously in the Black Sea only penetrated the Late Miocene to Quaternary sedimentary cover. Therefore, the sediments recovered were unhelpful in interpreting the region’s original structures (Ross, 1978a). Later studies collected geophysical data around DSDP site 380 along with several seismic transects which revealed that the timing and origin of the Black Sea as a Cretaceous back-arc basin (Nikishin et al., 2003).

According to Muratov et al. (1978), there were three stages in the formation history of the Black Sea. The first stage began in the Cretaceous-Paleogene Periods. During this time, there was no deep-sea trough, only a shallow basin was present (Muratov et al., 1978). During the second stage, in the Oligocene-Miocene Periods, the eastern and western depressions (Fig. 6 & Fig. 7), which are still present today, were formed and were associated with rapid deposition and subsidence, that, in some areas, reached up to 3-5 km in thickness. Diatom analysis conducted on this Oligocene-Miocene section at DSDP Site 380 indicate that the Black Sea was a freshwater lake at that time, however then turned brackish/marine during this interval as evident by the first marine assemblage, suggesting a marine connection (Muratov et al., 1978). The third stage takes place in the Miocene-Quaternary periods that are characterized by successive fluctuations between brackish to freshwater conditions with continued subsidence occurring within the deep-sea basin (Muratov et al., 1978).
Figure 6. Regional tectonic setting and location of the Black Sea’s eastern and western basins (Nikishin et al., 2003).
The lithology of the sediment recovered at DSDP Site 380 is divided into five stratigraphic units solely based on sedimentary characteristics (color, grain size, composition, etc.) (Fig. 8), and is then further subdivided to allow for lithostratigraphic correlations within the Black Sea (Ross et al., 1978b). The major stratigraphic units are: Unit I (0-332.5 m) made of terrigenous sediments including muds, sandy silts; Unit II (332.5-448 m) made of various chemical sediments such as aragonite, sideritic and calcitic lake marls (referred to as “seekreide”), interbedded with muds; Unit III (448-646 m) made of lake marls and calcitic oozes; Unit IV (646-969 m) composed of various chemical sediments, calcitic, sideritic, aragonitic and dolomitic, interbedded with muds; and finally the Unit V (969-1074 m) made of black shales interbedded with dolomitic and zeolitic silt layers (Fig. 8). Because this work refers to the first 70 m of DSDP Site 380, which corresponds to Unit I, this stratigraphic unit is detailed in the following paragraph.

Unit I spans from 0 to 332.5 m in the core recovered by DSDP 380. Within Unit I there are eight subunits defined by Ross et al. (1978a), the uppermost four are of interest in this study (Fig. 8). Out of these four subunits, the upper three subunits (Subunit Ia, Ib, and Ic) had either no
recovery or very poor recovery due to the fact that drilling rarely recovers surface and other top core sediments (Ross et al., 1978a). In Subunit Ia, a 30 cm nannofossil ooze layer was present in the Black Sea piston cores. Nannofossil oozes are of special interest as they are a common component of present day Black Sea sediments. They will be discussed in greater detail in Section 2.2.

Figure 8. Distribution of salinity (Popescu, in press).

Subunit Ib, a sapropel (a mud rich in organic matter formed at the bottom of a body of water), was recovered ~2 meters, but was badly disturbed during drilling processes. This sapropel unit consists of organic (10%) and diatom rich (15%) dark grey mud (Ross et al., 1978a). While this subunit was classified as a sapropel in the Initial Reports of the Deep Sea Drilling Program Volume 42 Part 2 (Ross et al., 1978b), new $C_{\text{org}}$ sediment analysis states that it is non-sapropelic (0.60% $C_{\text{org}}$); however, this may be a result of sediment mixing during drilling (Ross et al., 1978a). Recovery of Subunit Ic, (~2 to 42 m, was poor and badly disturbed from drilling (Ross et al., 1978a). This
subunit is one of the sandiest sections in the core recovered from DSDP Site 380 (Ross et al., 1978a). Small amounts of dark gray sapropelic mud ($C_{org}$ of ~1%) are found along with terrigenous mud and sandy silts. The sapropel was believed to be in place, but down-hole contamination is possible (Ross et al., 1978a). The terrigenous sandy silts dominating this subunit were deposited in fresh-water settings as suggested by fresh-water diatom species recovered from this subunit. This will be discussed further in Section 2.2. The last lithologic subunit is Subunit Id, ranging from 45 to 76 m. It consists mostly of diatomaceous muds (Ross et al., 1978a). While a strong marine influence at the time of deposition is suggested by the abundance of marine diatoms (up to 25%) recovered from this subunit, the absence of diversified nannofossils and foraminifers indicates that this section was likely a brackish-water environment (Ross et al., 1978a).

The sedimentation rates and compositions of Black Sea sediments are largely dependent on climatic conditions (Muratov et al., 1978). The Black Sea’s high sedimentation rate during the Quaternary is estimated to be ~33-43 cm/10$^3$ yr, which is comparable to the Gulf of Mexico’s Quaternary rate of ~38 cm/10$^3$ yr (Ross et al., 1978a). During interglacial eustatic-high intervals, the sea becomes densely stratified and the formation of sapropelic muds takes place (Muratov et al., 1978). During glacial periods with no marine connection, terrigenous sedimentation occurs and is characterized by extensive turbidite formations (Muratov et al., 1978). Sedimentation near the Bosphorus Strait is largely controlled by inputs from the Danube River (Muratov et al., 1978).

The current status of the Black Sea as a semi-enclosed basin began during a global high stand (MIS 1) between 5.30 and 7.00 ka BP (Kerey et al., 2004). This high stand created the most recent connection between the Aegean and the Black Sea via the Bosphorus Strait. Previous connections between the Black and Mediterranean Seas, since 5 Ma, are indicated by the presence of marine organisms including calcareous nannoplankton (Percival, 1978), marine diatoms (Schrader, 1978) and foraminifers (Gheorghian, 1978) (Fig.8). The eastern basin, which is of interest in this study, trends east-west and is composed of oceanic crust overlain with up to 19 kilometers of undisturbed horizontal sedimentary cover on the apron basin ranging from Cretaceous to Holocene (Nikishin et al., 2000; Neprochnov and Ross, 1978).
2.2 Microfossils and Fossils Since the Last Climate Cycle

A large suite of fossils is used to date and correlate sediments deposited in the Black Sea for the last major glacial cycle (Fig. 9). Percival (1978) discusses the coccoliths he found at DSDP Site 380, as well as at Sites 379, and 381. Percival (1978) states that within these sites, only three indigenous species are found: *Emiliania huxleyi*, *Gephyrocapsa caribbeana*, and *Braarudosphaera bigelowi*. *Emiliania huxleyi* is dated late Quaternary in age, and *Gephyrocapsa caribbeana* is dated Quaternary in age (*Braarudosphaera bigelowi* cannot be used for dating) (Percival, 1978). The age on the bottom of the core section used for this study from Site 380 (~70 m) is considered to be Eemian (crossover *Emiliania huxleyi*, *Gephyrocapsa caribbeana*, at about 120 ka BP, Raffi et al., 2006). Fig. 9 illustrates sharp peaks of *Emiliania huxleyi* correspond with possible Mediterranean Sea and Black Sea connections. In Percival (1978), approximately 80 different species of reworked calcareous nannofossils are reported at Site 380. Most of the reworked species derived from the Cretaceous (*Watznaueria barnesae*, *Arkhangelskiella cymbiformis*, *Prediscosphaera cretacea*, *Micula decussata*, *Eiffellithus turrieseiffelli*, *Cretarhabdulus crenulatus*, *Eiffellithus augusts*, *Kamptnerius magnificus*, *Cribrosphaerella ehrenbergi*, and *Broinsonia parca*), Eocene to Oligocene (*Reticulofenestra* spp., *Cyclococcolithina neogammation*, *Dictyococcites scrippsa*, *D.biectus*, *Discoaster deflandrei*, *Chiasmolithus solitus*, *Cyclococcolithina reticulatus*, *Discoaster barbadiensis*, *Discoaster lodoensis*, etc.), and a few from the Miocene: *Helicopontosphaera ampliaperta*, *Sphenolithus heteromorphus*, *Discoaster exilis*, and *Discoaster brouweri* (Percival, 1978).

Gheorghian (1978) states in the Initial Reports of the DSDP that 339 samples from Sites 379, 380, and 381 were analyzed for microfossils, but only 119 samples contained microfossils. Benthic foraminifers found within the Black Sea sediments include: *Bolivina inflata*, *B. spiralis*, *Laryngosigma semitexta*, *L. Williamsonii*, *Ammonia beccarii*, *A. parkinsoniana*, *A. perlucida*, *A. tepida*, *A. viennensis-compacta*, *Elphidiumadvenum ponticum*, *E. macellum*, *E. reginum*, *Glabratella cf. G. kartveli* (Gheorghian, 1978). *Bolivina inflata* and *B. spiralis*, both stenohaline species from the Mediterranean, as well as the presence of *Laryngosigma semitexta*, and *L. Williamsonii*
proves that there were times during the Miocene, Pliocene, and Quaternary of migrations from the Mediterranean Sea to the Black Sea. Their adaptation to the Black Sea’s lower salinity is seen by their reduction in overall size and by the thickening of their wall (Gheorghian, 1978). *Ammonia becarii*, and *Elphidium* spp. have also adapted to Black Sea’s low salinity (Gheorghian, 1978). Planktonic foraminifers in the Black Sea are rare and mostly absent from Neogene to Recent sediments, however juvenile specimens of the planktonic species *Globigerinoides* is the most abundant species for this time period (Gheorghian, 1978).

Schrader (1978) discovered both marine and brackish/freshwater diatom species at Site 380, and therefore provided an accurate salinity reconstruction due to diatom’s short reproduction cycle and there presence in the basin only being possible during times with a marine connection. Diatom species *Cyclotella caspia* and *Thalassiosira* spp. are marine warm water species, and therefore can only appear during times of strong marine connections (Schrader, 1978), such as
MIS 5 (Fig. 9). Species endemic to brackish/freshwater are most common in the Black Sea and include: *Stephanodiscus hantzschii*, *S. astrea*, and *S. robustus* (Schrader, 1978).

All ostracod faunas found within Site 380 were estimated to be *in situ* brackish/freshwater species (Olteanu, 1978). These include: *Amplocypris subacutus*, *Candona (C.) balcanica*, and all subspecies, *Callistocythere diffusa* (primitive taxon), *Hemicytherura*, *Cytheroma Paraconadon*, *Cypria*, and *Leptocythere*, which is typically marine but adapted to brackish waters (Olteanu, 1978). Reworked ostracod species include: *Loxoconcha ornata ornata* (survived up to the Pleistocene), and *Bacunella* which is found in Black Sea brackish/freshwater Pliocene sediments (Olteanu, 1978).

2.3 Holocene Connections with the Mediterranean Sea

The specific rate and method of connection is debated within modern literature, with three main models emerging: the Catastrophic Flood model, the Progressive Flood model, and the Caspian Sea model (e.g. Ryan et al., 1997; Asku et al., 2002; Chepalyga, 2007). We will further discuss these connection models to improve our interpretation of DSDP Site 380’s dinoflagellate data during MIS 5 to MIS 1 (~120 ka BP to present day).

A. The Catastrophic Flood Model

The catastrophic “Noah’s Flood” model (Ryan et al., 1997), (Fig. 10) proposes that the eustatic highstand following the Last Glacial Maximum (LGM) caused a flood of biblical proportions at 7,150 BP. According to this model, the Black Sea at the time of the flood was an isolated freshwater “lake-sea” (Wall and Dale, 1973b) that had evaporated well below its continental shelf. Due to the eustatic high stand at MIS 1, the Aegean Sea began breaching the Bosphorus strait and caused a catastrophic flooding event to the broad regions of the continental shelf (Ryan et al., 1997). A large unconformity discovered along the continental shelf at this time truncates a terrestrial stratum, drowning riverbeds, coastal deltas and dunes. A marine mud deposit marks the unconformity and was composed largely of the freshwater Caspian mollusk (*Drissena*
rostriformis), with $^{14}$C dating of algae confirming the date of this event (Ryan et al., 1997). The preservation of these low stand coastal features as well as the absence of coastal onlap in the marine mud layer are strong sedimentological indications of a rapid transgression (Lericolais et al., 2007; Siddall et al., 2004).

Since Ryan et al. (1997) first proposed the catastrophic flood model, several subsequent studies have agreed (Ryan et al., 2003; Lericolais et al., 2007; Major et al., 2006; Soulet et al., 2011). However, the exact timing of the reconnection has been debated and updated. In 2003, Ryan et al. changed the reconnection date from 7.1 ka to 8.4 ka BP, creating agreement among the model’s supporters. Several studies refer to Ryan et al.’s (1997) original 7.1 ka BP reconnection date as the time when salinity increased to present-day conditions, allowing for the introduction of euryhaline taxa following the first brackish species (Lericolais et al., 2007; Major et al, 2006).

![Diagram of Holocene connections: comparison of gradual inflow vs. catastrophic flood models (Popescu, personal communication).](image)

Figure 10. Holocene connections: comparison of gradual inflow vs. catastrophic flood models (Popescu, personal communication).
B. The Progressive Flood Model

The progressive flood model (or gradual inflow model) (Fig. 10) gives an alternate backdrop to the catastrophic flood model. In this model, it is argued that as early as 11 or 10 ka BP, the Black Sea rose above the Bosphorus Strait’s shallowest sill depth of ~30m and began spilling into the Marmara Sea (Asku et al., 2002a). This connection is believed to have been a one-way outflow of the Black Sea, at least for the first 1000 years, due to the shallow depths of the Marmara Sea (Asku et al., 2002b). As the water level of the Marmara Sea rose, two-way flow started at around 8 ka BP (Asku et al., 2002b). This corresponds to the reconnection date of the catastrophic flood model, but similarities between the two models end there.

The appearance of disparate age sapropel formations in the eastern Mediterranean Sea and Black Sea is one of the main arguments for a progressive connection model rather than a catastrophic flood (Asku et al., 1999). Between 8 and 5.30 ka BP, apparent overflow of low salinity waters from the Black Sea into the Aegean caused a gradual decrease in deep water circulation. This led to an increase in production and sapropel deposition (Lericolais et al., 2007). However, sapropel deposits did not appear in the Black Sea until approximately 550 years after their appearance in the Aegean. This delayed appearance of sapropel is not indicative of a catastrophic reconnection, but rather a slower process wherein the relatively denser water from the Aegean flowed into the Black Sea and forced the less dense but nutrient-rich bottom waters to rise to the surface and increase production there (Lericolais et al., 2007).

The second main argument for a progressive connection is the presence of a set of back-stepping barrier islands on the Black Sea shelf and a subaqueous delta composed of Black Sea sediments in the Marmara Sea near the Bosphorus Strait (Asku et al., 2002c). The lack of stratigraphic markers in the samples collected from the delta complex causes severe problems when defining its age, and Ryan et al. (2003) argues that it may have been caused by the Black Sea’s outflow during the Younger Dryas.
C. Outflow of the Caspian Sea Into the Black Sea and the Marmara Sea

The outflow of the Caspian Sea into the Black Sea and the Marmara Sea is the third main connection model. According to this model, the Caspian Sea was consistently overfilled and caused several flood events between 17 ka and 10 ka BP. These extensive flooding events linked several lacustrine and marine water bodies through spillways such as the Manych-Kerch and Bosphorus, ultimately forming what Chepalyga (2007) referred to as the Cascade of Eurasian Basins. A tremendous amount of water would have been required for the Caspian basin to overfill. As much as 70,000 km$^3$ would be needed in order to reach the 50 m height of the Manych-Kerch spillway to the Black Sea (Chepalyga, 2007). Surprisingly, this amount of water could have been readily provided from initial Scandinavian ice sheet melting, extensive permafrost melt, river valley super floods, or any of these sources combined with lower surface evaporation due to ice cover (Chepalyga, 2007).
CHAPTER 3. PRINCIPLES, MATERIALS AND METHODS

3.1 Dinoflagellate and Dinocysts

Dinoflagellates constitute a large group of flagellate plant-like protists. Most of them are marine, adapted to pelagic environments (swimming in surface-waters or in the water-column). Some are associated with shallow benthic zones (where they are associated to sediments, corals, or to macroalgal surfaces), others are common in freshwater habitats; however, the latter are not well preserved in the sediments. Many dinoflagellates are autotrophic (rely on photosynthesis), while some dinoflagellates are heterotrophic (eat plants and animal tissues), whereas others use a combination of these two nutrition types, mixotrophic, which complicates their classification as either a plant or animal. The life cycle of a dinoflagellate (Fig. 11) (Evitt, 1985; Fensome et al., 1993) is divided into two seasonal periods: (i) during warm season (summer) the organisms swim within the surface-waters or the water column (motile stage), and (ii) during the colder (winter)

Figure 11. Relationship between living algae and their cysts. (Popescu, personal communication).
season, some dinoflagellates construct a very robust dinoflagellate cyst (i.e. dinocyst) which is preserved within sediments. This stage is well-preserved in sediments; therefore can be utilized for biostraigraphy.

Dinoflagellate cysts are particularly useful to date Mesozoic and Cenozoic sequences. Additionally, they are considered reliable organisms for reconstructing the past marine environments (Wall et al., 1973, 1977; de Vernal et al., 1994; Dale and Dale, 1992; Warny et al., 2003). Significant studies have been performed on the relationship between the motile and cyst stage of dinoflagellates (Dale, 1976, 1986; Kokinos and Anderson, 1995; Lewis and Halett, 1997; Lewis et al., 1999; Ellegaard et al., 2003) in which important taxonomic revisions on dinoflagellate cysts taxonomy were achieved (Head, 1993, 1994, and 1996).

Dinoflagellates are sensitive organisms to environmental changes, and the modifications in cyst morphology represent a response to environmental stress (Wall and Dale, 1974). Such responses include the appearance of a cruciform endocyst, variations in septal development (Wall et al., 1973; Wall and Dale, 1974), and the reduction of process length (de Vernal et al., 2000; Dale, 1996; Lewis et al., 1999, 2003; Ellegaard, 2000; Mertens et al., 2009). Figure 12 illustrates such a response caused by reduced salinity of surface waters (Sorrel et al., 2007). In this work, the authors postulate that the process length of a dinoflagellate cyst of a species has evolved from long (at times of normal salinity) to short (at times of extreme- low or high- salinities). Laboratory experiments on the extant species confirmed the morphological changes observed in the extant fossil species, thus illustrate that some species may develop different process length (Kokinos and Anderson, 1995) or show different morphotypes under stable salinity conditions (Lewis and Halett, 1997). This suggests that morphological changes of cysts are controlled by multiple factors such as salinity, temperature, and nutrients.
3.2. Materials: Deep Sea Drilling Program Background

The DSDP was the first international scientific ocean-drilling program. It was formed in 1966, with its first expedition in 1968. Since that first project, it has provided invaluable evidence for the theory of plate tectonics including evidence of continental drift, Pangaea, and sea floor spreading at rift zones. The program’s name changed to the International Phase of Ocean Drilling [IPOD] in 1975, then to the Ocean Drilling Program [ODP] in 1985, and most recently to the Integrated Ocean Drilling Program [IODP] in 2004. The name change reflects different funding sources and participating countries, but the goal has always been to learn more about the Earth’s geologic and oceanographic past through marine cores.

As part of its efforts to understand the Black Sea’s geologic history, the DSDP drilled at Sites 380 and 380A (42°05.94’N, 29°36.82’E) of Leg 42B in the southwestern Black Sea were cores were recovered in a water depth of 2107 meters, near the Bosphorus Strait (Ross et al., 1975).
Site 380 was abandoned due to an injury onboard the drilling vessel, however the DSDP vessel returned a few hours after the accident and established a second hole 100 feet south and east of 380, and labeled it 380A. 380A was drilled to a depth of 1073.5 meters (Ross et al., 1975). Figure 13 presents the summary of the combined lithology recovered at site 380/380A. The two cores had a combined recovery of 531 meters of sediment (Ross et al., 1975).

3.3. Methods

3.3.1. Microscope Analysis and Identification

Samples for palynological study were extracted from the core DSDP 380 at 50 cm intervals when available between core depths 67.47 and 0.51 m. Twenty grams of sediment were sampled per depth. Samples were processed using the Cour (1974) standard method (Popescu et al., 2010). All samples were treated with HCl and HF acid to digest the unwanted carbonates and silicates. ZnCl₂ (density of 2.00 g/ml), a density separator, was used in order to ensure the highest amount of palynomorphs were mounted onto each slide by allowing palynomorphs to float in the upper part of the residue. Lastly, all samples were sieved at 10 μm to ensure a cleaner slide by removing large non-palynomorph particles (Popescu et al., 2010).
Glycerol at a density of 1.23 g/m³ was used as the mounting medium. Glycerol allows slides to be stored in an upright position and provides the permanence needed to go back to a particular dinocyst using coordinates collected thanks to an England Finder.

An Olympus BX41 microscope with oil immersion 60x or 100x magnification objectives was used for dinocyst analysis. Microphotographs were taken using a QCapture camera with a 0.5x coupler, and managed with QCapture software. A minimum of 300 identifiable dinocysts were counted on each slide to ensure an accurate representation of each sample. Reference slides and bibliographic material provided by the Center of Excellence in Palynology [CENEX] library were used to identify dinocysts at the species level.

The volumetric method was used to determine the dinoflagellate concentrations. For example, if the minimum of 300 dinoflagellates was counted in 6 out of a possible of 12 rows then the dinoflagellate number is then doubled to obtain the relative dinoflagellate concentration for the known 30 μL.

3.3.2. Biometry and Statistical Analyses

In order to analyze morphological changes for Galeacysta etrusca throughout our sample set, four dimensions were measured. The selected dimensions include lengths and widths of the endocyst, $L_{EN}$ and $W_{EN}$, and the lengths and widths of the ectocyst, $L_{EC}$ and $W_{EC}$ (Fig. 14). This selection was done to follow the model defined by Popescu et al., (2009) for the Mediterranean Sea regions. Four similar measurements were recorded for Spiniferites cruciformis in order to provide a greater morphological analysis due the relatively low abundance in dinoflagellate cysts present throughout the samples.

After preliminary exploratory investigations of the dataset, three distinct points were focused on:
1.) The multivariate descriptive analysis of the morphometric variability of the two taxa (first separate, then together) based on the four main descriptors ($L_{EN}$, $W_{EN}$, $L_{EC}$, and $W_{EC}$).
2.) The time series analysis of *G. etrusca* based on the three synthetic morphometric descriptors (following the model proposed by Popescu et al., 2009).

\[ X = \log \left( \sqrt[4]{\text{LEN} \times \text{WEN} \times \text{LEC} \times \text{WEC}} \right) \]

X is the log-transformed mean of the four initial variables; it is an estimate of the overall size of the dinoflagellate cyst (Popescu et al., 2009).

\[ Y = \log \left( \frac{D_{EN/EC}}{D_{EC}} \right) = \log \left( \frac{L_{EN} \times W_{EN}}{L_{EC} \times W_{EC}} \right) = \log \left( \frac{L_{EN} \times W_{EN}}{L_{EN} \times W_{EN}} \right) - \log \left( \frac{L_{EC} \times W_{EC}}{L_{EC} \times W_{EC}} \right) \]

Y is the log-transformed ratio of the endocyst and ectocyst length and width products (Popescu et al., 2009).

In addition, Z, a new descriptor was investigated:

\[ Z = \log \left( \frac{L_{EN} \times L_{EC}}{W_{EN} \times W_{EC}} \right) \]

3.) The statistical comparison between *G. etrusca* and *S. cruciformis* based on the three synthetic morphometric descriptors X, Y and Z.

All Principle Component Analysis in this study was conducted using PAST v. 2.10 freeware (http://nhm2.uio.no/norlex/past/download.html).
Figure 14. The four measured dimensions illustrated on scanning electron microscope (SEM) images of *Galeacysta etrusca* (right), and *Spiniferites cruciformis* (left).
CHAPTER 4 RESULTS

4.1. Dinoflagellate Analyses

More than 16,000 dinoflagellate cyst were counted during this study, yielding a total of 23 taxa (12 in situ species and 11 reworked species). The preservation of specimens is moderate to good, and particular effort was made to identify the “brackish endemic species” because they show a large morphologic spectra related to sea-surface physical parameters including temperature, salinity and nutrient content variability (Popescu et al., 2007; 2009). Dinoflagellate cyst flora is composed of nine marine taxa that are grouped according to the ecological requirements in two groups: (a) marine stenohaline taxa (species requiring restricted ranges of sea-surface conditions) include: Impagidinium sp., Spiniferites bentorii, Spiniferites mirabilis and (b) marine euryhaline taxa (species tolerating wide ranges of sea-surface conditions) include Nematosphaeropsis labyrinthus, Spiniferites spp., Achomosphaera andalusiensis, Hystrichokolpoma sp. and Lingulodinium machaerophorum (Figs. 15, 16). The “brackish endemic species” (Fig. 16) are represented by Galeacyusta etrusca (Plate 1) Spiniferites cruciformis (Plate 2), and Pyxinidopsis psilata (Plate 3). The various stenohaline and euryhaline species are illustrated on Plate 4. Additional species recovered include a series of reworked species (Plates 5 and 6) that include: Areoligeracean sp. (Cretaceous-Paleogene), Deflandrea phosphoritica (Late Eocene- Early Oligocene), Enneadocysta sp. (Paleogene-Eocene), Glaphyrocysta spp. (Eocene), Homotriblium sp. (Paleogene-Miocene), Oligosphaeridium spp. (Upper Cretaceous-Paleogene), Wetzeliella symmetrica (Oligocene), Spiniferites bentorii pannonicus (Miocene-Early Pliocene), and Virgodinium sp. (Miocene-Early Pliocene).

Marine species (Figs. 15, 16) show a low relative abundance (between 1% and 12%), except for the two deepest samples, where these species reach respectively 16% (at 62.95 m depth) and 42.3% (at 67 m depth). The presence of marine taxa may be related to the short-lived connections between the Black and Mediterranean Seas, which caused a small sea-surface salinity increase in the Black Sea probably between 5 and 22 ppt (S.-M. Popescu, personal communication). This low SSS of the Black Sea is well evidenced by high presence of endemic brackish taxa that are
dominating the assemblage throughout. These are *Pyxidinopsis psilata* and *Galeacysta etrusca*, which present together a relative abundance of about 90%. The third brackish species, *Spiniferites cruciformis*, achieves its maximum relative abundance (less than 20%) between 0 and 10 m depths.

According to the dinoflagellate cyst recovered and their distribution, four palynological zones are identified (Fig. 16):

**Palynological Zone 1** (from 70 m to 60 m) is defined by: (1) highest relative abundance of marine dinoflagellates (42.3% at 67.4m depth), represented by *Spiniferites bentorii*, *Achomosphaera andalusiensis*, *Hystrichokolpoma* sp. and *Lingulodinium machaerophorum*. With
the similar relative abundance (57.7%) at the bottom of the section, the brackish endemic flora is dominated by *G. etrusca* that fluctuates between 57% (at 67.47 m depth) and 99% (at 61 m depth) and *P. psilata* that varies between 0% (at 67.47 m and 62.5 m depth) and 3.2% (at 62.95 m depth). Reworked dinoflagellate cysts are found only in samples collected at 67.5 and 67 m depths.

**Palynological Zone 2** (from 53 m to 47 m) is marked by: (1) the highest relative abundance of reworked taxa (20%) for the entire section, with reworked species present throughout this zone; (2) a sharp increase in the total relative abundance of euryhaline taxa (6.1%), taxa present include *L. machaerophorum, Spiniferites* spp., *A. andalusiensis, Hystrichokolpoma* sp., and *N. labyrinthus*; (3) brackish taxa are present in high abundances as well and includes *G. etrusca*, which varies in this zone from 96% to 99%, *S. cruciformis* remains very low at approximately 2% relative abundance, and *P. psilata* fluctuates several times with a minimum of 19% and a maximum of 49%.
Plate 1. Light photomicrographs of key specimen of dinoflagellates from the Galeacysta etrusca complex and Pterocysta cruciformis at DSDP Site 380. All photographs were taken in 60x. 1-7: Galeacysta etrusca, 1, DSDP 380, 42.45m (slide 3), 9.5x136.7; 2, DSDP 380, 61.97m (slide 2), 12x121.9; 3, DSDP 380, 67.00m (slide 1), 14x143.4; 4-5, DSDP 380, 61.00m (slide 3), 10.5x118.7; 6, DSDP 380, 0.520m (slide 3), 9x117.6; 7, DSDP 380, 34.46m (slide 2), 9.5x122.2; 8-9: Pterocysta cruciformis, 8, DSDP 380, 16.00m (slide 3), 15.5x134.1; 9, DSDP 380, 42.45m (slide 3), 9.5x136.7.
Palynological Zone 3 (from 43 m to 29 m) is characterized by: (1) a sharp increase of reworked taxa at 42.5m depth; (2) brackish taxa *G. etrusca* and *S. cruciformis* show small decreases at the beginning of this zone while *P. psilata* increases from ~70% to 99% from 43 m to 29 m; (3) lastly, an increase in marine euryhaline taxa to a maximum of 10.3% is observed for this zone. Marine species includes *Spiniferites* spp., and *L. machaerophorum*.

Palynological Zone 4 (from 18 m to 0 m) is classified by: (1) a minor increase of reworked taxa. This increase is small at only a 3% relative abundance, however, the presence of these species is important for the palaeo-environmental reconstruction; it is associated with (2) an increase of euryhaline marine taxa of 5.3% relative abundance at the onset of this zone. *Spiniferites* spp., *A. andalusiensis*, *Hystrichokolpoma*, and *L. machaerophorum* are all present at 18m. (3) brackish taxa *G. etrusca*, *S. cruciformis*, and *P. psilata* are all present; however, fluctuate often in abundance in this zone. *S. cruciformis* obtains it highest relative abundance in Zone 4 of 20% at 3.5 m and fluctuates down to 0% at 8 m. *P. psilata* varies between 99% at 0.965m and ~70% at 3.5m; (4) the largest abundance of stenohaline marine taxa is present throughout this zone. At the beginning of Zone 4, at 18 m, a 1% increase is seen due to the appearance of *A. choanum*. At 8.95 m an abundance of 2.4% of *Impagidinium* sp. occurs. The largest abundance of marine stenohaline taxa at Site 380 is observed at 0.52 m. The occurrence of *S. bentorii* and *A. choanum* comprises the 3.4% abundance for the uppermost sample.

4.2. Paleoenvironment Reconstruction

Dinoflagellates are very sensitive to environmental changes and some taxa respond specifically to changes in salinity, temperature or nutrient content stress either by changes in relative abundance, or by morphological modification of their cyst. One of the main marine dinoflagellate cyst species identified in this work is *Lingulodinium machaerophorum* (Plate 4). This species is known to modify its process lengths in response to salinity stress. The presence of
Plate 2. Light photomicrographs of key specimen of the dinoflagellate cyst Spiniferites cruciformis at DSDP Site 380. All photographs were taken in 60x. 1-16 Spiniferites cruciformis, 1, DSDP 380, 34.46m (slide 1), 5.5x144.8; 2, DSDP 380, 34.46m (slide 2), 12x137.7; 3, DSDP 380, 2.50m (slide 1), 7.5x134.0; 4, DSDP 380, 2.50m (slide 2), 7x126.6; 5, DSDP 380, 62.50m (slide 1), 10x113.2; 6, DSDP 380, 33.5m (slide 3), 13.5x131.7; 7, DSDP 380, 0.520m (slide 1), 7x107.7; 8, DSDP 380, 41.50m (slide 2), 11x121.8; 9, DSDP 380, 48.02m (slide 3), 15x119.5; 10, DSDP 380, 61.97m (slide 2), 12x121.9; 11, DSDP 380, 0.965m (slide 1), 7.5x114.4; 12, DSDP 380, 0.965m (slide 2), 13x127.8; 13, DSDP 380, 8.495m (slide 2), 14.5x116.8; 14, DSDP 380, 34.46m (slide 1), 5.5x144.8; 15, DSDP 380, 34.46m (slide 2), 12x137.7; 16, DSDP 380, 8.495m (slide 1), 14x121.0.
L. machaerophorum’s has been recorded in coastal sediments from subtropical to tropical regions of the Southern hemisphere, and from tropical to temperate regions of the Northern hemisphere. L. machaerophorum’s distribution in marine environments is characterized by a SST between -1.5°C (winter SST) and 29.1°C (summer SST), and a SSS between 16.9 ppt (spring SSS) and 36.7 ppt (summer SSS), and nutrient ranges of 0.1 to 0.7 mM for phosphate and 0.1 to 7.8 mM for nitrate (Marret et Zonneveld, 2003). This species is found in low salinity environments such as the Black Sea (Wall and Dale, 1973a, Wall et al., 1973b; Mudie et al., 2001; Popescu et al., 2004, Marret et al., 2009), Caspian Sea (Marret et al, 2004), Baltic Sea (Ellegaard, 2000), and in hypersaline conditions (Sorrel et al., 2006). L. machaerophorum is able to have a wide range of process lengths (Figures 12 and 17), from long spines to short bulbous processes; therefore, this

![Diagram](image)

**Figure 17.** Distribution of two morphotypes of Lingulodinium machaerophorum in relation to other key species.

*L machaerophorum*: the blue curve represent the normal marine taxa, the red curve correspond to the taxa with short/bulbous processes.
Plate 3. Light photomicrographs of key specimens of dinoflagellate cyst *Pyxinidopsis psilata* for DSDP Site 380. All images were taken in 60x. 1, DSDP 380, 0.965m (slide 1), 12.5x125.4; 2, DSDP 380, 7.00m (slide 1), 7.5x130.4; 3, DSDP 380, 13.50m (slide 1), 13.5x137.5; 4, DSDP 380, 13.50m (slide 1), 13.5x142.5; 5, DSDP 380, 13.50m (slide 1), 14x137.1; 6, DSDP 380, 13.50m (slide 1), 14x131.3; 7, DSDP 380, 30.51m (slide 1), 14.5x115.8; 8, DSDP 380, 13.50m (slide 1), 17.5x114.6; 9, DSDP 380, 30.51m (slide 1), 12.9x139.9; 10, DSDP 380, 30.51m (slide 1), 13.4x130.8; 11, DSDP 380, 30.51m (slide 1), 8.5x121.6; 12, DSDP 380, 13.00m (slide 1), 19.5x127.0.
Plate 4. Light photomicrographs of key specimens of various dinoflagellate cyst species at DSDP Site 380. All images were taken in 60x. 1-2, *Achomospheera andalusiensis*, DSDP 380, 3.50m (slide 1), 14.5x131.5; DSDP 380, 49.47m (slide 1), 18x138.6; 3-4, *Oligosphaeridium*, DSDP 380, 6.490m (slide 1), 17x135.2; DSDP 380, 3.50m (slide 3), 17.5x120.9; 5-6, *Lingulodinium machaerophorum*, DSDP 380, 33.5m (slide 1), 18x136.8; DSDP 380, 0.520m (slide 2), 4x138.0; 7, *Cleitosphaeridium*, DSDP 380, 13.50m (slide 2), 15.5x122.5; 8, *cf. Ataxodinium choanum*, DSDP 380, 0.520m (slide 2), 6.5x133.6; 9, *cf. Hystrichokolpoma*, DSDP 380, 16.00m (slide 1), 11.5x138.5; 10, cyst of *Polykrikos schwartzii*, DSDP 380, 32.5 (slide 1), 7.5x126.3; 11, *Impagidinium* sp., DSDP 380, 8.495m (slide 2), 7.5x141.9; 12, *Romanodinium areolatum*, DSDP 380, 50.52m (slide 1), 10.5x142.8.
species is commonly used as a proxy for past sea-surface salinity (Wall and Dale, 1973b; Mudie et al., 2001; Sorrel et al., 2006; Mertens et al., 2009; Verleye et al., 2009; Marret et al., 2009;). Long processes are present during times of relatively normal marine salinity and little to no stress or growth obstruction to the dinoflagellate, while short/bulbous processes indicate times of low salinity and severe stress to the taxa (Mertens et al., 2008, Verleye et al. 2009). Mudie et al. (2001) classified L. machaerophorum long processes as >15 μm and short processes ranging from <5-10 μm. However, in our study long processes are classified as >5 μm without clavate tips due to no true long or “normal forms” present in our samples, and short processes are defined as having <5 μm with or without clavate tips present.

In addition to the variations in process lengths, changes in the morphological shape of the body have been observed for some marine/brackish endemic species. For instance, four morphotypes of Galeacysta etrusca were established based on biometric variations of the body in relation to salinity or nutrient variability. Galeacysta etrusca is one of the most common species recovered at our site and seems indeed to be endemic to the Black Sea region. Popescu et al. (2009) indicated that this species most likely originated from Pannonian basins (Hungary) and/or from the Eastern Paratethys basins (Southern Romania, Black and Caspian Seas). Popescu et al. (2007; 2009) also demonstrated that the migration of this species into the Mediterranean Sea occurred during late Miocene and early Pliocene high-stands.

The second endemic taxon recovered in large quantity from our samples at DSDP Site 380 is Spiniferites cruciformis. This species has been described in Black Sea sediments by Wall et al. (1973a) and was attributed to the Early Holocene. However, this species has since been observed in Late Miocene to Early Pliocene sediments in the Black Sea at Site 380A (Popescu, 2006), as well as in Southern Romania (Popescu, 2001), Early Pleistocene sediments in Greece (Kouli et al., 2001), and in Pleistocene-Holocene sediments in the Black, Aral, Marmara and Caspian Seas (Verleye et al., 2009). In Late Pleistocene sediments this species appears during the Bølling-Allerød warm periods (c. 14,700 to 12,700 years BP), indicating a preference for warm surface waters.
Plate 5. Light photomicrographs of key specimens of various reworked dinoflagellate cyst species at DSDP Site 380. All images were taken in 60x. 1, Spiniferites sp. (Paratethys species, reworked Miocene-Pliocene), DSDP 380, 32.5m (slide 1), 14.5x126.9; 2, Protoperidinium, DSDP 380, 39.99m (slide 1), 8x126.8; 3, Homotryblium (Miocene - Paleogene), DSDP 380, 12.51m (slide 1), 5.5x134.2; 4, Homotryblium (Miocene - Paleogene), DSDP 380, 16.00m (slide 2), 4x140.0; 5, Spiniferites sp., DSDP 380, 49.47m (slide 1), 13x121.3; 6, Spiniferites sp., DSDP 380, 51.50m (slide 1), 13.5x128.0; 7, Virgodinium spp. (Miocene - Pliocene), DSDP 380, 16.00m (slide 1), 6.5x114.1; 8, cf. Enneadocysta sp. (Paleogene -Eocene), DSDP 380, 67.00m, (slide 1) 8x117.1; 9, Bentorii budajenoensis (Miocene), 49.47m (slide 3), 10x131.0.
Plate 6. Light photomicrographs of key specimens of various reworked dinoflagellate cyst species at DSDP Site 380. All images were taken in 60x. 1, Acritarch sp., DSDP 380, 0.520m (slide 2), 11x122.6; 2, Areoligeracean, DSDP 380, 0.520m (slide 2), 15x135.7; 3, Deflandrea sp. (Paleogene), DSDP 380, 0.965m (slide 1), 13x135.4; 4, Deflandrea phosphoritica (Late Eocene-Early Oligocene), DSDP 380, 1.51m (slide 1), 13.5x125.2; 5, Deflandrea phosphoritica (Late Eocene-Early Oligocene), DSDP 380, 12.51m (slide 3), 4x134.5; 6, Homoryblium (Miocene-Paleogene), DSDP 380, 3.50m (slide 2), 13.5x142.6; 7, Oligoshaeridium spp. (Paleogene-Upper Cretaceous), DSDP 380, 7.00m (slide 3), 15.5x111.7; 8, Wetzeliella sp., DSDP 380, 13.00m (slide 1), 10x132.0; 9, Wetzeliella symmetrica, 13.50m (slide 1), 10x142.7; 10, Wetzeliella sp., DSDP 380, 13.50m (slide 1), 13x139.6; 11, Cordosphaeridium, DSDP 380, 13.00m (slide 2), 8.5x135.2; 12, Spiniferites sp., DSDP Site 380, 13.00m (slide 1), 19.5x127.0; 13, Gephyrocysta spp. (Eocene), DSDP Site 380, 16.00m (slide 1), 19.5x109.3; 14, Protoperidinium, DSDP 380, 16.00m (slide 3), 5.5x141.7; 15, Spiniferites sp. (Paratethys species, Miocene-Pliocene), DSDP 380, 32.5 (slide 1), 8x112.6.
The last known endemic species that dominates our assemblage is \textit{Pyxidiniopsis psilata}, which is known only from Late Miocene to Early Pliocene beds in Eastern Paratethys (Popescu, personal communication), in Late Pleistocene sediments in the Marmara Sea (before the last connections between the Marmara and Mediterranean Seas occurred at about 10ka BP) (Mudie et al., 2001; Popescu, 2008), and lastly in Black Sea since the late Miocene (Popescu, 2008). Generally, this species increases during glacial periods (Popescu, 2008), which indicates a preference for cooler surface waters. The presence of this species in the Black Sea where the SSS ranges between 7 and 20 ppt, and not in the Caspian Sea where SSS ranges between 0 and 12 ppt, indicate a probable range of SSS between 7 and 12 ppt as suggested by Marret et al., (2009).

Based on the ecological requirements described above for the most abundant species recovered (\textit{G. etrusca}, \textit{S. cruciformis}, \textit{P. psilata} and \textit{L. machaerophorum}), the following environmental evolution of the Black Sea for the time-interval studied is proposed in Fig. 17.
Zone 1: Interglacial Marine Environments

The presence of 42.3% marine taxa at depth 67.47 m indicates a connection between the Mediterranean and the Black Seas. *L. machaerophorum* specimens exhibit short/bulbous processes between 67.47 m and 62.95 m, indicating a rapid adaptation to brackish conditions as this species is brought into the Black Sea from an inflow of marine waters through the Bosphorus Strait. The high relative abundance of *G. etrusca* (maximum of 96% at 63 m) throughout Zone 1, along with a low appearance of *P. psilata* (minimum of 0% to a maximum of 2% at 60 m) indicates warm surface waters. The presence of some reworked species in sediments at 67 m may indicate resuspension or reworking of sediments associated with the Bosphorus inflow and subsequent erosion.

Zone 2: Interglacial Brackish Environment

The fluctuations observed between *G. etrusca* and *P. psilata* throughout Zone 2 likely indicate SST variability at this time. An absence of stenohaline marine taxa indicates no Mediterranean connection, and therefore a brackish environment. A reworked dinocyst abundance of 20%, the highest of all depths, also appears in Zone 2 at 52 m. A large appearance of reworked dinoflagellates is a palynological indicator of high river input. At the top of Zone 2 (49 m), a brief marine influx is indicated by a 1.8% increase of *L. machaerophorum* with normal length processes. At this same depth, a decrease of *P. psilata* indicates a slow increase in SST due to a small influx of warm marine waters.

Zone 3: Brackish with Brief Marine Incursions

During Zone 3, two marine influxes were indicated by two peaks of increased abundance in *L. machaerophorum* with normal processes (at 40 m and 34 m depth). The appearance of marine species *Spiniferites* spp. also co-occurs during this zone. Despite the evidence for these two marine incursions and evidence for small fluctuations of SSS, this zone is overall considered to predominantly be a brackish environment because of the high abundance of *P. psilata* (49% minimum at 43 m and maximum of 99% at 34.5 m). A peak of reworked dinoflagellates occurs
right before the first marine influx takes place, which could be the first indication of this brief higher sea-level stand/warming period.

**Zone 4: Fluctuations Between Brackish and Marine Waters**

Several marine influxes during Zone 4 are indicated by the presence of marine stenohaline taxa (Impagidinium sp., S. bentorii, N. labyrinthus, etc.), along with an increase in L. machaerophorum with normal length processes, and the disappearance of brackish G. etrusca and S. cruciformis. Reworked taxa are relatively low compared to their appearance within the other zones with a maximum of only 2.3%.

**4.3 Biometry and Statistics**

In addition to the classic palynological assemblage study, a morphometric analysis of the two key species recovered was undertaken. Morphometric variability for both G. etrusca and S. cruciformis was first analyzed by graphing the X, Y, and Z descriptors (see method sections for details) using Principal Component Analysis (PCA). This analysis produced exactly the same results for each taxon; therefore, in these two cases the overall morphometric variability can be decomposed exactly in the same way, involving three principal components (PCs), which are independent linear combinations of the four variables. Together these three PCs explain over 90% of the overall morphometric variability within each taxon for this dataset.

The first PC explains approximately 60% of the overall variability within the G. etrusca dataset and is an overall-size descriptor (Table 1), which is very usual in this kind of analysis. The second PC explains 17-18% of the overall variability and sets the two EN-descriptors against the two EC-descriptors, thus being an EN/EC descriptor. The third PC explains 12-16% of the overall variability and sets the two L-descriptors against the two W-descriptors, thus being an L/W descriptor. The fourth and last PC explains less than 7% of the overall variability and has no obvious meaning – likely to be a “noise-parameter” accounting for the inter-individual variability not explained by the 3 previous PCs.
In Figure 19 (A, B, C, & D) the green vectors superimposed onto the PCA scatter plots are projections of the 4 original axes or variables onto the scattergram. This is simply another way to visualize the correlations between the original descriptors and the resulting principal components. These vectors only help at interpreting the meaning of the principal components in terms of the original measured descriptors. For instance, in both *G. etrusca* and *S. cruciformis* “PC1 vs. PC2” scatter plots all 4 original variable vectors point toward and thus project on positive values of the first component (PC1). This indicates that all four variables contribute positively (and rather equally as they project on approximately the same PC1 value) to PC1’s value: a larger PC1 value involves larger values of all 4 original variables, making PC1 an “overall-size” axis. *G. etrusca’s* PC2 opposes $L_{EC}$ and $W_{EC}$ (projecting on positive PC2 values) vs. $W_{EN}$ and $L_{EN}$ (projecting on negative PC2 values: when $L_{EC}$ and $W_{EC}$ increase relatively to $Len$ and $W_{EN}$, it gives larger (more positive) PC2 values; conversely, when $L_{EN}$ and $W_{EN}$ increase relatively to $L_{EC}$ and $W_{EC}$, it gives smaller (more negative) PC2 values, making PC2 an “EN vs. EC size” axis. Lastly, *G. etrusca’s* PC3 opposes $L_{EN}$ and $L_{EC}$ (both projecting on negative values) while $W_{EN}$ and $W_{EN}$ project positively, making PC3 a length vs. width axis (Fig. 19B). This method was applied to *S. cruciformis* as well and produced these same relationships (Fig. 19C & D); some slight variations are seen; however, the meaning of each PC does not deviate.

Table 1. Summary of PCA results for *G. etrusca* at DSDP Site 380.

<table>
<thead>
<tr>
<th></th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>% expl. var.</td>
<td>59.55</td>
<td>17.34</td>
<td>16.29</td>
<td>6.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>r</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L.EN</td>
<td>0.804</td>
<td>-0.070</td>
<td>-0.512</td>
<td>-0.295</td>
</tr>
<tr>
<td>W.EN</td>
<td>0.767</td>
<td>-0.581</td>
<td>0.034</td>
<td>0.268</td>
</tr>
<tr>
<td>L.EC</td>
<td>0.760</td>
<td>0.588</td>
<td>-0.104</td>
<td>0.258</td>
</tr>
<tr>
<td>W.EC</td>
<td>0.755</td>
<td>0.074</td>
<td>0.615</td>
<td>-0.218</td>
</tr>
</tbody>
</table>

**Meaning of the resulting PCs:**
- **PC1** = overall size (large PC1-value $\leftrightarrow$ large overall specimen size)
- **PC2** = EN vs. EC size (large PC2 $\leftrightarrow$ small EN/EC-size ratio)
- **PC3** = Lengths vs. widths (large PC3 $\leftrightarrow$ small L/W ratio)
- **PC4** = noise
A PCA mixture analysis of *G. etrusca* and *S. cruciformis* was then computed in order to easily observe how similar/dissimilar the two species are morphometrically. The first important point to notice is the large amount of overlapping between the two species meaning that these two taxa are morphometrically similar when described by our four descriptors (no similarity between them morphometrically would have produced a complete separation between them on this PCA plot). In both the PC1 vs. PC2 (Fig. 20A) and the PC2 vs. PC3 (Fig. 20B) plot this shows that they are very similarly shaped when defined by our four descriptors.

Further analysis of our mixture PCA graphically illustrates individuals of both species projects on the same range of PC1 values, leading to completely overlapping frequency distributions of PC1 values (Fig. 21A). This is the same situation for PC3 (Fig. 21B) but not for PC2 (Fig. 20C).
Thus, individuals of the two species are very similar with respect to their PC1 and PC3 values, but are more dissimilar with respect to their PC2 values. This involves that on average, *G. etrusca* and *S. cruciformis* shows similar “overall size” (PC1) and L/W ratios (PC3), but on average *S. cruciformis* individuals show smaller EN/EC-size ratios (i.e., more negative PC2 values).

![Figure 20. Principle Component Analysis (PCA) for *G. etrusca* and *S. cruciformis*. A= PC1 vs. PC2 for mixture analysis. B= PC2 vs. PC3 for mixture analysis.](image)

Furthermore, it is interesting to take note that there is a clear trend in an increasing overall size (Fig. 22A), a decreasing EN/EC size ratio (Figure 22B), and a decreasing length/width ratio (Figure 22C) for *G. etrusca*. Note that such trends apply to mean-values, and they are not so
obvious when all individuals are plotted purely against depth as seen in Figure 23. This finding can be attributed to the fact that the specimens have a large inter-individual variability with relatively stable minimum and maximum values throughout time.

![Figure 22. A: X vs. PC1, overall increasing size of *G. etrusca*. B: Y vs. PC2, overall decreasing EN/EC size ratio of *G. etrusca*. C: Z vs. PC3, decreasing L/W ratio of *G. etrusca*.](image)

While the two taxa seem to have only slight variations in the results given by PCA, when the dataset obtained for this study is analyzed using discriminant analysis (DA), which tests for equality of the mean between two groups based on several (here four) variables considered simultaneously, it is clear that the taxa separate out nicely on the base of the total morphometric values. Results highlighted in Figure 24 clearly show that, with a probability of 88.9% for *G. etrusca* and 86.2% for *S. cruciformis*, we can correctly identify any specimen to the correct taxa based solely on only these four measurements. In other words, based on these four morphometric
variables and on the available dataset, and provided that the taxonomic assignment of all the studied specimens is correct, there is a highly-significant multivariate difference between the two taxa.

Following Popescu et al. (2009), a mixture analyses was performed on the five most abundant depths for *G. etrusca* in order to identify possible mixtures of morphometrically distinct sub-groups of *G. etrusca*. However, no such sub-groups appear when X, Y, and Z are graphed at the most abundant depths (as seen in Figure 25) indicating that *G. etrusca* is morphometrically homogeneous at DSDP Site 380.

Figure 24. Discriminant analysis for *G. etrusca* and *S. cruciformis*.

Figure 25. *G. etrusca* mixture analysis for our most abundant sample: Depth 62.5 m (N=298).
Lastly, when our mixture analysis (Fig. 26) is compared to Popescu et al.’s (2009), it is evident that the sole group present at this site appears as the *G. etrusca* subgroup defined by Popescu et al. (2009) as small “group-b”, and clearly differs from Popescu et al.’s (2009) “group-a” and “group-d” specimens.

![Graph](image_url)

**Figure 26.** Colored-ellipses represent 70% Confidence Intervals (CI) of the distributions of Popescu et al.’s (2009) ’groups a-d’; the dark-grey ellipse represents 70% CI of DSDP Site 380-*G. etrusca* (black dots: individuals) and the light-grey ellipse is the 70% CI of DSDP Site 380-*S. cruciformis* (grey dots: individuals).
CHAPTER 5 DISCUSSION

5.1. Chronology and Biostratigraphic Significance of Assemblage Recovered

The present dinoflagellate study, completed by previous studies of micro- and macrofossils found in DSDP Site 380 samples (Percival, 1978; Gheorgian, 1978; Schrader, 1978; Olteanu, 1978; Popescu, 2006, 2008), suggests that the Black Sea evolved generally in brackish conditions. These conditions; however, shifted periodically due to marine invasions related to short-lived connection to the Mediterranean Sea. Most biostratigraphic microfossil markers (calcareous nannoplankton and foraminifers) known from global oceans are essentially missing in the Black Sea, except at times of marine connections. This makes it difficult to date the environmental signal defined from the dinoflagellate assemblage recovered. In an attempt to bypass this problem, the following alternate dating method is proposed: using a temperature index based on ecological requirements of pollen flora, represented by the ratio between thermophilous trees (that show maximal development during warm and humid periods, i.e., interglacial), and steppe elements (herb originate from Anatolia, that became dominant during cooler and dry periods, i.e., glacial), correlated to global isotopic curve (Lourens et al, 2004). This curve is partially controlled by the rare layers where nannoplankton markers (Raffi, et al, 2006; Martini, 1971) were recovered. Popescu et al., (2010) successfully established a high resolution chronology for the brackish sediments in the Black Sea at other sites using this method.

Following this model and using the thermophilous/steppe ratio data from Popescu (personal communication, Fig. 27) for the studied sediments, a series of five warm and humid periods (67-58 m, 48-43 m, 34-29 m and 13-0 m) are indicated by the development of thermophilous trees alternating with four cooler and dry periods. Correlating these warmer periods, that may represent the most probable high sea level at the global scale, and calibrating these data with the appearance of calcareous nannoplankton (Percival, 1978) and foraminifers (Gheorgian, 1978), two chronology models (A and B, Fig. 27) are proposed.
Figure 27. Age model, and fluctuation in thermophyle species vs. Artemisia providing bases of calibration for two potential age model.

In Age Model A (Fig. 27), we propose that interval 70-38m represents MIS 5, interval 38-34m is MIS 4, interval 34-29m is MIS 3, interval 29-13m represents MIS 2, interval 13-0m represents MIS 1. In this model, peaks in thermophilous pollen and the presence of nannoplankton and foraminifera occurs at every proposed interglacial high-stand. During glacial periods an abundance of steppe pollen appears at time when calcareous nannoplankton and foraminifera disappear. Therefore, this model fits the microfossil data for the Black Sea. However, since no absolute ages were generated, Model B is a possibility as well.

If we follow Model B (Fig. 27), the interval 70-27.5m represents MIS 5, 27.5-25m is MIS 4, interval 25-13m is MIS 3, interval 13-5m is MIS 2, and lastly 5-0m represents MIS 1. This model diverges from Model A by having condensed interglacials (MIS 1). In MIS 5c, an
increase in thermophilous pollen along with the appearance of nannoplankton and foraminifera both occur during a high stand. They do not occur at the beginning of MIS 5c, suggesting a gradual marine connection for this stage. During the next proposed high stand, MIS 5a, these microfossils appear once again due to the marine connection at this time. During MIS 4 no nannoplankton or foraminifera occur due to marine isolation. An increase in steppe pollen supports this as well. Highstand MIS 3 in this model does not contain nannoplankton or foraminifera. Therefore, if a connection existed during this interglacial, it was probably a brief connection. Furthermore, no presence of these microfossils has been observed within MIS 1 for the Black Sea, however a large peak of thermophilous pollen is present.

In order to distinguish which of these two models is the most credible, the marine dinoflagellates were plotted using global age control for each stade/interstade, respectively (Fig. 28). An interpolation between the stadial/interstadial ages and the sediment deposition depth control are used for comparing the marine dinoflagellate cyst record and the global sea-level curve (Dutton et al., 2009). The present sills depths (Bosphorus at 30m, and Dardanelles at 60m) are indicated in Figure 28 against sea-level fluctuations. Using this approach, Model B seems to give the best stratigraphic match as the dinoflagellate marine records falls systematically during the interglacial periods (MIS 1 and MIS 5A, MIS 5c and MIS 5e), during which the global sea-level and the depth of Bosphorus and Dardanelles sills permit marine Mediterranean invasions into the Black Sea. When comparing our dinoflagellate data to Model A, it is clear that there are some offsets in the appearance of marine taxa, and the connections that are needed to allow their deposition in MIS 5c and MIS 5a. Therefore, Model B is the preferred age correlation model for this site.

When using Model B for the stratigraphic control of our assemblages, and focusing on the last twenty thousand years of deposition, some interesting observations can be made. Figure 29 presents the distribution of marine dinoflagellates (blue curve) and brackish dinoflagellates (purple and orange curve) over the last 20 ka. This clearly indicates short marine connections at a) 17 ka (similar, Popescu, 2008) most likely coincident with the rapid sea-level rise following the Last Glacial Maximum; b) 15-14 ka (similar Popescu, 2008; Bazeley, 2010); c) about 8 ka (“Noah’s
Figure 28. Dinoflagellate cyst distribution following stratigraphic Model A and B. The percent of relative abundance is represented on Model A and B’s y-axis, while the x-axis represents the proposed ages for these two models. The red line in the Sea level curve indicates the shallowest depth of the Bosphorous and possible marine connections to the Black Sea.

...flood” proposed by Ryan, 1997; Mudie et al., 2001; Popescu, 2004, 2008; Marret et al., 2009, Verleye et al., 2009) and; d) the last permanent connection at approximately 6 ka. In our data, the marine dinoflagellate record for the last 8,000 years is not continuous due to the poor recovery of the top of the core (Fig. 29). However, an increase of S. cruciformis (orange curve) occurring with a decrease of P. psilata (purple curve) indicates warmer surface waters, which takes place during the highest sea-level stands within stage MIS 1.

The marine connection seen in our dinoflagellate data at approximately 15 ka can be interpreted as the onset of the Bølling-Allerød interstadial, well marked in our data set by an increase in marine dinocysts. Adding to this interpretation, in Figure 29 a sharp rise of S. cruciformis represents a time of warm SST. After this increase, the seemingly sudden and complete
disappearance of marine taxa could be interpreted as the mark of an abrupt cooling, possibly the mark of the Younger Dryas (12.9-11.7 ka)

Figure 29. Dinoflagellate distribution during the last 20,000 years.

### 5.2 Flood Model Evaluation

At our sampling resolution, it is difficult to pronounce the character (catastrophic or progressive) of the Black Sea’s last marine connection at about 8 ka, although we see a clear and possibly sudden increase in marine palynomorphs at 8 ka. But if marine species appear at 8 ka BP, they decrease in abundance in the next samples, and do not reappear until 6 ka BP. Therefore, the nature of the last reconnection is unclear. Since marine data alone cannot provide this information, the presence of reworked dinoflagellate cysts during this time was looked at to see if any information could be provided. If the last marine connection was a catastrophic event,
then a large increase in reworked dinocysts would be present. Based on our results, there are not. However, once again due to insufficient sampling intervals and moderate recovery, a definitive flood model choice cannot be supported at this time.

5.3 Environmental Implication of Assemblage Recovered

Verleye et al.’s (2009) Holocene dinoflagellate cyst study from the Black Sea (located 130 km southeast of Site 380) indicates that five different dinocyst associations can be distinguished. Dinocyst assemblages that define brackish environments during glacial intervals include species such as *Pyxidinopsis psilata*, *Spiniferites cruciformis*, and *Lingulodinium machaerophorum* var. *clavatum* (Verleye et al., 2009). Saline-tolerant species such as *Lingulodinium machaerophorum*, *Pentapharsodinium dalei*, and *Peridinium ponticum* represent a marine connection causing salinization of the Black Sea (Verleye et al., 2009; Mudie et al., 2002). In addition, *Gonyaulax apiculata* and *Pediastrum* currently reside in European alpine lake waters, but occur sporadically in the Marmara and Black Seas during the Holocene, indicating periods of high precipitation and runoff (Mudie et al., 2002).

According to Verleye et al. (2009), the timing of the Holocene reconnection of the Mediterranean Sea to the Black Sea began at 8.25 ka BP due to the decline of brackish dinocysts and the appearance of *Operculodinium centrocarpum sensu strictum* and *Spiniferites* spp. (indet.). Verleye et al. (2009) also proposes the Black Sea was close to fully connected to the Aegean at 7.97 ka BP due to the presence of a 95% marine dinocyst assemblage.

Recovery at DSDP Site 380 was lower than Verleye et al.’s (2009) study site, and therefore the exact timing of the marine reconnection cannot be determined based solely on our dinoflagellate data. Indications can be made; however, with less certainty as will be discussed further below.

5.4 Timing of the Last Reconnection

The highest peak of reworked taxa seen at 53 m depth, indicates a time with high river input. In our data, at the onset of MIS 1, we do not have evidence for a large amount of reworking.
This means that we cannot support the catastrophic flood model based on this dataset.

The main problem in trying to reconstruct a reconnection model for this dataset is largely due to the sample distribution and the poor recovery for the site. No samples were available between 17 and 29 m (during MIS 1 for Model A and MIS 4-3 for Model B), causing severe age reconstruction and reconnection model issues. Another issue for this dataset is that there is no $\delta^{18}O$ isotope curve from the Black Sea. Using a global $\delta^{18}O$ curve such as the Bloom and Törnqvist (2000) or Zachos et al. (2008) curves is not an accurate measurement for the Black Sea due to its disconnection to the global ocean by three other seas (Mediterranean, Aegean, and Marmara Sea). Therefore, Popescu et al.’s (2009) high-resolution thermophile vs. steppe pollen data from Site 380 was the only current way to correlate our dinoflagellate data to an age model.

From our available data, at 13 m (one of our first data point after a long time-interval sample gap), a large increase and diversity of *in situ* euryhaline marine species (*Spiniferites* spp., *A. andalusiensi*, *Hystrichokolpoma* sp., and *L. macherophorum*) are observed. This occurs concomitantly to the appearance of *A. choanum*, a stenohaline marine species. The highest abundance of *L. macherophorum* with long processes is found at near this 13 m depth as well, indicating a strong marine incursion at that level. This observation along with the appearance of several other marine species could mark a possible MIS 1 connection as low as 13 m (as seen Fig. 26). However, this cannot be fully supported due to poor sample distribution below this depth, and our Model B position higher in the sequence might be a better option when you consider the sedimentation rates for the Black Sea. When considering this additional set of data, the placement of MIS 1 could be off by as much as 6 meters. Indeed, Degens and Ross (1972) proposed a high sedimentation rate from 22,000 to 9,000 years BP of about 0.1 cm/year. At this pre-connection rate, MIS 1 could occur at approximately 7 m, which agrees much more with Model B (Fig. 26). The average sedimentation rate from ~7,000 to present (since a full marine connection) has drastically lowered to 0.01 cm/year likely due to turbulence (Degens and Ross, 1972). At this lower sedimentation rate our MIS 1 should begin around 0.7 m, therefore Age Model B fits this much better, because MIS 1 begins at 5 m in Model B. However, it is important to keep in mind
that these rates may be fairly outdated and represent the average for the whole basin. Therefore, they can only be used as a loose guide for Site 380.

5.5 Significance of Assemblage Recovered

The fact that DSDP 380 is so abundant in two species; *Galeacystca etrusca* and *Spiniferites cruciformis* is important as these species have limited occurrence, even within their greater Black Sea home. Upon first examination of DSDP Site 380’s palynological slides, it was clear that these two species made up the majority of the total count percentages, especially *G. etrusca*, with very few other species present in large numbers. Since they are representative of low salinity during glacial periods in the eastern Mediterranean region (Wall and Dale, 1973b; Mudie et al., 2010; Verleye et al., 2009), and DSDP 380 has a uniquely high abundance of these two species, we conducted a multifaceted statistical morphological analysis in order to determine if process length variations and morphological cyst changes could be beneficial in producing a more detailed salinity reconstruction of the Late Quaternary.

Wall and Dale (1973b) was the first to notice that salinity changes related to glacial and interglacial connections in the Black Sea could be observed using a dinoflagellate record. A clear shift between the normal brackish salinity of the Black Sea, and close to freshwater salinity was observed based solely on dinoflagellate assemblage changes. In Wall et al. (1973a), several of these dinocysts, which defined these salinity shifts, such as *S. cruciformis*, were described as “plastic species” due to drastic morphological changes. Drastic interspecies changes in the endocyst had never been seen to such a degree and therefore not only challenged the taxonomy of the species but also produced the hypothesis that even more salinity information could potentially come from the occurrence of each “plastic” morphotype.

In Popescu et al.’s (2009), four morphometric subgroups of *G. etrusca* were identified in Messinian-age sediment. The presence of subgroups was assumed to have been forced by the Messinian Salinity Crisis, wherein *G. etrusca* suffered great stress produced by unstable salinity conditions pre- and post-Zanclean. No distinct morphometric subgroups were found within the
collected high-resolution biometric data of *G. etrusca* at DSDP site 380. The homogeneity of this species precludes making salinity reconstructions based on the methods of Popesu et al. (2009) for this study. However, we can conclude that overall, the Black Sea never had salinity fluctuations over 12 psu.

*S. cruciformis* has been under much debate not only recently but since its discovery. It has been defined classically as a fresh/brackish water indicator (Wall and Dale, 1973b), however more recently has been hypothesized by Kouli et al. (2001) to be a freshwater species. Eaton’s (1996) study provided a case similar to our own where *S. cruciformis*, and other cruciform dinocyst species, such as *P. psilata* were not only present in the Black Sea samples, but also completely dominated the assemblages. From these findings, he was the first to suggest that this rare cruciform shape must be a stress effect of low salinity waters of less than 12 psu (Eaton, 1996).

Kouli et al. (2001) was able to further this hypothesis when they identified only the ellipsoidal type (e-type) of *S. cruciformis* (Plate 2) in sediment collected from a Greek freshwater lake. The common cruciform (c-type) shape (Plate 2) found in the brackish greater Black Sea region was not present, which implied c-type are representative of brackish environments. While DSDP Site 380 has both morphotypes present, no clear correlation between SSS and morphotypes present can be determined. Our PCA analysis of *S. cruciformis* morphotypes shows a much more complex relationship with SSS, at least for MIS 5e-1. Mudie et al. (2001) encountered this same problem for the *S. cruciformis* morphotypes that were found within Holocene sediments of the greater Black Sea region. In Mudie et al. (2001), five morphotypes were identified based on process lengths and endocyst and ectocyst shapes. Neither PCA nor comparisons to the δO\textsuperscript{18} sea level curve allowed them to create concrete salinity reconstructions. Therefore, these “plastic species,” as described by Wall et al. (1973a) have an unclear relationship with salinity. Transportation may be one of the main causes for this however cannot be determined.

One interesting observations gathered from the measurements of several thousand specimens of *S. cruciformis* and *G. etrusca* is that the mixture analyses (Figs. 20 and 21) indicate that overall, these two species exemplify morphometric similarities. These findings tends to
support a recent theory proposing that a common extinct dinoflagellate produced two types of cysts (namely *S. cruciformis* and *G. etrusca*) in response to different environmental parameters.
CHAPTER 6. CONCLUSIONS

The palynological analysis conducted used dinoflagellate cysts to obtain (1) evidence for possible connections between the Black and Mediterranean seas, (2) to characterize the paleoenvironmental changes on the Black Sea since the MIS 5. This detailed palynological study of site DSDP Site 380 on the edge of the Black Sea’s continental slope, is the first paleoenvironmental study of the MIS 5e to MIS 1 sequence with a focus on the evolution of marine connections and isolations between the Black Sea and the Marmara Sea. Our data show that during this time interval, several marine influxes occurred in the Black Sea as a result of global sea level rise and fall. This resulted in small differences in sea-surface salinity for the Black Sea during the Last Glacial Climatic Cycle.

6.1. Dinoflagellate Cyst Assemblage

Recovery was moderate to good while biodiversity was relatively low throughout the section. Brackish/freshwater species *P. psilata*, *G. etrusca*, and *S. cruciformis* were the dominant taxa found at Site 380. *P. psilata*, a fresh/brackish species, is an important indicator of cooler SST during glacial periods. While *G. etrusca* and *S. cruciformis*, brackish species as well, are excellent indicators of warmer sea-surface temperature when warm marine waters are able to breech through the Bosphorus connection. Marine species recovered include *L. macherophorum, S. bentorii, A. andalouxiense*, and others. They are present during interglacial periods indicating connections between the Black and Mediterranean Seas during high sea level.

A. Reconnections Observed for the Last 20ka

Several marine incursions are observed throughout the past 20,000 years at Site 380. The beginning of the Bölling-Allerød is indicated through a relative rapid rise in SSS and SST. The Younger Dryas directly follows indicated by the abrupt disappearance of marine taxa combined with species indicative of lower sea-surface temperature as seen in the increased abundance of *P.*
psilata. The Last Glacial Maximum (~20 ka) is indicated by a time when no marine species were recovered from the assemblage as connections are interrupted at that time.

**B. Biometric Conclusions**

Both ellipsoidal and cruciform central body shapes are present during times of Black Sea isolation and during times of marine connection. Therefore, based on statistical data alone, detailed salinity reconstructions for the Black Sea’s Late Quaternary history could not be determined. PCA confirmed this when no true sub-groups were produced as seen in Popescu et al. (2009). Therefore, these specimens may have not undergone enough environmental stress during the Late Quaternary. This is seen to indicate that the salinity in the Black Sea during the study interval never varied to full marine status, but rather isolated between lower to higher brackish values.

**C. Is Spiniferites cruciformis a Fresh Water Species?**

Both morphotypes (c-type and e-type) of *S. cruciformis* being present within many of the sample intervals along with it occurring most often with *G. etrusca*, a known brackish water dinoflagellate species, we conclude that *Spiniferites cruciformis* is not a freshwater species. We propose that the specimens found within Kouli et al.’s (2001) study were likely reworked. Furthermore, this species has never been found in other freshwater locations, except for the evidence presented by Kouli et al., (2001) and the presence of marine gateway trough the Balkans functioning during the Early Pliocene (Clauzon et al., 2005, Popescu et al., 2009, Bache et al., 2012). This area is close to the freshwater lake where Kouli et al., (2001) found *S. cruciformis*, and therefore this supports our hypothesis.

**D. Could S. cruciformis and G. etrusca be the Cysts of the Same Dinoflagellate Algae?**

The PCA mixture analysis from this study indicates that these two species are morphometrically similar and thus, the hypothesis that these two species would be generated by the same algae under different environmental conditions is supported. Furthermore, as seen in Plates 1 and 2, a gradation of morphotypes evolving from *Spiniferites cruciformis* type to *G.
*etrusca* type have been recovered, further supporting this hypothesis. This said, the species are now extinct, and this cannot be proven.
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Shannon Ferguson was born in Columbus, Georgia, and raised in the neighboring small town of Ellerslie, Georgia. Following her attendance at Harris County High School she attended Columbus State University and then Georgia Southern University in order to obtain her Bachelor of Science degree in Geology. After completing her undergraduate degree in December 2009, she continued her academic studies as a graduate student at Louisiana State University in Baton Rouge, Louisiana.