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New Interpretation of Glacial History of Cape Cod May Have Important Implications for Groundwater Contaminant Transport

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Fresh water resources of sufficient quantity and quality are critical for maintaining societies and for supporting additional growth and development. When these resources are threatened or compromised, as can occur through the release of hazardous compounds, additional stress is placed on the water supply system from loss of the resource and changes in the demand structure.

In western Cape Cod, Massachusetts, such problems are currently being encountered as a result of contaminant releases from the Massachusetts Military Reservation (MMR). An effective long-term response to subsurface contamination requires, among other things, determining the lithology, stratigraphy, and structure of aquifer materials and their effects on groundwater flow and contaminant transport. A recent review and analysis of subsurface data across Cape Cod offers a new interpretation of the geologic history of the Cape, with potential implications for groundwater issues facing western Cape Cod (the Upper Cape).

Background

The groundwater contamination problem in western Cape Cod was brought to light in the 1970s by the U.S. Geological Survey, which was investigating a sewage plume resulting from infiltration ponds at MMR [*LeBlanc*, 1984]. In 1979, detergents from the sewage plume were detected in a water supply well south of MMR, and the well was subsequently closed. Since then, 15 groundwater contaminant plumes have been identified and attributed to historical activities at the Reservation. In the spring of 2002, the Town of Bourne closed three of its six supply wells because of contamination; two additional wells remain threatened.

Offsetting these losses by installing new supply wells is not straightforward, because many sites that had been identified by these towns for possible future development are now contaminated. In addition, demand for publicly supplied water has increased because many households with contaminated or threatened private wells have been added to the public system, although this increase is small relative to new demand as a result of growth and development.

In response to changes in the supply and demand structure brought about by the groundwater contamination, the U.S. Department of Defense has installed three water supply wells in an undeveloped area of MMR to be used by surrounding towns. In addition, numerous studies have been undertaken to define the extent of contamination, determine the nature of the groundwater regime, and identify important subsurface pathways for contaminant transport. In 2002, active remediation of 10 plumes was ongoing, in which 11.7 million gallons of groundwater per day were treated.

Recently, two interpretations of the subsurface geology in western Cape Cod have emerged that may have important implications for groundwater flow at depth. One interpretation recognizes a continuous fine-grained unit, indicative of glacio-lacustrine deposits

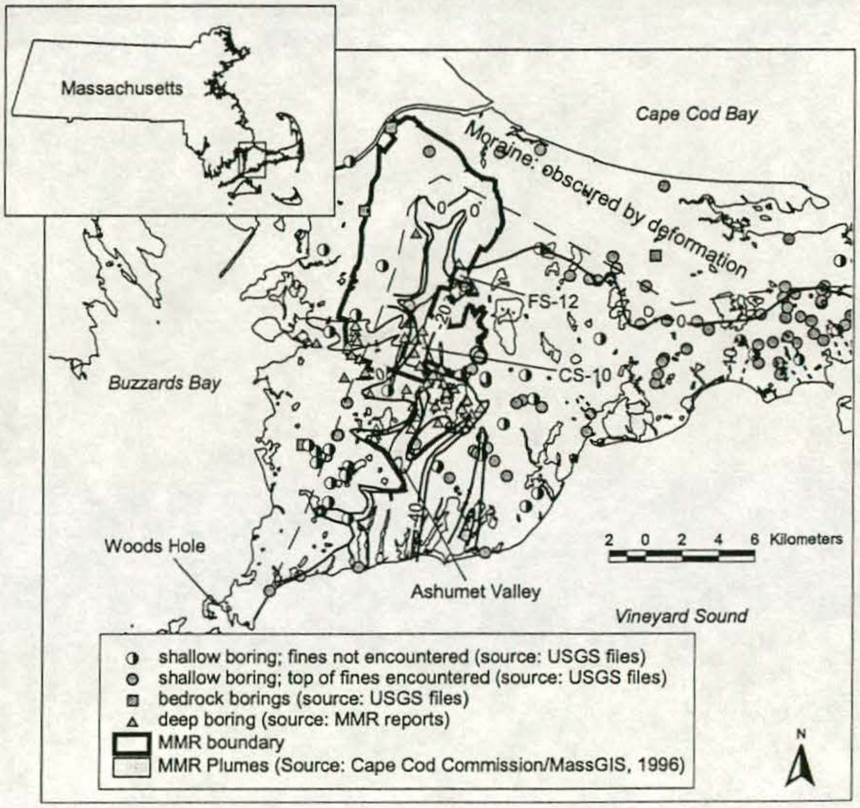

Fig. 1. Elevation of the glacio-lacustrine sediments in the subsurface of western Cape Cod. Contours are in meters relative to mean sea level. Groundwater contaminant plumes emanating from MMR are also shown.

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[*Masterson et al.*, 1997; *Mulligan and Uchupi*, 2002], below glacial outwash sediments. An alternative interpretation is that many of the fine-grained sediments at depth represent isolated lenses within the coarser-grained sand and gravel outwash (see site investigation reports available at http://www.mmr.org/adminrec.htm). Each of these conceptual models has different implications for groundwater flow because structural geometry exerts an important control when the permeability contrast between adjacent units is large.

A recent review of subsurface data from across Cape Cod was conducted to test the hypothesis that a glacial lake once covered parts of the present location of Cape Cod, and to place constraints on the timing and boundaries of such a lake. This work indicates that an extensive and thick fine-grained sand, silt, and clay unit is present in the subsurface, and supports the hypothesis that a glacial lake covered the east-west portion of Cape Cod ~19,000–17,000 years ago [*Mulligan and Uchupi*, 2002]. The inferred surface morphology of this unit indicates that these lake deposits have been eroded by drainage channels. These channels and surrounding lake sediments were covered by coarse-grained outwash deposits, establishing preferential flowpaths at depth in the groundwater system today. The new geologic interpretation is tested using groundwater contaminant plumes from MMR as tracers of groundwater flow. Three-dimensional visual evidence indicates that the geologic conceptual model is consistent with plume locations and shapes, suggesting that the permeable paleochannel pathways may be important influences on groundwater flow and contaminant transport.

Cape Cod Geology

The surficial geology on the Upper Cape is primarily of glacial origin, where outwash plains, terminal moraines, and ice-contact deposits are the predominant landforms [*Oldale and Barlow*, 1986]. Approximately 24,000 years ago, lobes of the Laurentide ice sheet extended as far south as Martha's Vineyard and Nantucket Islands [*Balco et. al.*, 2001]. Following the deposition of outwash plains and the creation of terminal moraines on the Islands, the ice sheets retreated to the area of the present-day south shore of Cape Cod. Ice-contact deposits were laid down, the remnants of which are represented today as six isolated hills across the south coast of Cape Cod [*Oldale and Barlow*, 1986]. The ice sheets subsequently retreated to approximately the north shore of the Cape. Outwash plains and terminal moraines were formed prior to further ice retreat to the north.

While the surface geology on Cape Cod has been well studied and documented, much less work has been done to develop a comprehensive picture of the subsurface sedimentary structure. Beginning in 1961, evidence has accumulated that a thick unit of fine-grained sediment, proposed to be of glacio-lacustrine origin, exists below the outwash plains [*Koteff and Cotton*, 1962; *Masterson et al.*, 1997]. In an effort to determine the extent of these deposits and place constraints on the subsurface geology across the Cape, borehole logs were collected from U.S. Geological Survey files (logs from various sources) and environmental investigation reports at the MMR. The intent of this investigation was to determine if there is regional evidence for a glacial lake. Therefore, only a subset of existing borehole logs was selected in an effort to obtain areal and vertical coverage regionally. Outside of the moraines, four subsurface lithologic units are present and classified as: (1) primarily sand and gravel with lenses of silt (glacial outwash); (2) a very fine sand, silt, and clay unit; (3) a poorly sorted mixture of gravel, sand, and silt resting on bedrock that we and others [*Koteff and Cotton*, 1962; *Masterson et al.*, 1997] have identified as till; or (4) bedrock.

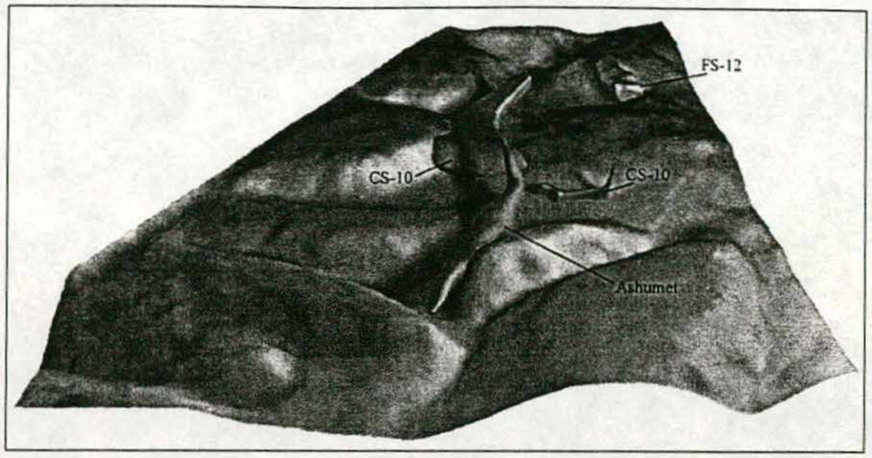

Fig. 2. Three-dimensional image of the glacio-lacustrine sediment surface and three of the groundwater contaminant plumes from MMR. All three plumes originated at the water table, and now are at least partially controlled by the topography at the outwash-glacio-lacustrine contact.

Borehole logs reveal that up to 45 m of fine-grained sediment exists in the subsurface across Cape Cod [*Mulligan and Uchupi*, 2002]. The areal extent of these fine sediments and the presence locally of seasonal deposition (varves) indicate that these sediments are of glacio-lacustrine origin. The stratigraphic relationships among the glacio-lacustrine sediments, outwash deposits, moraines, and ice-contact deposits indicate that two separate glacial lakes existed on Cape Cod at the time of their deposition. The Upper Cape lake (Lake Wampanoag) [*Mulligan and Uchupi*, 2002], the older of the two lakes, existed 19,000–17,000 years ago and spanned the east-west portion of present-day Cape Cod. Following the demise of Lake Wampanoag, the Sandwich Moraine was created, which later became the southern dam for a lake that covered Cape Cod Bay and the north-south arm of Cape Cod.

To date, research in Nantucket Sound, along the southern margin of Cape Cod, has not revealed fine-grained material at depth coeval with the deposits beneath the Upper Cape [*O'Hara and Oldale*, 1987; *Gutierrez et al.*, 2003]. We therefore infer that Lake Wampanoag was dammed to the south by continuous ice-contact deposits, and was bounded to the west, north, and east by lobes of the Laurentide ice sheet.

Structure maps of the top of the glacio-lacustrine sediments reveal several drainage channels oriented in a north-south direction across the Upper Cape draining into Nantucket Sound [*Mulligan and Uchupi*, 2002]. These channels arose either concomitant with or subsequent to lake drainage and eroded a considerable volume of the lake deposits. One of these channels is located in western Cape Cod and is partly below the MMR (Figure 1). After their erosion, the glacio-lacustrine sediments were covered by outwash deposits, thereby creating preferential, high-conductivity pathways through the drainage channels at depth.

Groundwater Flow and Stratigraphic Heterogeneity at MMR

Groundwater on Cape Cod is unconfined, occurs as a series of six lenses, and flows from the center and apex of each lens radially outward and toward the coast. The largest lens, called the Sagamore lens, is located in western Cape Cod. The MMR, which covers approximately 34 square miles (Figure 1), is located above the apex of the Sagamore lens.

To date, approximately 15 groundwater contaminant plumes have been detected at the MMR, ranging from relatively small plumes, to volumes that span several kilometers in length and width and 10s of meters in thickness. (For recent plume maps, see www.mmr.org/cleanup/plumes.htm). The different contaminant plumes are at various stages of detection and delineation, remedial design, or active remediation. Contaminants of concern (COC) in these plumes include benzene, trichloroethene (TCE), tetrachloroethene (PCE), dichloroethene (DCE), ethylene dibromide (EDB), and explosives.

In plan view, the paleochannel carved into the glacio-lacustrine sediments in western Cape Cod coincides with the location of several groundwater contaminant plumes emanating from the MMR (Figure 1). However, the sand and gravel outwash resting on the fine-grained sediment is up to 90 m thick, and the water table is located within these coarser sediments, so any inferred stratigraphic controls on contaminant transport must be based on three-dimensional observations. As a test of the subsurface conceptual model and to assess the potential for stratigraphic control of groundwater flow, three contaminant plumes were used as tracers of groundwater flow.

Three-dimensional images of the plumes were generated and superimposed on a three-dimensional representation of the glacio-lacustrine sediment surface contoured in Figure 1. Plume delineations contained in environmental investigation reports of the MMR were used to develop the images (Figure 2; other orientations not shown). Plume locations (horizontal and vertical) and dimensions were obtained from the most recent reports completed prior to remediation activity at the plume of interest, and translated into three-dimensional graphics. Each contaminant plume is delineated as the volume of water with contaminant concentrations equal to or greater than drinking water standards or maximum contaminant levels.

The data density for delineating the plumes is much higher than that used to determine the extent and surface morphology of the glacio-lacustrine sediments. For example, the CS-10 plume is delineated using data from over 100 borehole locations. Many of these locations have multi-level piezometers for vertical sampling. Inspection of Figure 1 shows that about 13 borehole logs are used to interpret the geology near the CS-10 plume.

Source areas for all three plumes are near the top of the Sagamore lens; hence, vertical hydraulic gradients can result in downward contaminant migration. The Ashumet plume (COC = TCE, PCE, DCE), which originated at the water table and traveled vertically downward and to the south, appears to be confined to the coarse outwash sediments in-filling the paleochannel (Figure 2). Groundwater also appears to be transporting the contaminants around a high in the glacio-lacustrine sediments as it flows primarily through the channel-fill deposits. The western lobe and middle portions of the CS-10 plume (COC = TCE, PCE) appear to have been transported into the glacio-lacustrine unit. In this case, the density of geologic data is likely insufficiently high to adequately represent local-scale heterogeneities in our large-scale conceptual model of the subsurface.

However, the main portion of the plume does appear to be confined to the paleo-channel in-filling sediments. The eastern portion of this plume appears to be traveling upward under strong vertical gradients and discharging into a surface pond. Data to constrain the contamination below the pond are relatively new, and the inferred shape of the plume in this area may reflect insufficient sampling density. The plume FS-12 (COC = EBD and benzene) is relatively small compared to the scale of our conceptual model. Nonetheless, the plume extends vertically down to the top of the fine-grained sediments. Hence, plume transport may have been halted by the glacio-lacustrine sediments.

Conclusions

Visual evidence suggests that paleochannels in the subsurface of western Cape Cod may act as preferential pathways for groundwater flow at depth. If this hypothesis is correct, the fine-grained, glacio-lacustrine sediments act as an aquiclude, and flow and transport are focused in the high-permeability outwash deposits. The surface morphology of the lake sediments results in both horizontal and vertical flow restrictions. These properties will control future contaminant transport at depth, and are likely to be important as water supply pumping from the aquifer increases to meet the needs of the expanding residential and tourist populations.

The surface of the glacio-lacustrine sediments has been eroded and back-filled with permeable sand and gravel (Figure 1). Determining the surface morphology of this stratum solely from borehole data is quite difficult because of local complexity. However, a review of data from across the Cape does reveal an areally extensive and thick unit of fine-grained, glacio-lacustrine sediments. Integrating borehole data from across Cape Cod, including descriptions of deformed sediments in the moraines, was required to constrain the nature and extent of these lake deposits and their surficial structure. If additional contamination is detected and as water supply withdrawals increase in the future, it will become increasingly important to base analyses of the aquifer on a geologically consistent framework of the subsurface.

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Should Memphis Build for California's Earthquakes?

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State and local authorities in parts of the central U.S. that are at risk from earthquakes in the New Madrid Seismic Zone (NMSZ) are considering adopting a new building code that would increase the earthquake resistance of new buildings to levels similar to those in southern California.

Here, we argue against this proposal on the dual grounds that the earthquake hazard has been overestimated, and that the costs of the proposed change are likely to far exceed the potential benefits. Instead, we recommend weighing the costs and benefits of alternative strategies that could yield reasonable seismic safety at significantly lower cost.

The new building code, IBC2000, is a national code developed under direction of the Federal Emergency Management Agency (FEMA), which includes regional provisions for seismic safety. Surprisingly, these have been proposed with almost no consideration of the costs and benefits. We estimate that building costs (about $2 billion annually in the Memphis area alone) could increase significantly, perhaps by 10%, or more, depending on building type. This cost, in excess of $200 million, is more than 10 times FEMA's own estimate of the anticipated annualized earthquake loss of $17 million [*FEMA*, 2001]. Moreover, FEMA's estimates show that buildings in Memphis are 5 to 10 times less likely to be damaged than in San Francisco or Los Angeles. Hence, in our view, the new code should not be adopted unless justified by careful analysis.

Because most earthquake-related deaths result from the collapse of buildings—a

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