Anatomy of a Migrating, late Holocene Strand Complex: A GPR-based Architectural Study of the Zion Beach-ridge Plain, SW Lake Michigan

Mattheus, C.R., Barklage, M., and Braun, K.

***Illinois State Geological Survey**, Prairie Research Institute, University of Illinois at Urbana-Champaign*

I. ABSTRACT

The Zion Beach-ridge Plain (ZBRP) defines the northernmost portion of the Illinois coast of SW Lake Michigan, where it hosts a variety of unique ecosystems within its 'washboard-style' ridge-and-swale topography (e.g., pannes). The sands comprising this coastal lithosome were sourced by southward littoral fluxes and the present strand contains an ~5,000-year paleorecord. An effort has been underway to map the depositional architecture of the ZBRP using GPR (with ~12 trackline km of data along shore-perpendicular road sections thus far), LiDAR data (2012 USACE/NOAA topo-bathymetry), historic shoreline positions (from nautical charts and aerial photographs), lithologic information (e.g., cores and auger descriptions), and geochronological data (C-14 and OSL ages). We strive to better understand how the shape of the underlying till surface and late Holocene climate changes may have influenced littoral/shoreline dynamics and strand geomorphology.

Shore-perpendicular GPR transects (collected using a 250 MHz setup) resolve lakeward-inclined reflectors of high amplitude within the ~upper 6 m of the strandplain subsurface. These are interpreted as former foreshore profiles. Radar surfaces truncating landward reflections and/or characterized by onlap of more lakeward ones suggest ravinement of former terrains. Presence of overwash deposits is inferred by landward-dipping reflections along the backside of prominent ridgelines. Zones unassociated with overwash, across which a succession of foreshore profiles are found at higher elevations, correlate spatially with high-relief, compound ridges that obliquely truncate landward (i.e., older) ridges and are onlapped by more lakeward (i.e., younger) ones.

Unlike embayed strandplains of the Upper Great Lakes, often studied for paleohydrographic information, the Zion Beach-ridge Plain is a system that has undergone near-continuous reworking along its northern extent and accretion along its southern extent. This general dynamic has been punctuated by the effects of climatic shifts, which are manifested in the strand's highly compartmentalized architecture. Potential culprits are major changes in lake level (beyond decadal signatures) and/or storm climate (e.g., prevailing storm-wind directions). Efforts are underway to refine the strand geochronology for an improved evolutionary model and for regional/paleoclimatic contextualization.

II. BACKGROUND

Renewed interest in mapping the architecture of the Zion Beach-ridge Plain (ZBRP) is underpinned by prior efforts of Hester and Fraser (1973), Fraser and Hester (1974, 1977), Larsen (1985),and Chrzastowlski and Frankie (2000) to map and study its stratigraphy and evolutionary history. The ZBRP is a migrating strand system characterized by a net-loss of materials along its northern portion and a net-gain along its southern. This general dynamic, quantified from sedimentary trends in the nearshore (Morang et al., 2019), is reflected by long-term (>decadal) shoreline dynamics (**FIGURE 1**). The remaining coastal margin of IL (along the till bluff shorelines and the Chicago urban lakefront to the south) is sand-deprived. Nearshore regions here are blanketed by only thin and discontinuous sand bodies atop scoured glacial clay till, gravel-lag deposits, and bedrock outcrops (Creque et al., 2010; Mwakanyamale et al., 2020).

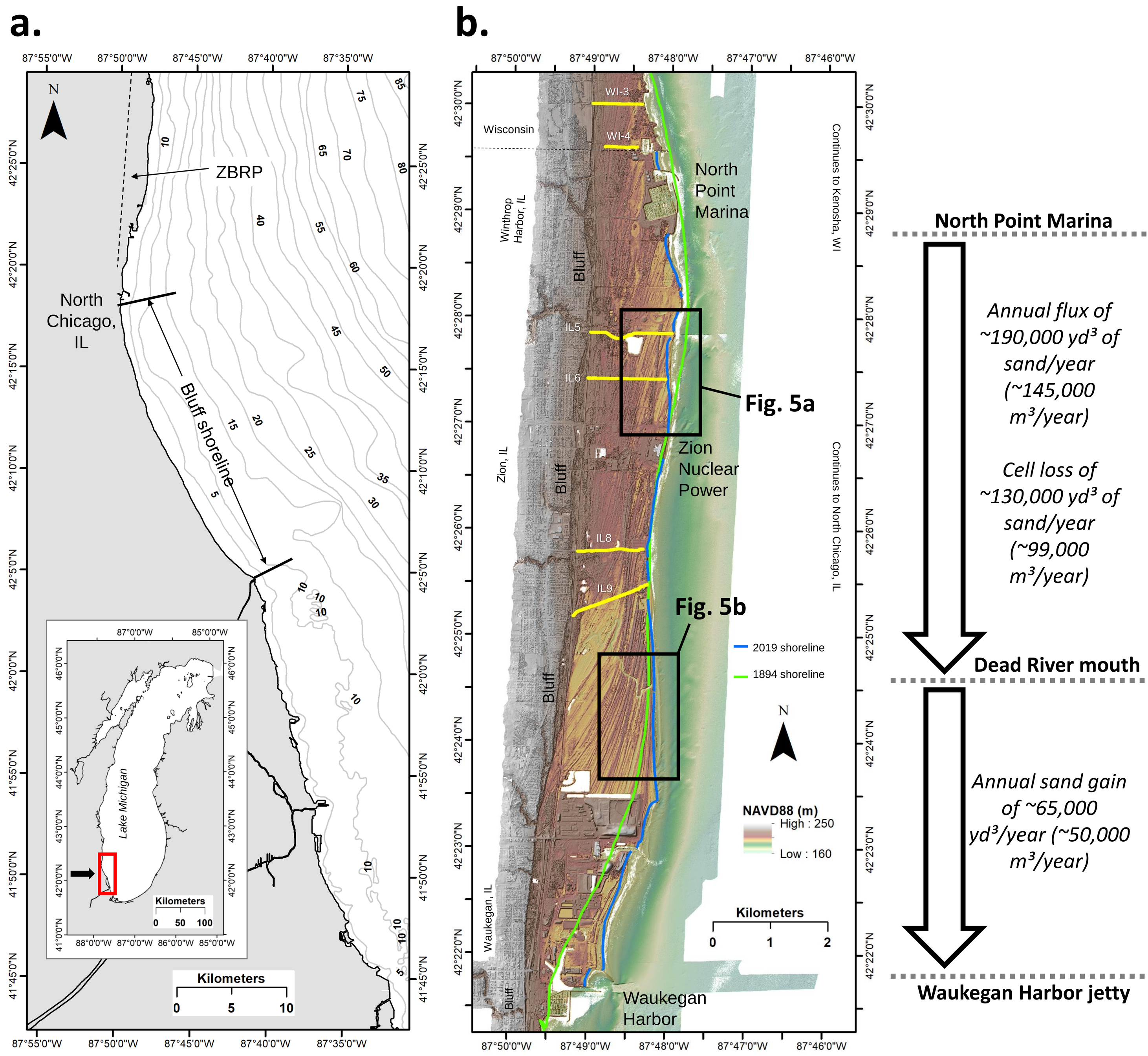


***FIGURE 1 (left)** - Maps showing (**a**) The location of the Zion Beach Ridge Plain (ZBRP) in context of the greater Illinois Lake Michigan margin; and (**b**) a 2012 USACE topo-bathymetric LiDAR-based DEM of the ridge plain and its nearshore with 1884 and 2019 shorelines superimposed (in green and blue, respectively) along with the locations of several GPR transects (as spatial reference). Shown also is information on the littoral system, with associated sand-transport volumes established by Morang et al. (2019).*

III. METHODS

The Illinois State Geological Survey (ISGS) collected >10 km of GPR data in 2021 using a 250 MHz setup. This coverage, mostly along shore-perpendicular road sections, spans from Kenosha, WI, to Zion, IL (**FIGURE 2**). Radar data were processed in Ekko Project™. Two-way travel time was converted to depth based on a radar velocity of 0.15 m/ns, a standard for dry sand verified by hyperbola fitting. Topographic corrections were based on a 10 m USGS DEM extraction along transect lines. More than 100 lithologic descriptions (e.g., water-well logs) aided correlation efforts. GPR records were evaluated based on stratigraphic principles (e.g., cross-cutting relationships) and radar-facies distinctions (RF1-RF3; **FIGURE 3**).

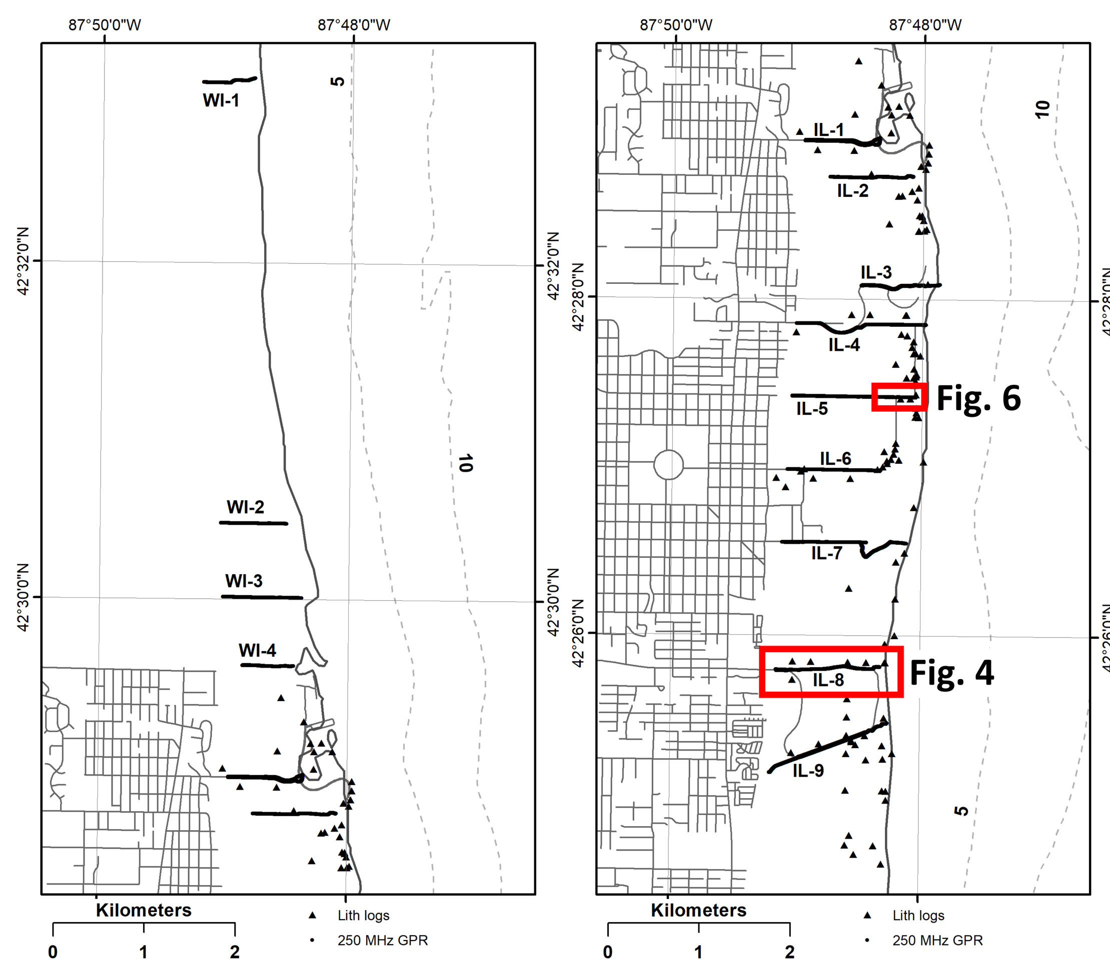
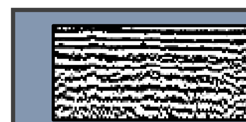


***FIGURE 2 (left)** – Map of subsurface data distribution. Solid black lines (labeled WI-1 through WI-4 on the Wisconsin side of the border and IL-1 through IL-9 on the Illinois side) represent GPR transects, which in subsequent figures are always plotted from bluff to shoreline (left to right). Triangles demark locations of ISGS lithologic database information (https://prairie-research.maps.arcgis.com/apps/webappviewer/index.html?id=e06b64ae0c814ef3a4e43a191cb57f87) and recently collected sediment cores.*

IV. RESULTS AND DISCUSSION

The GPR data provide a high-resolution image of subsurface architecture to depths of ~6 meters, resolving depositional structures at the decimeter scale. Three distinct radar facies are distinguished based on reflective pattern (**FIGURE 3**). These radar units are often well delineated and can be mapped across expansive stretches of the ridge plain (**FIGURE 4**). Detailed sedimentary characterizations by Hester and Fraser (1973) along Wadsworth Road (IL-8) provide lithologic constraints that generally correlate with these interpretations (**FIGURE 4**). Coarse sand and gravel deposits described in core section correlate with a high-amplitude, topographically-varied zone separating RF2 and RF3 (landward of PA-5), where surface topography across the ridge plain is subdued (**FIGURE 1**). PA-5, PA-7, and PA-8 contain an overall upward-coarsening sedimentary succession (from fine shelly sands to medium/coarse gravels) representative of the nearshore-beach energy gradient (Booth, 1994).


RF1 - Radar facies suggestive of horizontal bedding (i.e., vertical accretion). Correlated with fine-grained (clayey), occasionally organic-rich wetland swale deposits (see tops of PA-9 and PA-10; **Figure 4**).


RF2 - Chaotic radar facies lacking distinct reflective patterns of continuity. Correlated with deposits of fine-grained sand of potential eolian origin (see PA-5, PA-6, PA-9, and PA-10; **Figure 4**), but may also characterize other lithologies and road fill.

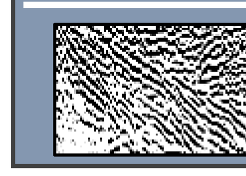

RF3 - Radar facies suggestive of mostly lakeward-inclined bedding surfaces bound by unconformable surfaces (onlap of more lakeward and truncation of more landward packages). Suggests interbedded sands (fine-coarse) and gravels of former shoreline and nearshore environments (see PA-5, PA-7 and PA-8; **Figure 4**).

***FIGURE 3 (above)** – Characterization of dominant radar facies by internal reflection configuration. Lithologic pairings are based on constraints provided by detailed sedimentary descriptions made by Hester and Fraser along IL-8 (see **Figure 4**).*

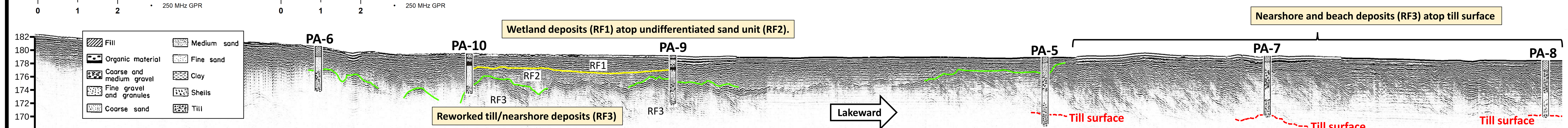


***FIGURE 4 (above)** – Processed GPR line IL-8 (from west to east) overlain by Hester and Fraser's (1973) lithologic interpretations (see legend for unit descriptions) and demarcations of major stratigraphic subdivisions (based on radar facies pattern, lithologic data, and continuity of major reflective surfaces). The separation between RF3 and RF2 (green) is particularly well pronounced between PA-10 and PA-5. The till surface (dashed red) is inferred from the lithologic dataset and marked where substantiated by radar reflective pattern (e.g., as downlap surface). The base of organic-rich wetland deposits overlying fine sands (possibly eolian) is penetrated by PA-10 and PA-9 and correlates to a boundary between RF2 and RF1 (yellow).*

Subsurface data and surficial assessments of the ZBRP suggest a change in coastal dynamics. Strand portions closer to the bluff environment tend to be topographically subdued (i.e., have less relief) than the more 'washboard-style' ridge-and-swale terrains closer to the modern shoreline, particularly towards the southern end of the strand (**Figure 1b**). This is best captured along IL-8 (**FIGURE 4**). The lakeward increase in topographic character (not obvious in **Figure 4** as GPR data were collected along a leveled road) is manifested in the subsurface as an increase in structural complexity and a general coarsening of deposits towards the lake. Sands overlying a thin basal unit of coarse sand and gravel in PA-9 and PA-10 (probably lag deposits atop till) are generally fine and lack the internal stratigraphic complexity and textural coarseness encountered in the subsurface lakeward of PA-5. This may indicate that the energy of the littoral system has increased. While surface topography argues that the terrain south of the Dead River (DR) is comprised of largely conformable ridge packages (with no obvious discordant relationships between landforms), several distinct ridgelines compartmentalize the northern ridge plain into unconformity-bound terrains (**FIGURE 5**). Modern shoreline dynamics offer a process-based perspective of how such angularly unconformable ridge relationships form (by ravinement and overwash; Mattheus et al., 2020; **FIGURE 5a**). Major transgressive ridgelines, generally higher in relief that surrounding topography, are manifested in the subsurface as broad zones of elevated shoreface-profile amalgamation (**FIGURE 6**). Efforts are currently underway by the ISGS to improve upon the existing strand geochronology using OSL by targeting key landscape elements.

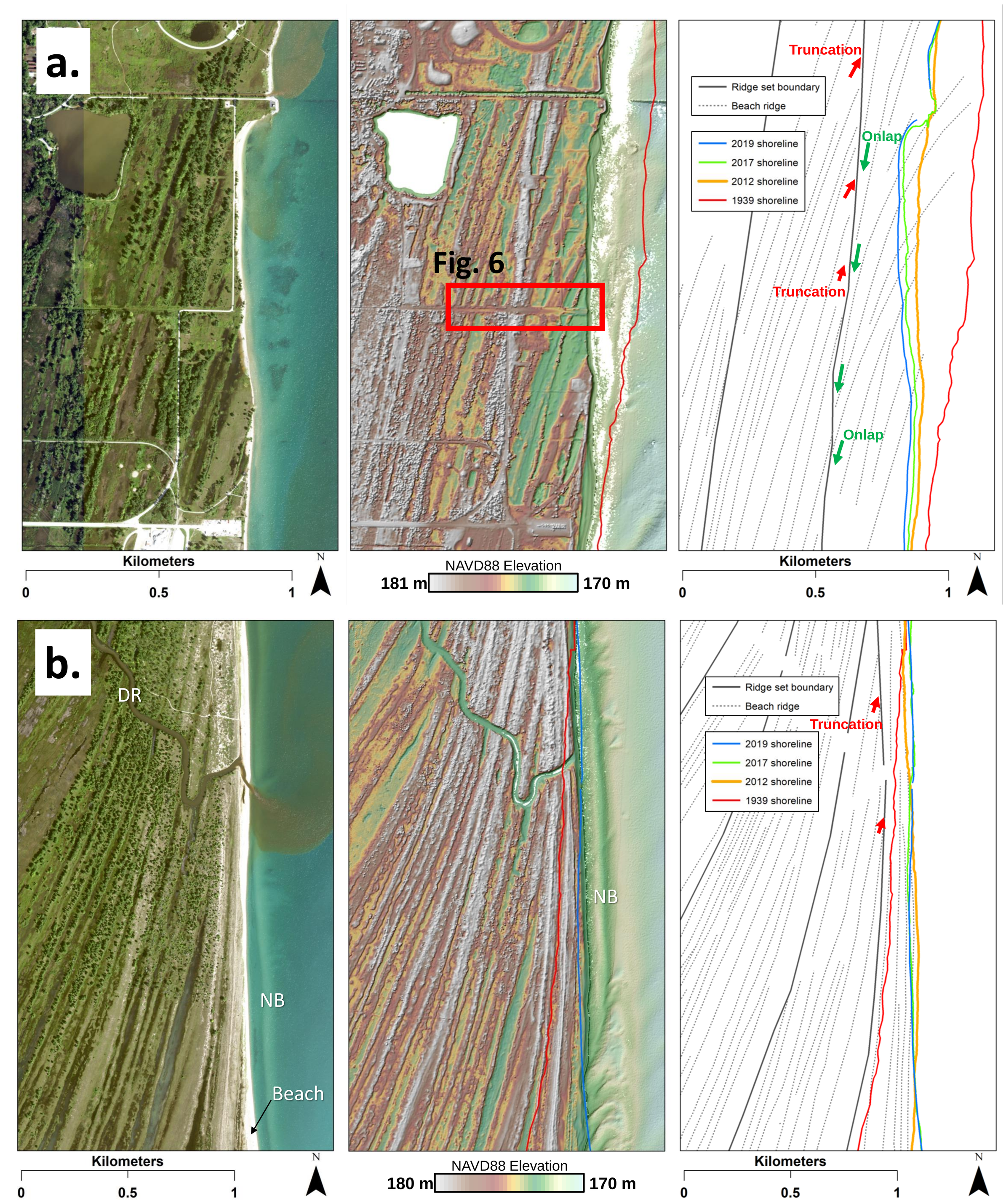


***FIGURE 5 (left)** – Map collage series of net-erosional (a) and net-accretionary (b) sections of the ZBRP shoreline, showing 2019 NAIP aerial photographs, 2012 LiDAR-derived DEMs (USACE), and historic shoreline reconstructions against strand lineament maps (highlighting ridge-set boundaries of interest).*

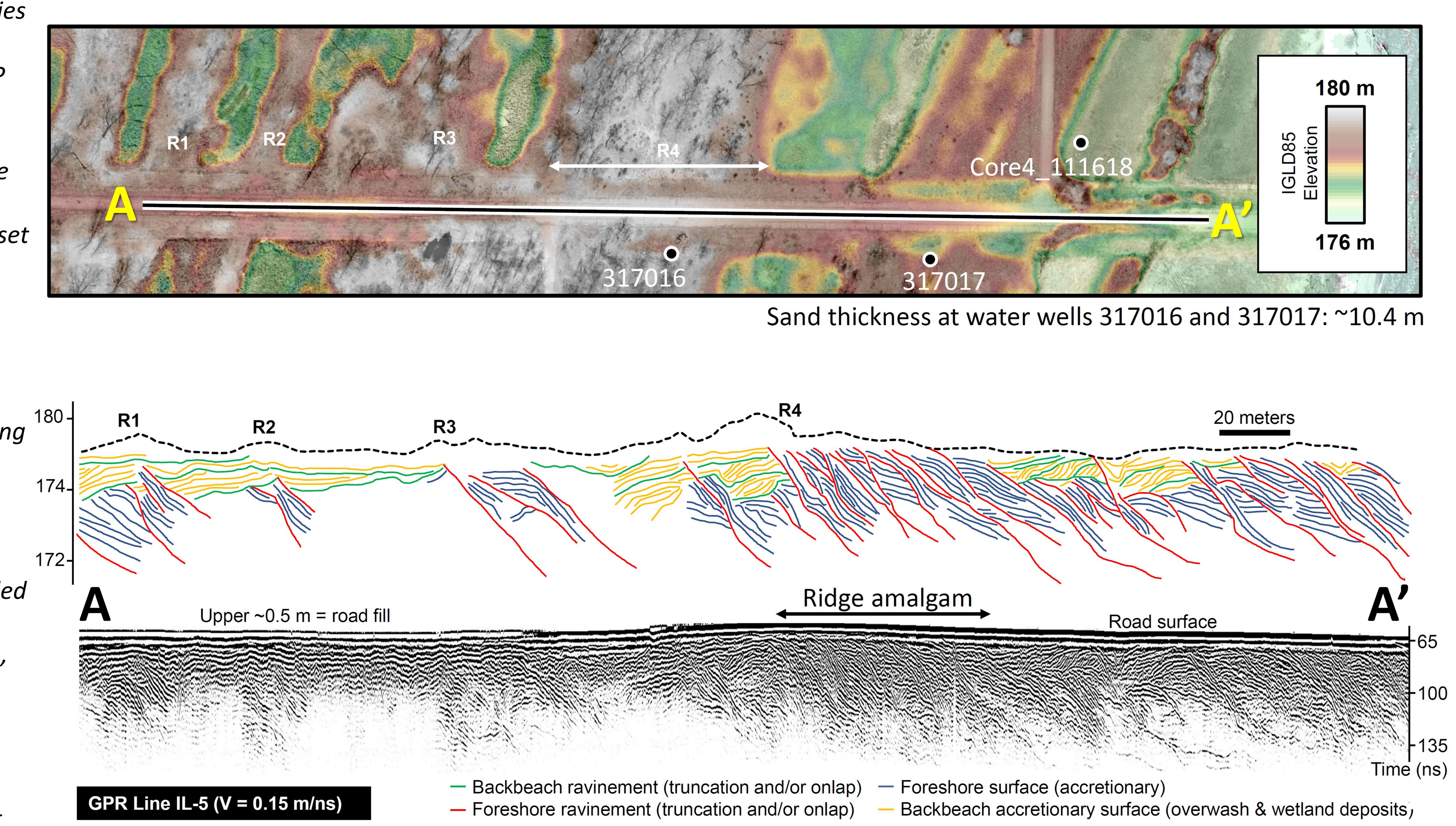


***FIGURE 6 (right)** – Uninterpreted and interpreted lake-proximal subsurface of GPR line IL-5 (see **FIGURES 2 and 6** for location), relating subsurface architectures to surrounding strand topography (i.e., ridgelines), extracted road-proximal from a 2012 DEM. Different architectural elements are color-coded and assigned depositional facies interpretations based on orientation, stratigraphic superposition, and inferred relationship to modern surface topography and sedimentology. Lakeward-inclined surfaces are interpreted to be paleo-beach face profiles (foreshore and inner nearshore); sedimentary data corroborate this relationship elsewhere (**FIGURE 4**). Landward-dipping surfaces are interpreted to represent overwash, based on strict association with the landward-sloping terrains behind ridgelines, which are often observed to be lobate.*

V. REFERENCES AND ACKNOWLEDGEMENTS

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