

Why should the Odra River mouth area not be regarded as an estuary? A geologist's point of view

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Key words: Odra River mouth, Szczecin Lagoon, estuary, lagoon

Abstract

The authors find no arguments that would justify application of the term “estuary” to the area of the Odra River discharge into the Baltic Sea. The physiography, geology, and hydrology of the Odra river mouth show that the area possesses many more characteristics typical of flow-through coastal lagoons than those of estuaries. Of key importance in this respect is the Szczecin Lagoon, an extensive, shallow water body separated from the open sea by a barrier intersected by three narrow and long straits. The lagoonal nature of the area is demonstrated also by its geological history.

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INTRODUCTION

The various meanings of the term “estuary” in different scientific disciplines are often the cause of numerous misunderstandings. These emerge due to the use of different criteria with which to classify river mouth areas. For physical oceanographers and hydrologists, the basic criterion for regarding an area as an estuary is the mixing of fresh (riverine) and saline (sea) water. Geologists, however, need additional criteria: the origin of the area, its geomorphological characteristics, and the presence of tides, which affect the nature of sedimentation.

The origin of the term *estuary* can be traced to the Latin word *aestus*, the *tide*, and its adjective form *aestuarium*, which means *tidal*. According to one of the more generally used definitions (Pritchard 1967), an estuary is a semi-enclosed, coastal water area connected with the sea, in which the sea water is being diluted by the freshwater draining from the land. With reference to Pritchard’s classification of estuaries, Kjerfve and Magill (1989) contend that a *sensu stricte* estuary denotes only a tidal system of river valleys or coastal plains, drowned during the Holocene, in which the sea water is being diluted by riverine water.

For some time, a number of river mouth areas in non-tidal seas, including the Baltic, have been termed estuaries. When viewed from a geological standpoint, this approach raises doubts. The present authors are not convinced that the area of the Odra River discharge into the Baltic Sea – frequently described as “the Odra River estuary” – should be regarded as such. In the authors’ opinion, the Odra River mouth lacks a few basic characteristics that are typical of estuaries.

HYDRODYNAMIC CHARACTERISTICS OF THE ODRA RIVER MOUTH AREA

Both the etymology and relevant definitions unambiguously associate the term “estuary” with tides. Tide-generated changes in water level in the Baltic Sea are very slight and play no particular role. The Baltic tidal amplitude ranges within 2-5 cm, with the tidal wave height in the Odra river mouth area amounting to ca. 4 cm (Jasińska and Robakiewicz 1993). Changes in the water level in the Odra river mouth area are primarily random, while the effects of wind and atmospheric pressure on water level are decisive (Meyer and Buchholz 1988, Jasińska and Robakiewicz 1993).

The Baltic water is brackish rather than typically marine. The mean annual salinity of the Pomeranian Bay between 1980 and 2003 ranged from 5 to 7.5 PSU in the surface layer and from 6 to 9 PSU near the bottom (Landsberg-Uczciwek 2004). Water exchange between the Odra and the sea is hindered by

the presence of a barrier formed by a spit, the Świna Gate. As a result, the Odra water discharge proceeds via the shallow Szczecin Lagoon and three relatively long and narrow straits (Fig. 1). Water in the straits is partly or fully mixed, and occasionally stratified. Stratification is at its strongest in the Świna strait where the salinity changes from about 1 to 8 PSU. Density stratification is, however, not stable; it is markedly stochastic (Jasińska 1991).

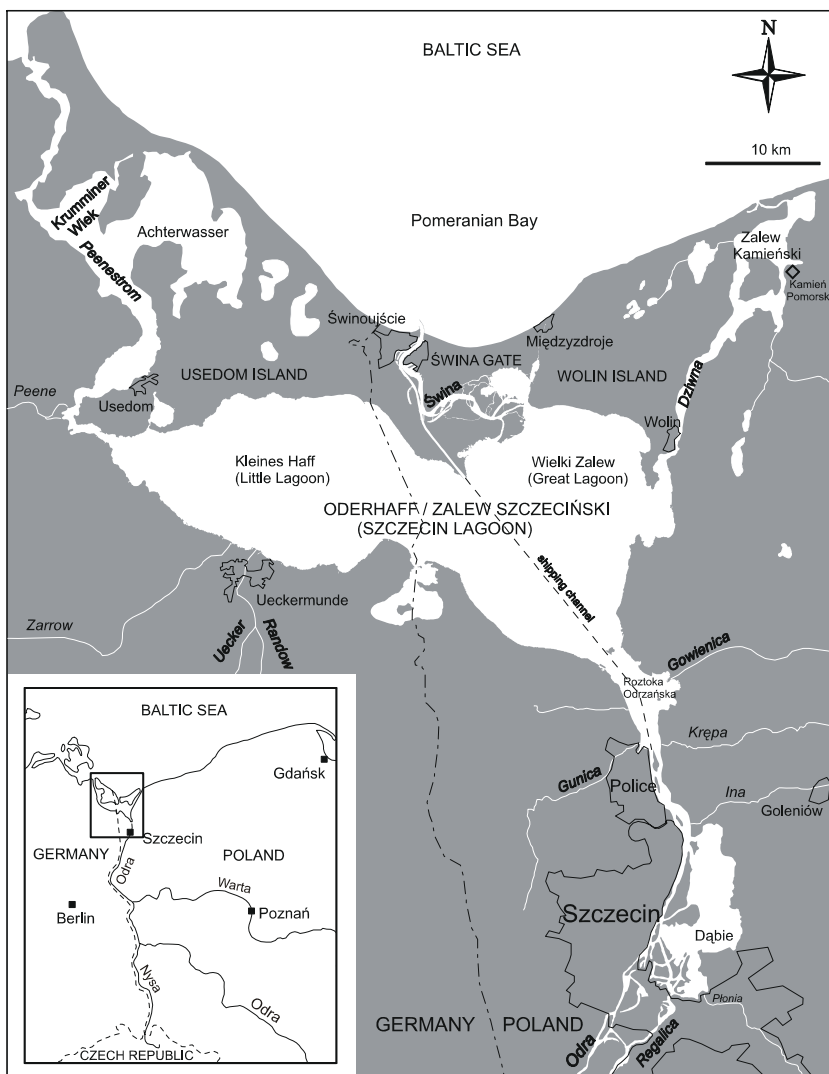


Fig. 1. Location map of the Odra River mouth area.

The average salinity of the Szczecin Lagoon ranges between 0.6 and 0.9 PSU and changes seasonally; the pattern of changes differs between various parts of the Lagoon. The seasonal salinity changes are related to the annual river discharge pattern. Early in the year, after the ice has thawed and the river outflow increased, the Lagoon's water is rapidly freshened. Salinity changes occur, however, with some time lag with respect to the maximum in riverine discharge. The lowest mean salinity (0.2-0.5 PSU) is usually observed in May and June. Later during the summer, the salinity increases gradually to reach its maximum during the November storms, and intensified sea water intrusions are observed at that time. The salinity then increases to an average of 0.8-1.3 PSU. The highest salinity in the Szczecin Lagoon is recorded in the immediate vicinity of the straits, particularly the Świna, as well as in the trough of the shipping channel and in the bottom depression between two parts of the lagoon. Larger sea water intrusions raise the near-bottom water salinity to 6-7 PSU. The Świna strait is the major pathway of the sea water inflows into the Lagoon. The water flowing via the Peene and the Dziwna, which are much longer than the Świna, forms extensive embayments (Achterwasser, Krumminer Wiek, Jezioro Wrzosowskie, Zalew Kamieński) and hardly ever reaches the Szczecin Lagoon (Majewski 1980).

As shown by the data reported by Wypych (1970), sea water may, in some instances, intrude into the shipping channel along its entire length. Stratification in the channel is, however, not stable. As demonstrated by Jasińska (1991), the saline water may be driven by currents and wind from the shipping channel in a direction perpendicular to it. Consequently, deeper areas of the Szczecin Lagoon may contain local lenses of brackish water. However, the water column structure in the shipping channel and other bottom depressions in the Lagoon changes constantly and alternates between being stratified and homogenous. In shallow areas of the Lagoon, the water column is usually thoroughly mixed down to the bottom (Majewski 1980).

THE SZCZECIN LAGOON AS A LAGOONAL WATER BODY

The Szczecin Lagoon is a shallow area in which the natural depths do not exceed 8.5 m, with ca. 96% of the bottom lying at depths shallower than 6 m. Shallows (<2 m depth) cover about 25% of the bottom surface. The major parts of the two main sections of the Lagoon are formed by a relatively flat and poorly differentiated bottom at depths of 4-6 m (Osadczuk 2004).

The Szczecin Lagoon bottom morphology fully justifies its division into two sections, called the Little Lagoon (Mały Zalew in Polish, or Kleines Haff in German) and the Great Lagoon (Wielki Zalew in Polish or Grosses Haff in German). Although the connection between the two is as wide as 7.5 km, the

sandbanks reach far offshore (Ławica Osiecka and Repziner Haken) and constrict the connection so that it forms a 1.5 km-wide passage with depths exceeding 2 m. It is around the passage that the deepest natural regions of the Lagoon occur.

Most of the Little Lagoon bottom is relatively poorly differentiated, 4-5.5 m deep. Distinct features of the bottom morphology are the extensive shallows: the Borkenhaken in the northwestern parts and the Kamighaken, Hart-Schaar, and Repziner Haken in the southern part. Most of the Great Lagoon also has a relatively flat and level bottom, which is slightly deeper (4.5-6.5 m). The most diverse bottom topography is found in the northern part of the Great Lagoon where extensive sand banks (<2 m depth), stretching for a few km into the lagoon (Wyskok Krzecki, Mielizna Wolińska), are dissected by a trough-like depression 4-6.5 m deep (Fig. 2).

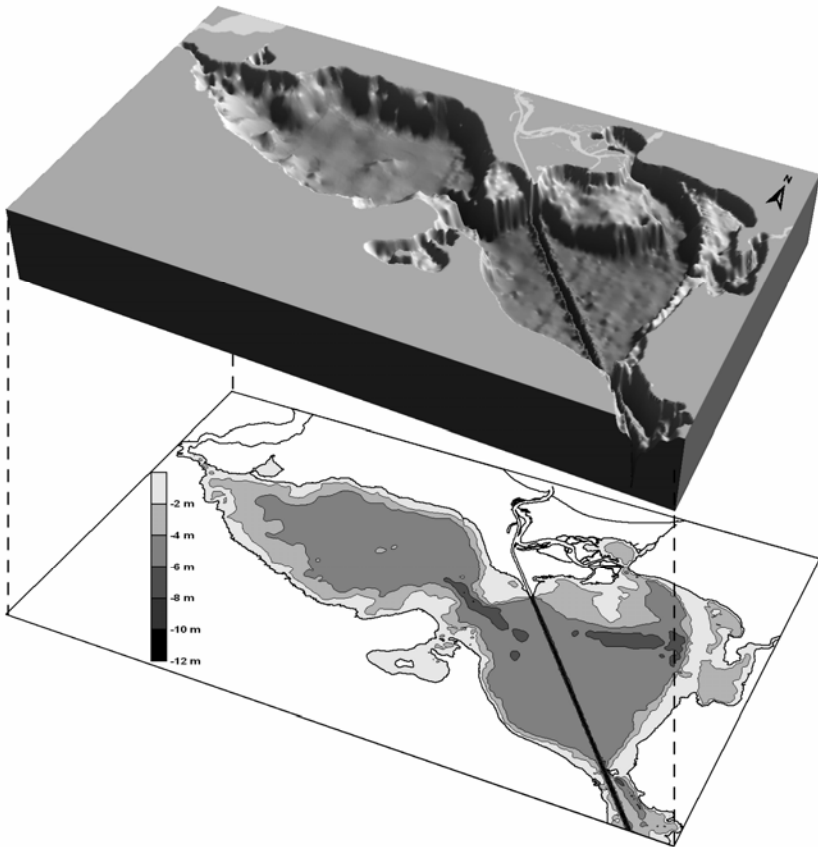


Fig. 2. Bottom relief of the Szczecin Lagoon.

The natural bottom of the Szczecin Lagoon has been altered by man. In the western part, i.e., in the Great Lagoon, the bottom is intersected by a shipping channel, which is deep enough for large ships to pass through. The channel construction required that a 10-11 m deep and 100 m wide trough be dug. The channel was dug in 1875-1880, whereupon, together with the channel (*Kaiserfahrt*) cut across Usedom Island (Osiecimski 1966), the shipping route to Szczecin that originally led via the Świna was shortened. Doubtless, the two channels altered the Lagoon circulation system.

The Szczecin Lagoon is separated from the sea by a spit barrier, hence mixing of sea and fresh water is limited. Exchange of riverine and sea water in the Lagoon proceeds via three long and narrow straits. Because of the barrier and the strait-restricted connection with the sea, water circulation in the Lagoon is more lagoonal than estuarine. During storm surges, the straits function like tidal inlets of classic tidal lagoons. On the other hand, the reverse delta of the Świna strait, formed in the hinterground of the spit, may be regarded as a specific variety of a flood tidal delta.

One characteristic of most lagoons is that their circulation is predominantly wind-driven. This is the case in the Szczecin Lagoon as well: the circulation, generated initially by riverine discharge and episodic sea water intrusions, is essentially modified by wind action. As shown by Robakiewicz (1993), the Lagoon has characteristic circulation cells that are dependent on wind speed and direction.

Considering Szczecin Lagoon's physiography and hydrology, the area should be classified as a restricted lagoon, according to the lagoon classification system proposed by Kjerfve and Magill (1989). In their opinion, such lagoons are characterised by the presence of a number of inlets, the lack of density stratification (the water column is mixed throughout), and a strong wind effect on circulation. On the other hand, using the classification of Nichols and Allen (1981), Szczecin Lagoon is most similar to the partially closed lagoon, characterised by an elongated barrier intersected by narrow inlets, a reduced ebb tidal delta, restricted water exchange with the sea, and sedimentation of sand in the part closest to the sea and deposition of silt in the remaining part.

The contemporary bottom of the Szczecin Lagoon contains both muddy and sandy sediments. This division is, however, simplified, as it is based on the contribution of major grain size fractions only, no attention being paid to the chemical variability of sediment components and their origin, important when the sediment is highly enriched with organic matter. The organic matter content (expressed as per cent loss on ignition) of the Szczecin Lagoon sediments ranges from 13.8 to 35.2%. The decomposing organic matter, mainly of planktonic origin, renders the mud gelatinous in texture and dark, almost black, in colour (Osadczuk 2004).

The Szczecin Lagoon sediments are not amenable to any straightforward classification, because they have been deposited in a specific sedimentation area formed by the discharge of a major river to the sea. The sedimentation here is very specific, and quite different from marine, fluvial, and limnic sedimentation processes. However, the macroscopic appearance of Lagoon's organic-mineral muds as well as their lithological and geochemical properties corresponds closely to lacustrine gyttjas. Although the original meaning of "gyttja" is associated with the limnic environment, the term can be applied to the Szczecin Lagoon sediments as well. This is particularly appropriate when the definition of gyttja as proposed by Hansen (1959) is applied, whereby gyttja is a mixture of remains of all organisms, mineral components, and inorganic compounds precipitated from the water by biochemical processes. The original definition of gyttja, introduced in the geological literature by von Post (1862), according to which gyttja is a coprogenic formation consisting of a mixture of zoo- and phytoplankton remains, mollusc shells, remains of insects and crustaceans, plant pollen and spores, and grains of quartz and micas, is also applicable to the Szczecin Lagoon sediments.

Physiographic characteristics of the Szczecin Lagoon, its morphology and hydrodynamics, as well as the sedimentation regime clearly demonstrate that the area possesses many more features typical of coastal lagoons than of estuaries (Phleger 1969; Musielak 1983; Osadczuk 1999a,b; 2004). The lagoonal nature of the area is a net result of the presence of a barrier separating the lagoon from the open sea (the connection with the latter being provided by three narrow and long straits), the emergence of a reverse delta in the hinterground of the barrier, shallow depths of the sedimentary basin (another typically lagoonal characteristics), the absence of density stratification, the predominantly wind-driven circulation, and sedimentation of organic-rich muddy sediment. The lagoonal nature of the area is indicated also by its geological history.

GEOLOGICAL HISTORY OF THE ODRA RIVER MOUTH AREA

About 15 thousand years ago, the majority of the Szczecin Lowland was still covered by an icesheet (Kozarski 1995). The pre-Odra flowed westward along the Toruń-Eberswalde ice-marginal valley, and farther away, together with the Elbe and Rhine, discharged into the Atlantic. However, deglaciation was fairly rapid. When the icesheet retreated to the area of the present-day Szczecin Lagoon, the pre-Odra changed its course. Most probably, the river broke through the moraine belts near Cedynia via the former subglacial trough, and turned to the north-east (Borówka and Musielak 1997). An extensive ice-marginal lake formed in front of the icesheet margin; the remains of the lake can

be traced today as the Goleniowska and Wkrzańska Plains, with several distinct terrace horizons. These, according to Karczewski (1968), developed from about 14.5 to 13 thousand years BP. Data reported by Kramarska (1998) show that, from 14 to 13 thousand years BP, the icesheet margin must have been located only a few tens of km north of the present coastline. This is evidenced by limnic and swampy sediments found in the bottom of the Baltic 26 km north of Dziwnów. At that time, the pre-Odra was most probably flowing towards the northwest along the Peene valley, into the marginal lakes in today's Pomeranian Bay between Rügen Island and the coast around the Rega River mouth. The pre-Odra discharged into the Baltic near the eastern part of Rügen Island (Kolp 1986). Most probably, as recently as about 8 thousand years ago, the entire bottom of Pomeranian Bay was still part of the landmass (Fig. 3).

At the end of the Pleistocene and in the early Holocene, the area of today's Szczecin Lagoon was the development site of the Odra valley. Initially, the Odra was most likely a braided river, with its waters flowing along numerous channels. This is indicated by analyses of sediment cores and data from high-resolution seismic surveys, performed on the Szczecin Lagoon bottom (Borówka et al. 2002, 2003, 2005; Osadczuk and Borówka 2001). In the early Holocene, the braided river changed to a meandering one, and eroded down to 4 m into terrace horizon VI. The subfossil sediments of the present Szczecin Lagoon were found to contain limnic and swampy components, most probably representative of the palaeomeanders. During the middle Holocene, the Odra became an anastomosing river flowing among swamps and bogs, with the banks of its many channels stabilised by vegetation – similar to today's Lower Odra south of Szczecin (Borówka and Osadczuk 2003).

During the late Atlantic period, while the Littorina transgression was in progress [about 6 thousand carbon (^{14}C) years BP], the Odra River valley was flooded by sea water. Thus, a marine embayment, covering almost the entire area of today's Szczecin Lagoon, was formed. The embayment extended far up the lower Odra valley to the present day city of Szczecin. It cannot be ruled out that the transgression was a catastrophic event, as pointed out by Rosa (1963). Sedimentation at that time was definitely marine, as evidenced by accumulation of sandy and sandy-muddy deposits containing the marine bivalve *Cardium glaucum*, whose shell size is indicative of salinity higher than that of today's Pomeranian Bay (Borówka et al. 2003, Woźniński et al. 2003). However, fairly soon the processes related to erosion of steep moraine shores of the Wolin and Usedom and to bedload transport and accumulation began to form two spits which gradually isolated the embayment. The highly dynamic process of the spit's accretion is evidenced by the age of *Cardium* shells found in the Usedom spit beach facies [3760±140 carbon (^{14}C) years BP] (Osadczuk K. 2004). Thus,

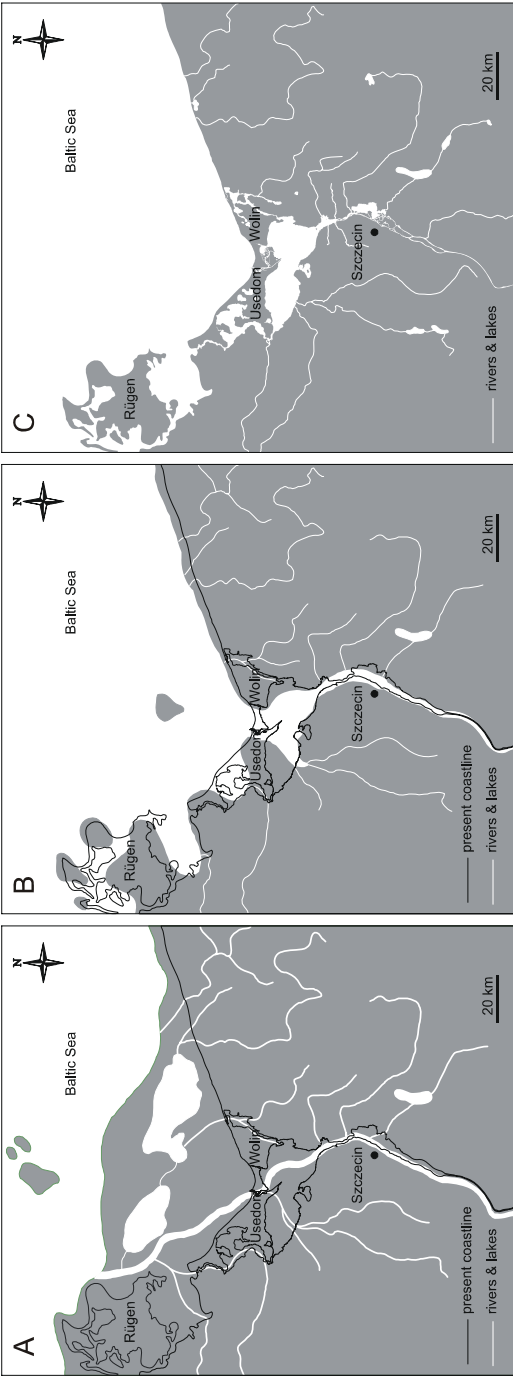


Fig. 3. Scheme of the Odra River mouth evolution. A - before Littorina transgression, B - maximum Littorina transgression, C - present day.

it may be asserted that the basic part of the spit was formed over the course of ca. 1000 years.

As a result of the barrier gradually isolating the embayment, the latter began assuming characteristics of a coastal lagoon, today called the Szczecin Lagoon. As shown by the most recent research (Borówka et al. 2001, 2002; Latałowa and Borówka 2003), the area emerged about 3 thousand carbon (^{14}C) years BP. Separation of the Szczecin Lagoon from direct influences of the sea resulted in a change in the sedimentation pattern from marine to lagoonal. The organic matter content of the accumulating sediments increased, and marine malacofauna and diatom flora were superseded by brackish and freshwater species (Woźniński et al. 2003, Witkowski et al. 2004).

CONCLUSIONS

There is no unimpeded sea-river water exchange in the Odra River mouth; such exchange, typical of estuaries, is restricted by the Świna Gate (spit barrier). Exchange of water between the Odra and the Baltic Sea proceeds via the shallow Szczecin Lagoon and three relatively narrow and long straits.

The absence of tides, low salinity, and restricted water exchange in the Odra river mouth virtually rule out density stratification, which is typical of estuaries. The lack of density stratification is also a consequence of the shallowness of the Szczecin Lagoon, an area of a key importance in the Odra River discharge system.

During the Littorina transgression, the mouth area of the pre-Odra, which discharged into the Baltic, could have been estuarine in nature. Later on, however, as a result of the gradual formation of the barrier separating the mouth area from the open sea, there emerged a water body displaying characteristics of a coastal lagoon. Those characteristics have been preserved until today.

In view of all the arguments listed above, it is surprising that one still hears and reads about the “Odra estuary”. Most probably, the term has persisted because hydrographers and oceanographers too often use a simplified definition of an estuary. Such a definition assumes an estuary to be synonymous with an area of river discharge into the sea, in which fresh and saline waters are mixed (e.g., Majewski 1972, Jasińska 1991). However, mixing of fresh and saline waters occurs in all river mouth areas, yet not all of them can be regarded as estuaries. Some authors, e.g., Ketchum (1951), attempted to extend the term “estuary” to all areas in which sea water is diluted by fresh water. With such an approach, the entire Baltic Sea could well be regarded as an estuary, because it is characterised by mixing processes between freshwater discharges of numerous rivers and the saline water of the North Sea. The approach of Ketchum (1951) could be stretched to the extent that, in addition to all the river

discharge areas into the sea being treated as estuaries, estuaries could also denote regions where glaciers descend and calve, thus releasing large amounts of freshwater into the sea.

The present authors find no convincing arguments that would justify the application of the term “estuary” to the area of the Odra River discharge into the Baltic Sea.

ACKNOWLEDGEMENTS

The information contained in this paper was presented during a scientific conference “*Water exchange in estuarine waters in the Southern Baltic - hydrology and ecology*” organized by the Institute of Oceanography, University of Gdansk on April 21, 2006. The conference was dedicated to Professor **Jerzy Cyberski** in celebration of his scientific career which has spanned forty-five years.

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