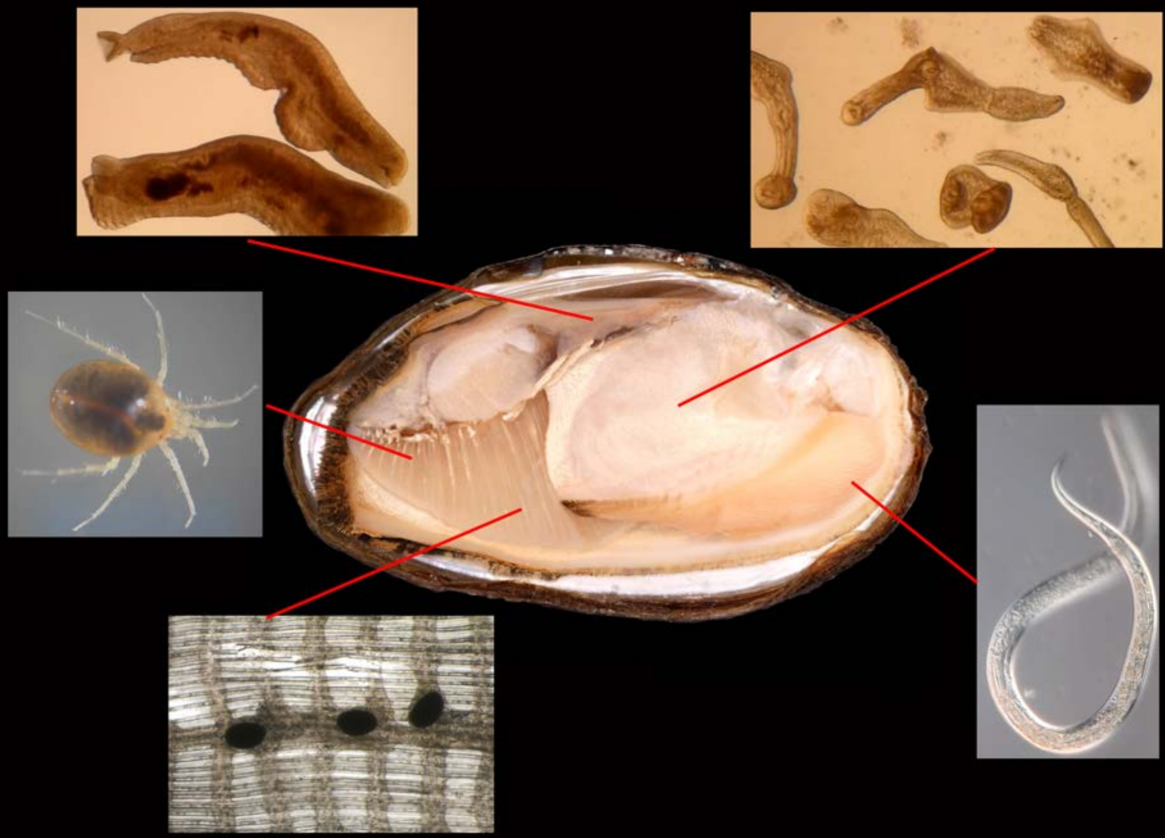
Are Parasites and Diseases Contributing to the Decline of Freshwater Mussels (Bivalvia, Unionida)?



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Introduction

Reviews in Fisheries Science, 17(4):425–467, 2009

ISSN: 1064-1262 print
DOI: 10.1080/10641260902879000

Taylor & Francis

Infectious Diseases of Freshwater Mussels and Other Freshwater Bivalve Mollusks

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Numerous species of freshwater mussels (order Unionoida) are imperiled in the wild, and unionoids and other freshwater bivalves are important components of many ecosystems. Freshwater mussels also are propagated in captivity for production of pearls and enhancement of wild populations. However, infectious diseases of these mollusks have received relatively little attention. Unionidae is the most diverse family of freshwater bivalves, and most of the information available for this review is about species in this family. Eukaryotic organisms, especially trematodes, mites, and Conchophthirus *spp. (Ciliata) are common inhabitants of unionids, and some have the potential to decrease the fitness of the host unionid. Several species of potentially pathogenic bacteria have been isolated from freshwater bivalves, but their role in diseases of bivalves has not been established. Evidence for viral diseases has been found in only one species of freshwater bivalve, a Chinese pearl mussel,* Hyriopsis cumingii. *The potential for some pathogens to cause greater harm to freshwater bivalves during periods of suboptimal conditions has not been evaluated adequately. Additional research is also needed to determine whether other types of pathogens are present in freshwater bivalves.*

Keywords unionoida, viruses, bacteria, trematodes, mites, ciliates

INTRODUCTION

Freshwater Bivalves

The freshwater mussels (class Bivalvia, order Unionoida) include six families: Unionidae, Margaritiferidae, Hyriidae, Mycetopodidae, Iridinidae, and Etheriidae (Graf and Cummings, 2007). This order has a worldwide distribution, but about a third of all species are found only in North America. The characteristics that set the order Unionoida apart from other bivalves are restriction to freshwater, parental care of offspring until they are released as larvae, and parasitic larvae (Graf and Cummings, 2006). Adults are relatively sedentary, but the larvae (glochidia) are parasitic on fish or amphibians (Howard and Anson, 1923; Watters, 1997), which provides a mechanism for dispersal. Additional species of freshwater bivalves are in the families Corbiculidae, Sphaeriidae, and Dreissenidae (all in the order Veneroida). These include the Asian clam *Corbicula fluminea* and the zebra mussel *Dreissena polymorpha*, which have received increased attention because of invasion of habitats outside of their original range. Several other bivalve families include a low number of species found in freshwater (Bogan, 2008), but these are not included in our review.

This review includes information about most freshwater bivalves (Table 1), but the emphasis is on the freshwater mussel family Unionidae because information available related to diseases or potential pathogens of freshwater bivalves is primarily about species in this family. Parasites of zebra mussels were reviewed by Molloy et al. (1997), and some of this information is included in our review. Names of bivalves in our review follow Turgeon et al. (1998).

The conservation status and environmental threats to freshwater mussels have been well documented (Bogan, 1993; Williams et al., 1993; Neves et al., 1997; Bogan, 1998; Neves, 1999; Garner et al., 2004a, 2004b; Lydeard et al., 2004; Strayer et al., 2004; Williams et al., 2008). There are about 300 recent species of freshwater mussels in North America, but many are extinct or imperiled. Among freshwater mussels in the U.S., 37

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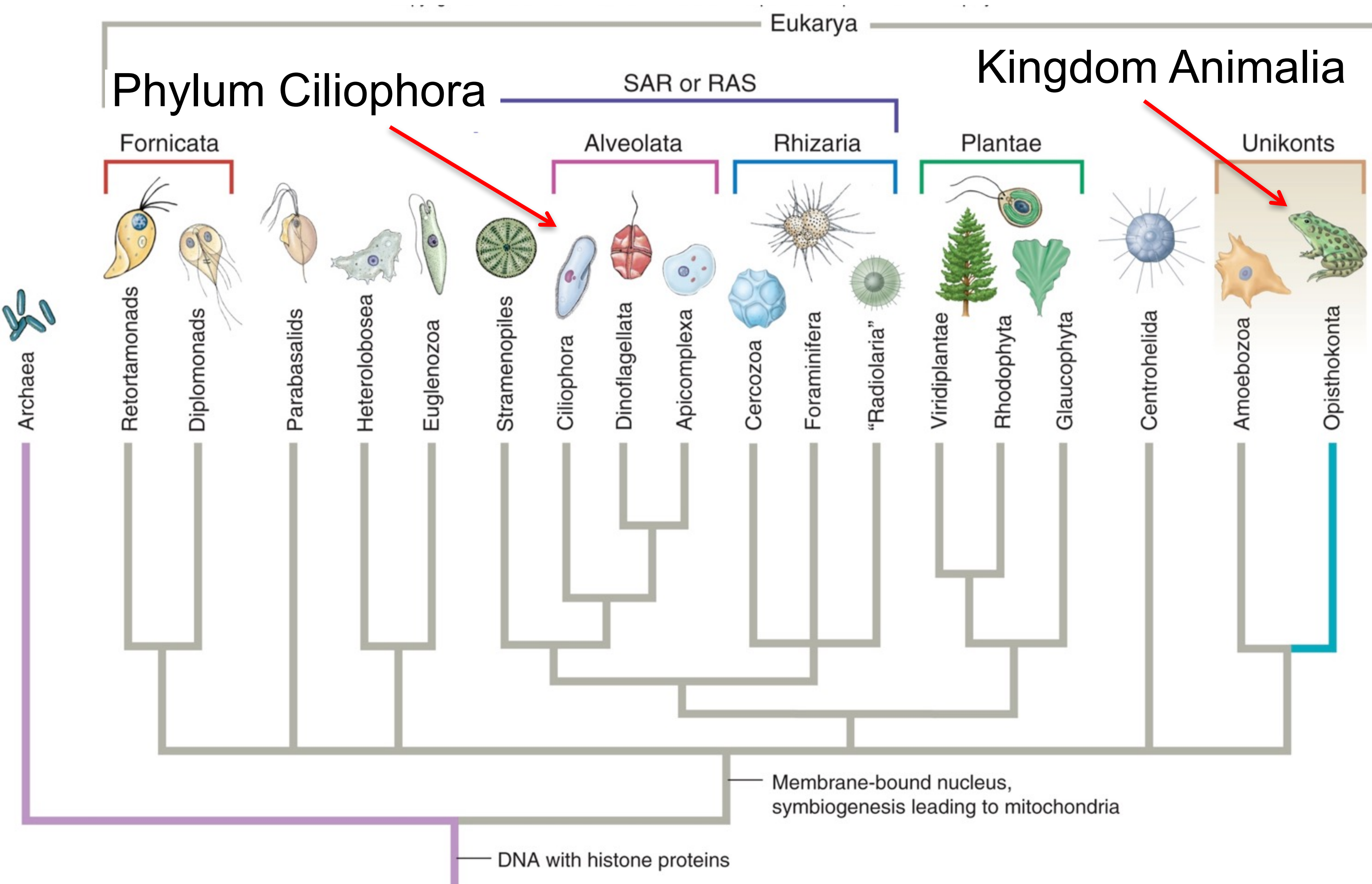
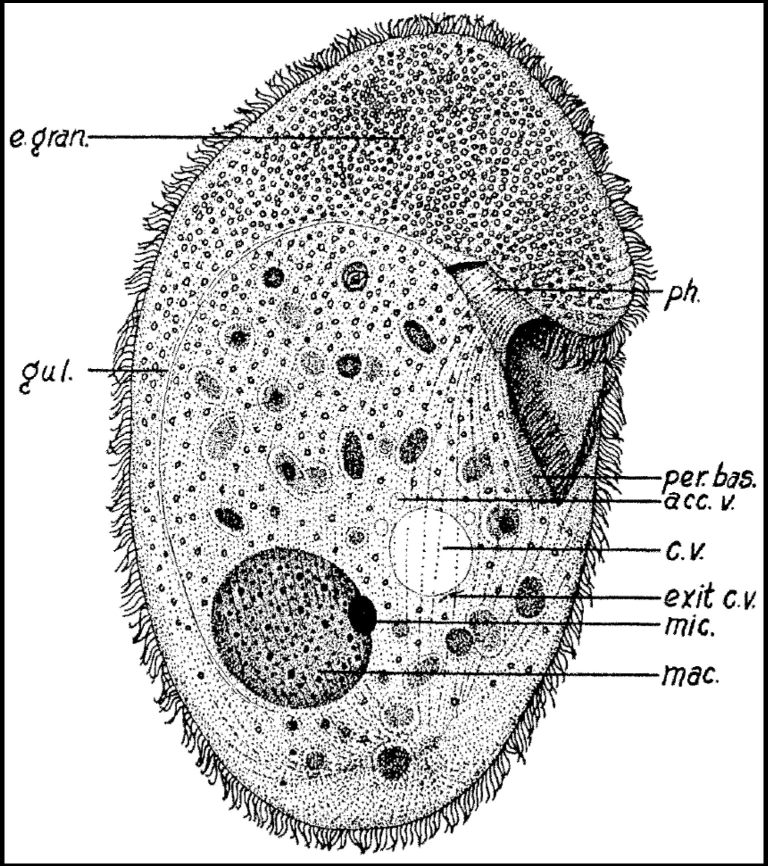
Evolutionary Relationships of Eukaryotes



From: Hickman et al. (2014)

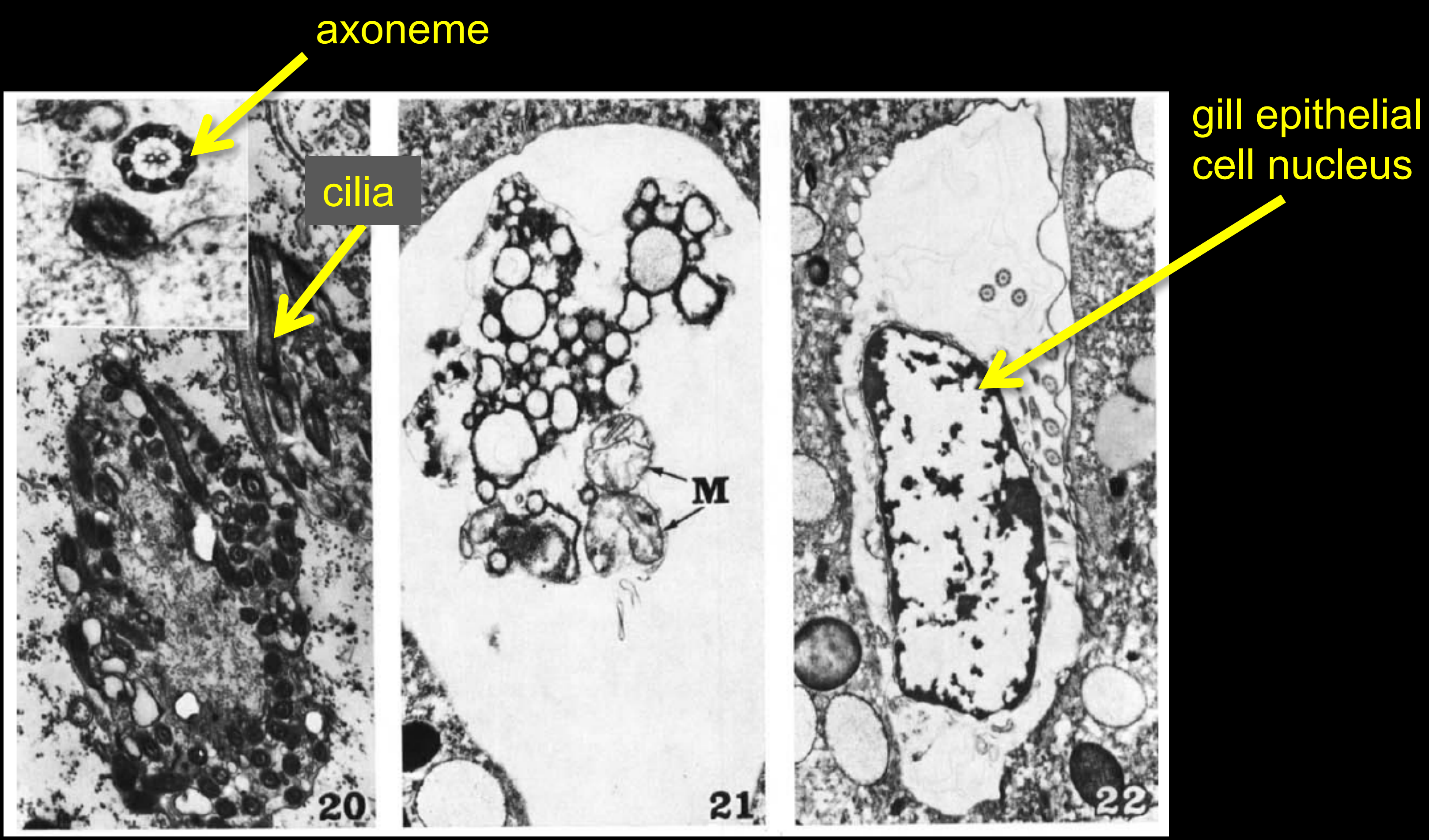
Phylum Ciliophora ("Ciliates")

- *Conchophthirius* or *Conchophthirus* spp. most frequently reported
- Reported from the mantle cavity
- Cosmopolitan distribution
- Some species are host specific while others are less so
- May attach to tissue
- Food vacuoles may contain bacteria, algae, host cells
- No evidence these ciliates injure their host (commensalism?)
- Asexual reproduction by binary fission, sexual reproduction by conjugation (direct life cycle?)



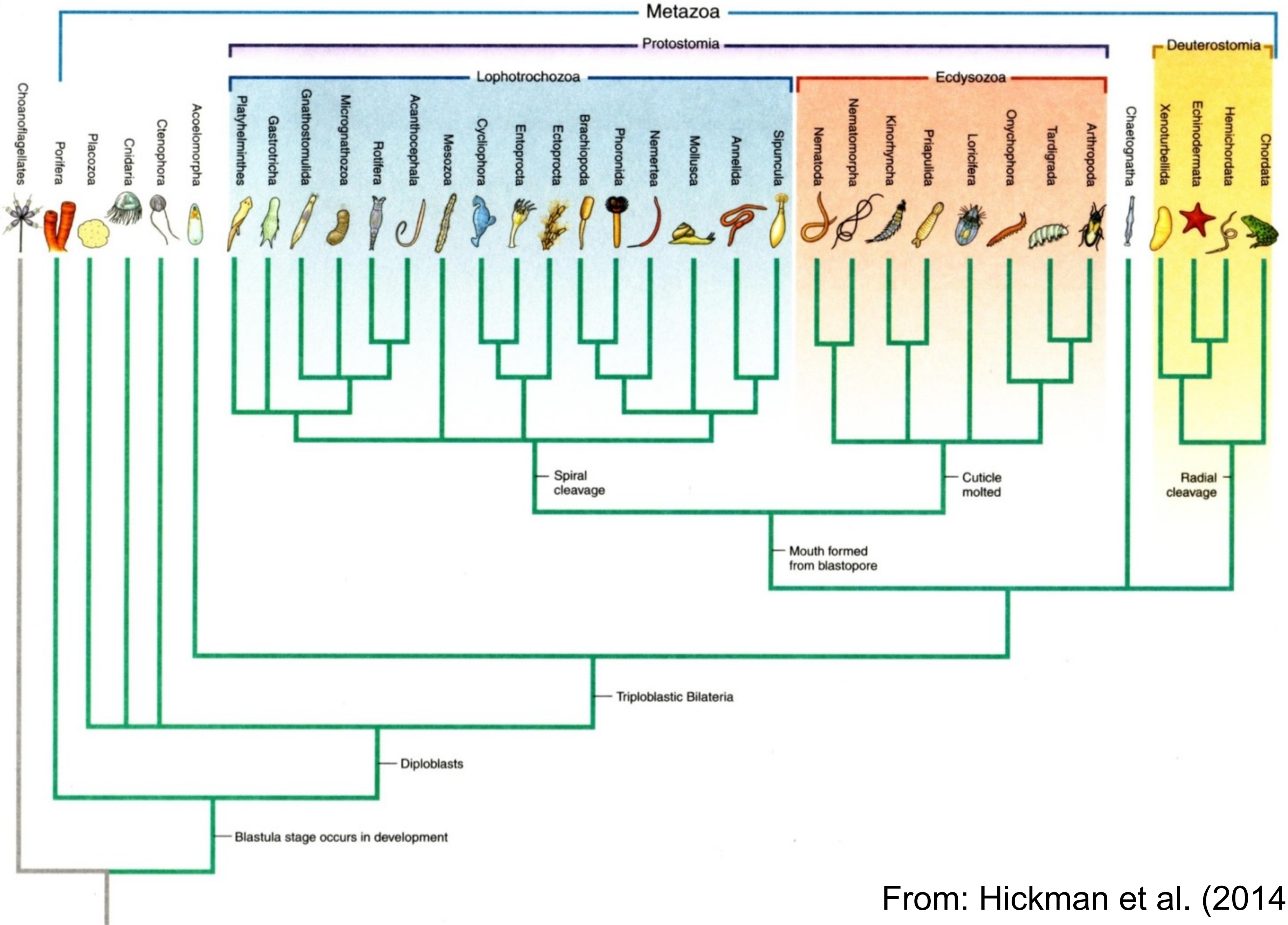
Conchopthirus anodontae at 600 X (From: Kidder, 1934)

Possible remnants of gill epithelial cells in food vacuoles of *Conchopthirus curtus*



From: Antipa and Small (1971a)

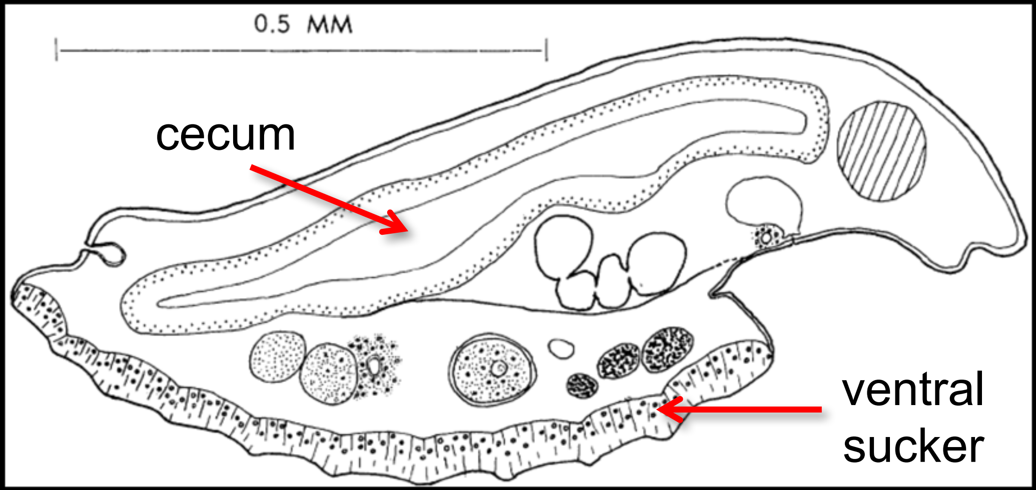
Evolutionary Relationships of Animals

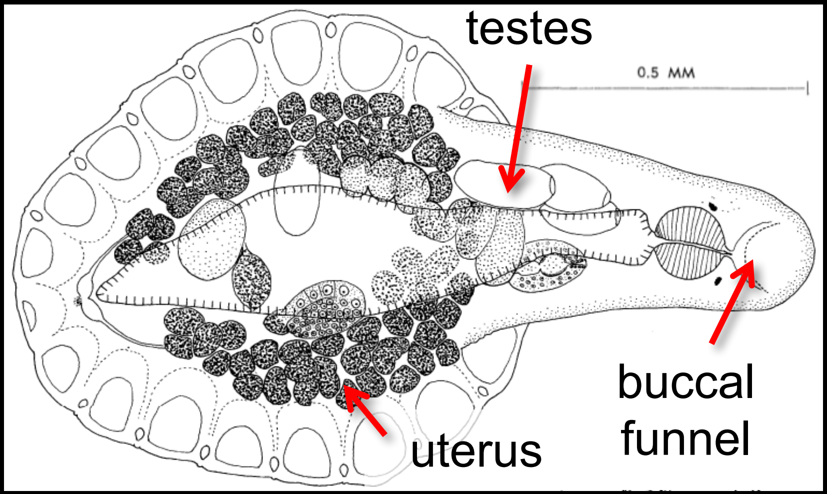


From: Hickman et al. (2014)

Phylum Platyhelminthes: Class Trematoda: Subclass Aspidogastrea (“Aspidogastreans”)

- Reported from mollusks, fishes, turtles
- Basal trematodes or “proto-trematodes”
- Poorly adapted for parasitism
- Complex sensory organs
- Simpler life cycles than digeneans
- Can complete ontogenetic development in a mollusk





Cotylaspis insignis From: Hendrix and Short (1965)

Aspidogastreans reported from unionids

Aspidogaster conchicola

- Infects pericardial cavity, nephridium
- Reported from many unionid spp.
- Widely distributed

Cotylaspis insignis

- Infects gills, suprabranchial cavity
- Reported from many unionid spp. and turtles. Turtles may not be a required host.

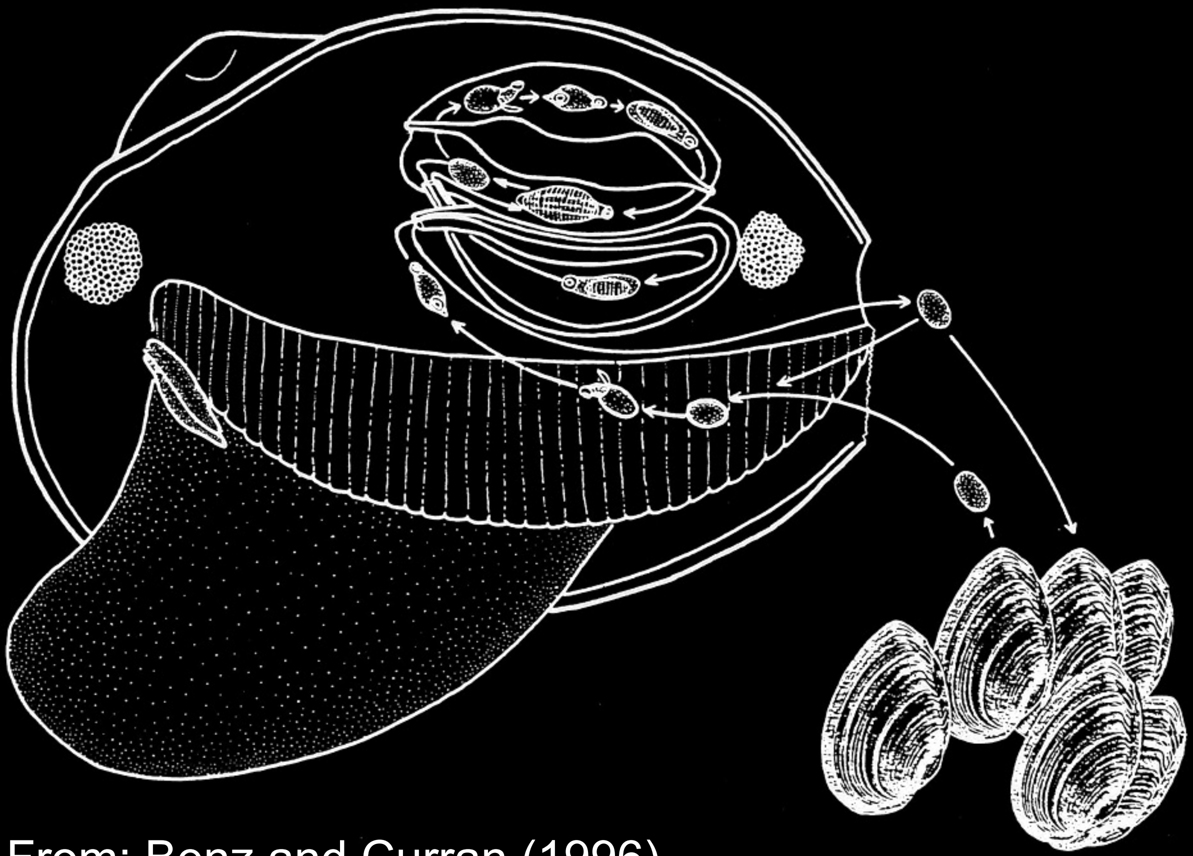
Cotylogaster occidentalis

- Infects intestine
- Reported from unionids, snails, freshwater drum; less common than *A. conchicola* or *C. insignis*

Lophotaspis interior

- Only juveniles reported from unionids
- Adults reported from alligator snapping turtles (indirect life cycle?)
- Least common aspidogastrid

Life cycle of *Aspidogaster conchicola*

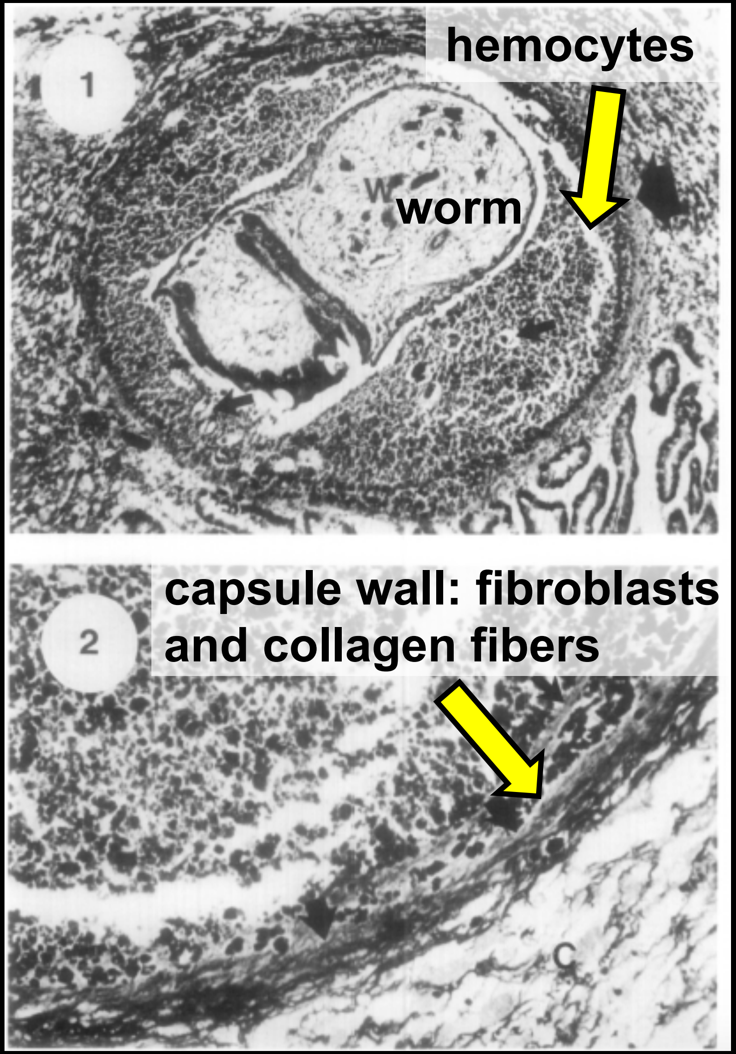


From: Benz and Curran (1996)

- Direct life cycle
- Life cycle stages include: Operculated egg, juvenile, adult
- Adults mature in pericardial cavity or nephridium
- Eggs may be released into mantle cavity
- Mussels may acquire eggs while filtering water
- Can complete life cycle without leaving mussel

Pathogenicity of aspidogastreans

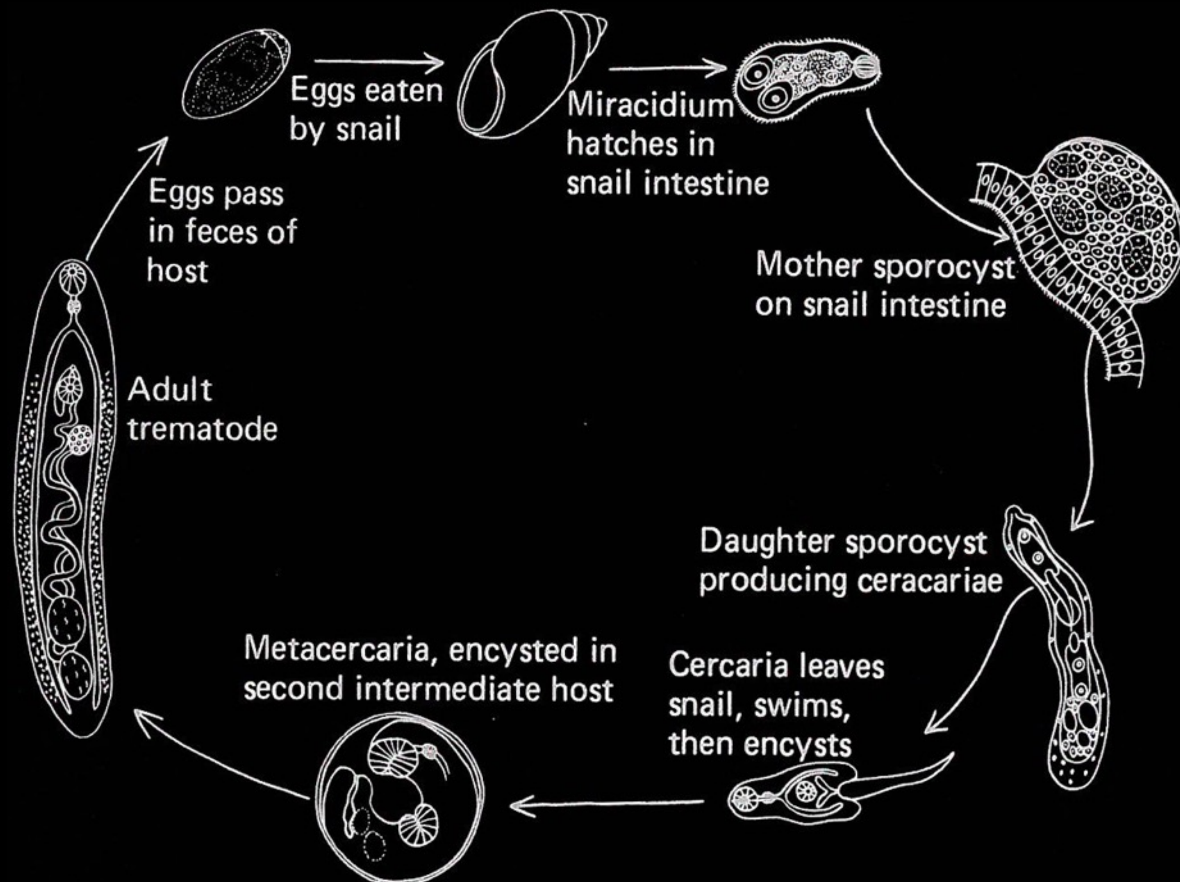
- Most pathology studies focus on *Aspidogaster conchicola* (Pauley and Becker, 1968; Bakker and Davids, 1973; Huehner and Etges, 1981; Huehner et al., 1989)
- Some studies have not observed lesions
- May injure mussels through attachment and feeding
- Localized cellular changes such as necrosis, metaplasia
- Mussels may encapsulate (encapsulation response or granuloma) aspidogasters if they invade the visceral mass



Figs. 1–2 From: Huehner and Etges (1981) showing encapsulation of *Aspidogaster conchicola*.

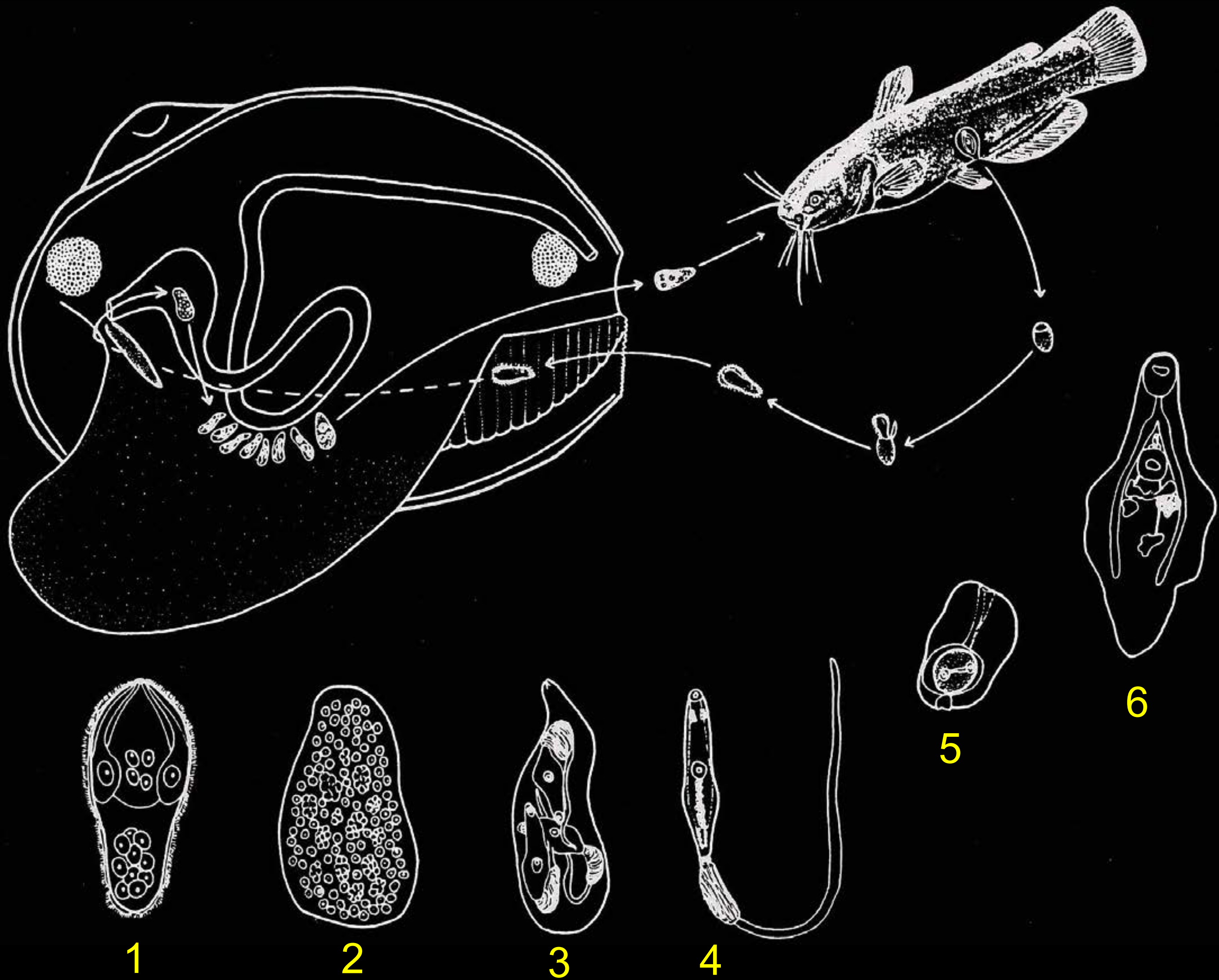
Phylum Platyhelminthes: Class Trematoda: Subclass Digenea ("Digenetic trematodes")

- Indirect life cycle
- Mollusks can be first and or second intermediate host
- Vertebrates are definitive hosts
- Larval stages occur in mollusks: Sporocyst, redia, cercaria, metacercaria
- Cosmopolitan distribution



Generalized life cycle of a digenean. From: Schell 1970.

Life cycle of a trematode



Life cycle stages
1. Miracidium
2. Mother sporocyst
3. Daughter sporocyst
4. Cercaria
5. Metacercaria
6. Adult

Generalized life cycle of Gorgoderinae. From: Benz and Curran 1996.

Digenean families reported from mussels

Bucephalidae

- Unionidae can be 1st intermediate host
- Sporocyst, redia, cercaria

Gorgoderidae

- Unionidae can be 1st intermediate host
- Mother and daughter sporocyst, cercaria

Allocreadiidae

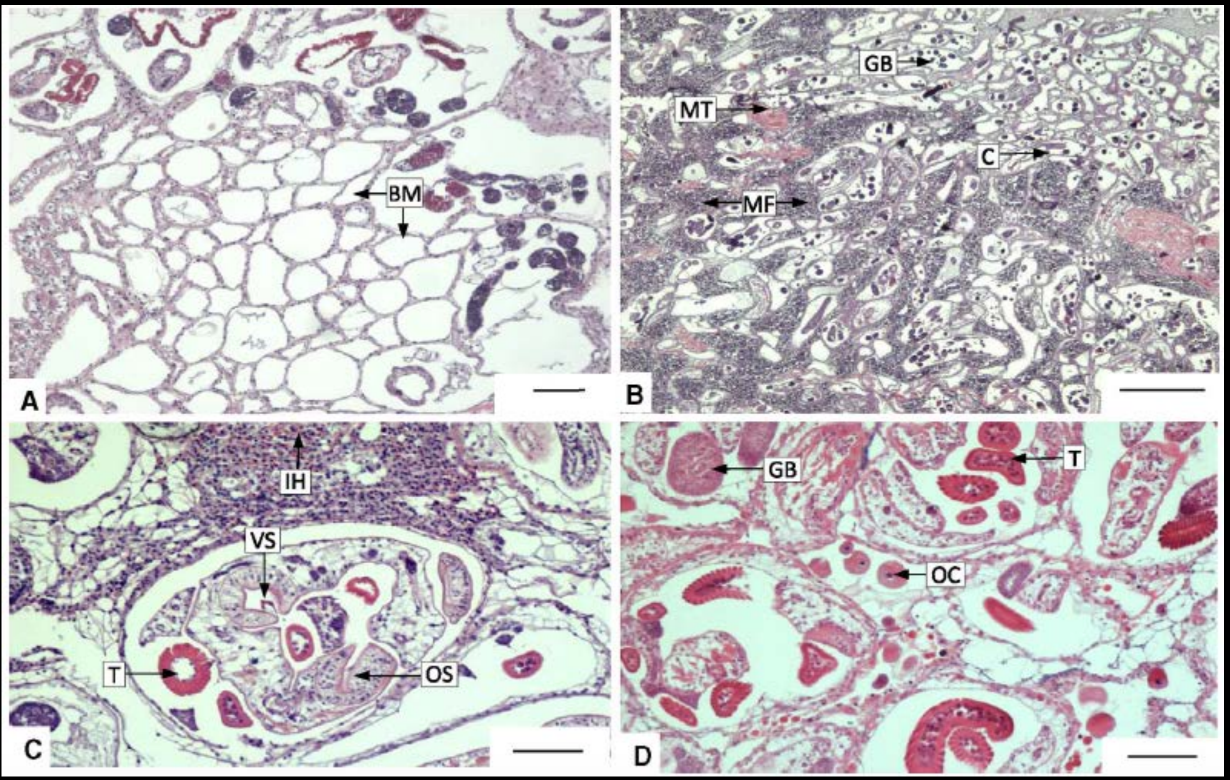
- Unionidae can be 1st or 2nd intermediate host
- Sporocyst, redia, cercaria, metacercaria

Apocreadiidae

- Unionidae can be 1st or 2intermediate host
- Sporocyst, cercaria, metacercaria

Sources: Cribb et al. (2001); Grizzle and Brunner (2009), and literature therein

Pathogenicity of sporocysts and rediae



Damage to the gonad of *Anodonta anatina* caused by *Rhipidocotyle campanula* (A–B) and *Phyllodistomum* sp. (C–D). From: Müller et al. 2015

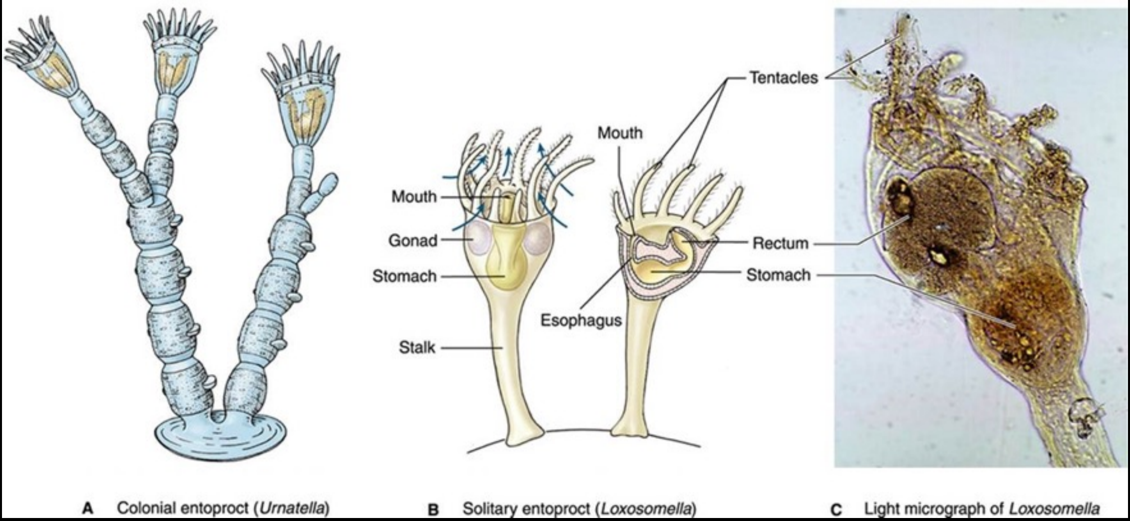
- Sporocyst and redia stages can damage the digestive gland and or gonad and potentially castrate the host
- Sporocysts, rediae, cercariae, metacercariae may sometimes induce pearl formation
- Pathology described by: (Kelly, 1899; Fischthal, 1951; Kniskern et al. 1952; Jokela et al. 1993; Chittick et al. 2001; Müller et al. 2015)

- Sometimes hemocytes surround or infiltrate digenean infections and sometimes no host response is apparent

Bryozoans: Phyla Ectoprocta and Entoprocta

- "Moss animals"
- Solitary or colonial
- Reported from the exterior shell of unionids
- Reported from exterior shell of "baldies" from Tennessee River (Fuller 1974)
- Bryozoans generally feed on particulate matter using their lophophore (ciliated tentacles)
- Relationship with mussels is unclear, probably commensalistic

Pectinatella magnifica attached to a submerged branch

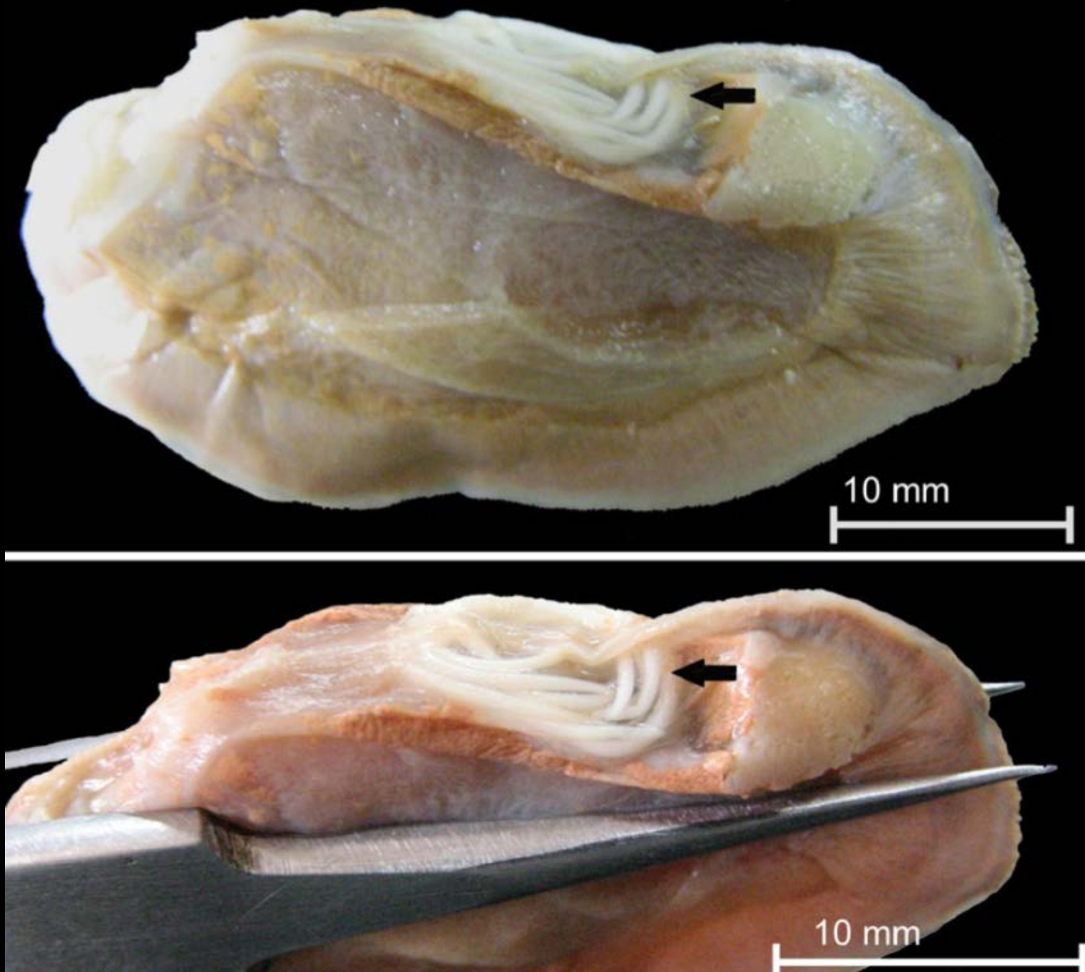


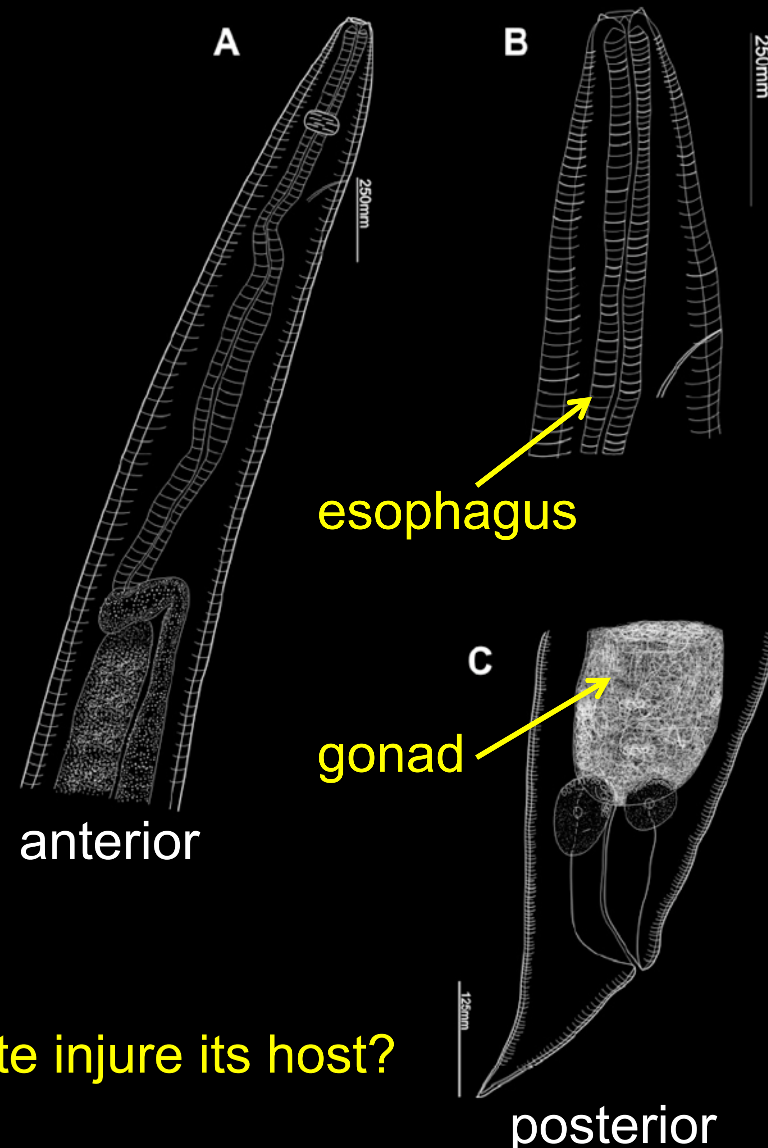
Representative entoprocts. From: Hickman et al. (2014)

Phylum Nematoda

- “Roundworms” mostly reported from marine bivalves
- Marine bivalves reported as intermediate hosts
- Clark and Wilson (1912), Wilson and Clark (1912), Coker et al. (1921) reported *Ascaris* sp. or *Ascaris*-like worms from the digestive tract of unspecified unionids
- No species descriptions from freshwater mussels
- Did worms occur in the lumen of the gut or if they were embedded in tissue?
- Lopes et al. (2011) reported 3rd stage larvae of *Hysterothylacium* sp. (Anisakidae) from the pericardial cavity of *Rhipidodonta suavidicus* (Hyriidae)

Hysterothylacium larvae (Anisakidae) in pericardial cavity of *Diplodon suavidicus* (Hyriidae)





From: Lopes et al. (2011)

Does this parasite injure its host?

Phylum Annelida: Class Oligochaeta

- *Chaetogaster limnaei* may occur inside the mantle cavity, gills or kidney of mollusks
- Reported from mantle cavity and kidney of unionids

Some records portray *C. limnaei* as a parasite or predator of mollusks:

- Feeds on juvenile mussels (Coker et al. 1921)
- Kidney cells and concretions of *Lymnaea pereger* observed in the gut (Gruffydd, 1965)
- Reported to feed on subepithelial cells of *Physa acuta* (Gamble and Fried, 1976)
- Occurred in mantle cavity of *Corbicula fluminea* that appeared emaciated and diseased (Sickel and Lyles, 1981)
- Some invaded mantle, gill, visceral mass where they may feed on tissue of *Dreissena polymorpha* (Conn et al. 1996)

Chaetogaster limnaei limnaei from *Sinanodonta woodiana*. From: Cichy et al. (2016)

Phylum Annelida: Class Hirudinida

- Unspecified leeches observed in unspecified North American mussels by Kelly (1899), Clark and Wilson (1912), Coker et al. (1921)

- Leeches attach to mantle of some mussels, especially *Anodonta* spp. may feed on mucus and may feed on mussels as a scavenger (Coker et al. 1921)

Records of *Placobdella* from unionids

- *Placobdella motifera* may occur in the mantle cavities unspecified mussels (Moore 1912)

- *P. motifera* and *P. parasitica* may occur in the mantle cavities of unspecified mussels (Fuller, 1974)

- *P. motifera* reported from 8 unionid spp. from Louisiana by Curry and Vidrine (1976)

- *P. motifera* reported from *Anodonta cat*aracta in Delaware by Curry (1977)

- No observations of leeches feeding on live mussels

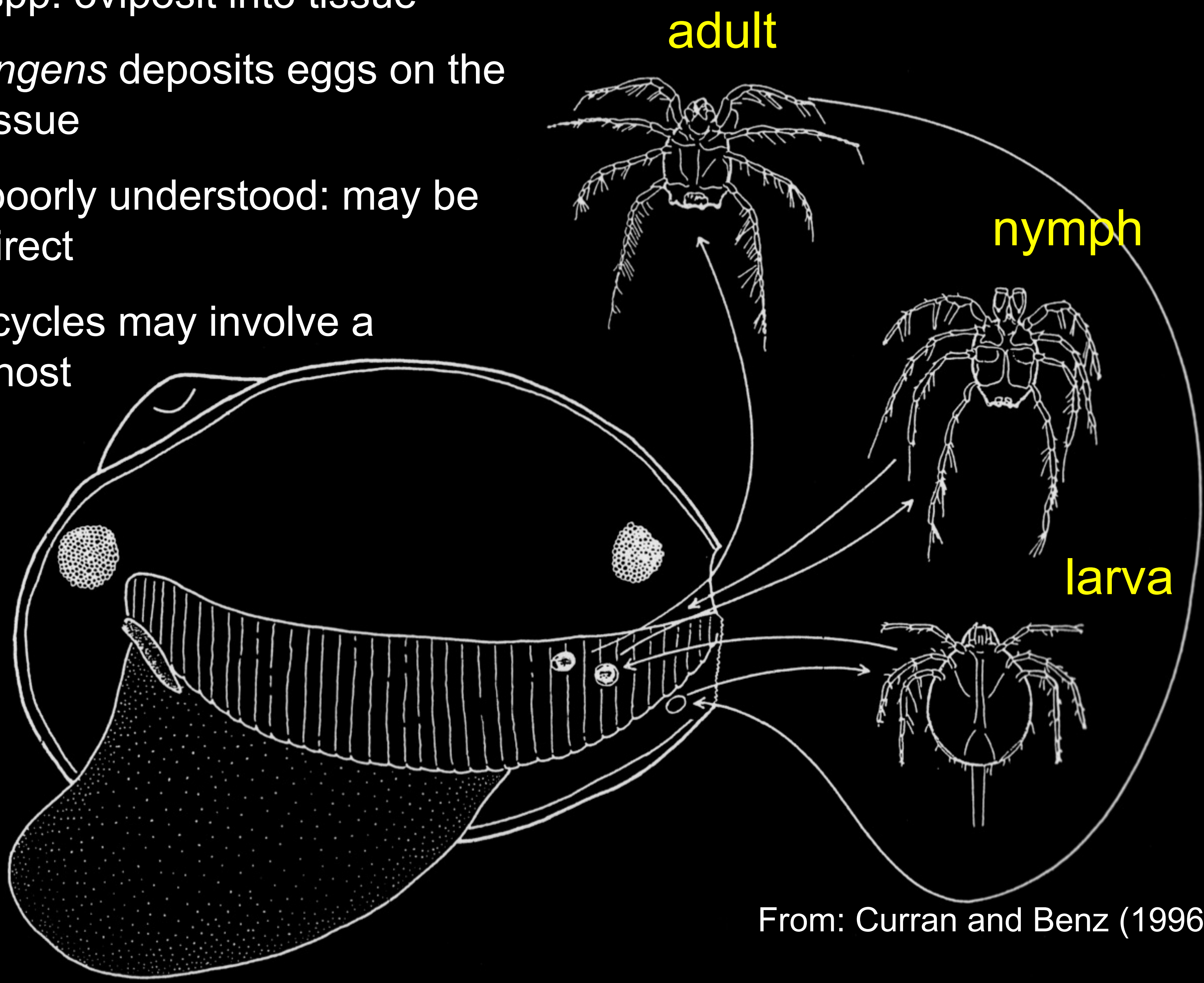
Phylum Arthropoda: Acari

Mites that associate with or infect mussels:

- Hygrobatidae, *Dockovdia* = 2 spp.
- Pionidae, *Najadicola* = 1 sp.
  - *Najadicola ingens* infects 30 mussel spp.
- Unionicolidae, *Unionicola* = 244 spp.
  - *Unionicola* spp. infect 137 mussel spp. representing Unionidae, Hyriidae, Mycetopodidae
- For a review see Edwards and Vidrine (2013)
- Mites may injure mussels through attachment, feeding, ovipositing, encystment of larvae and nymphs (McElwain and Bullard, 2016)
- *Najadicola ingens* may lay eggs inside the water tubes of mussels and obstruct the passage of ova (Humes and Jamnback, 1950; Humes and Russell, 1951)

Generalized life cycle of *Unionicola* spp.

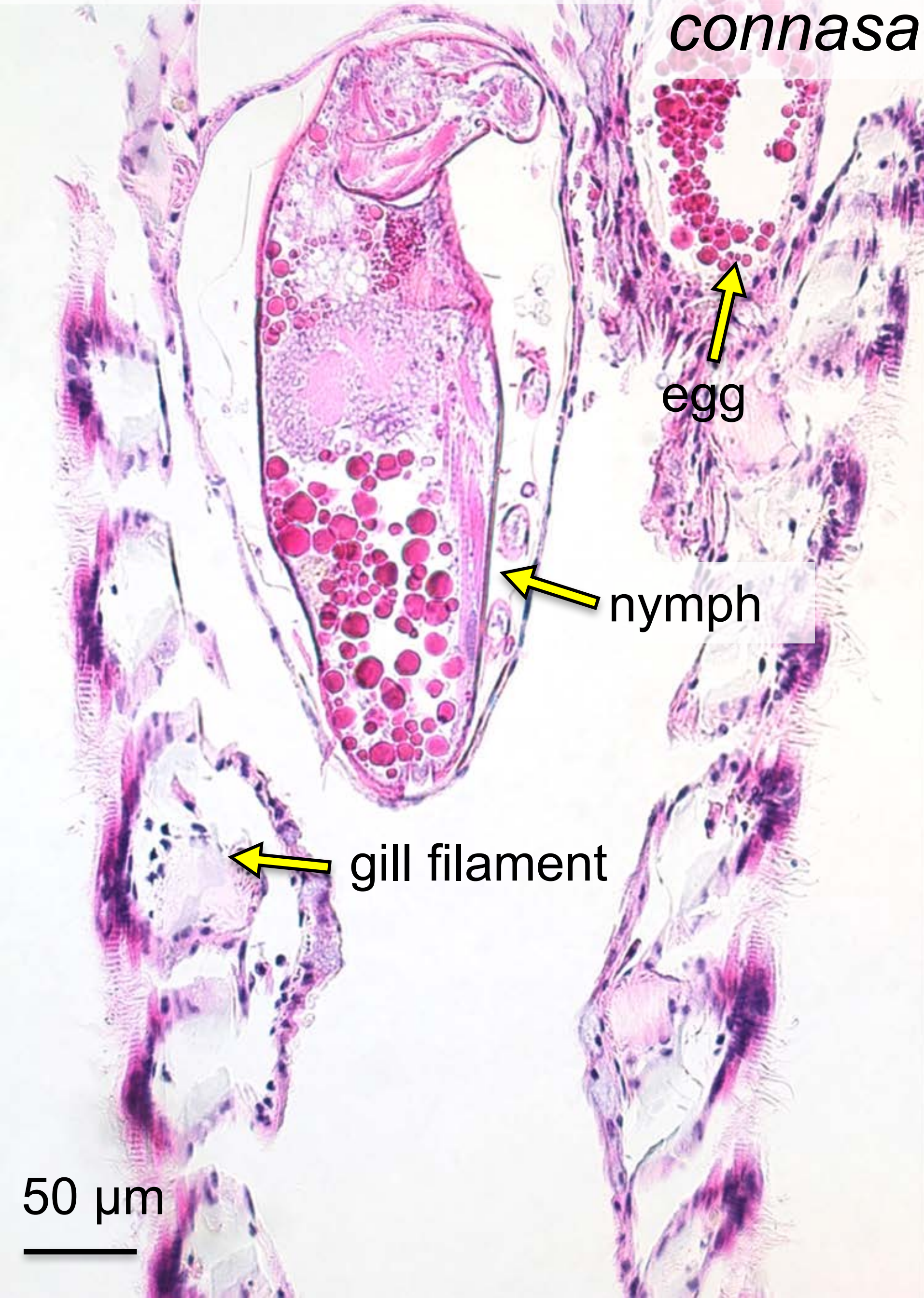
- *Unionicola* spp. oviposit into tissue
- *Najadicola ingens* deposits eggs on the surface of tissue
- Life cycles poorly understood: may be direct or indirect
- Indirect life cycles may involve a chironomid host

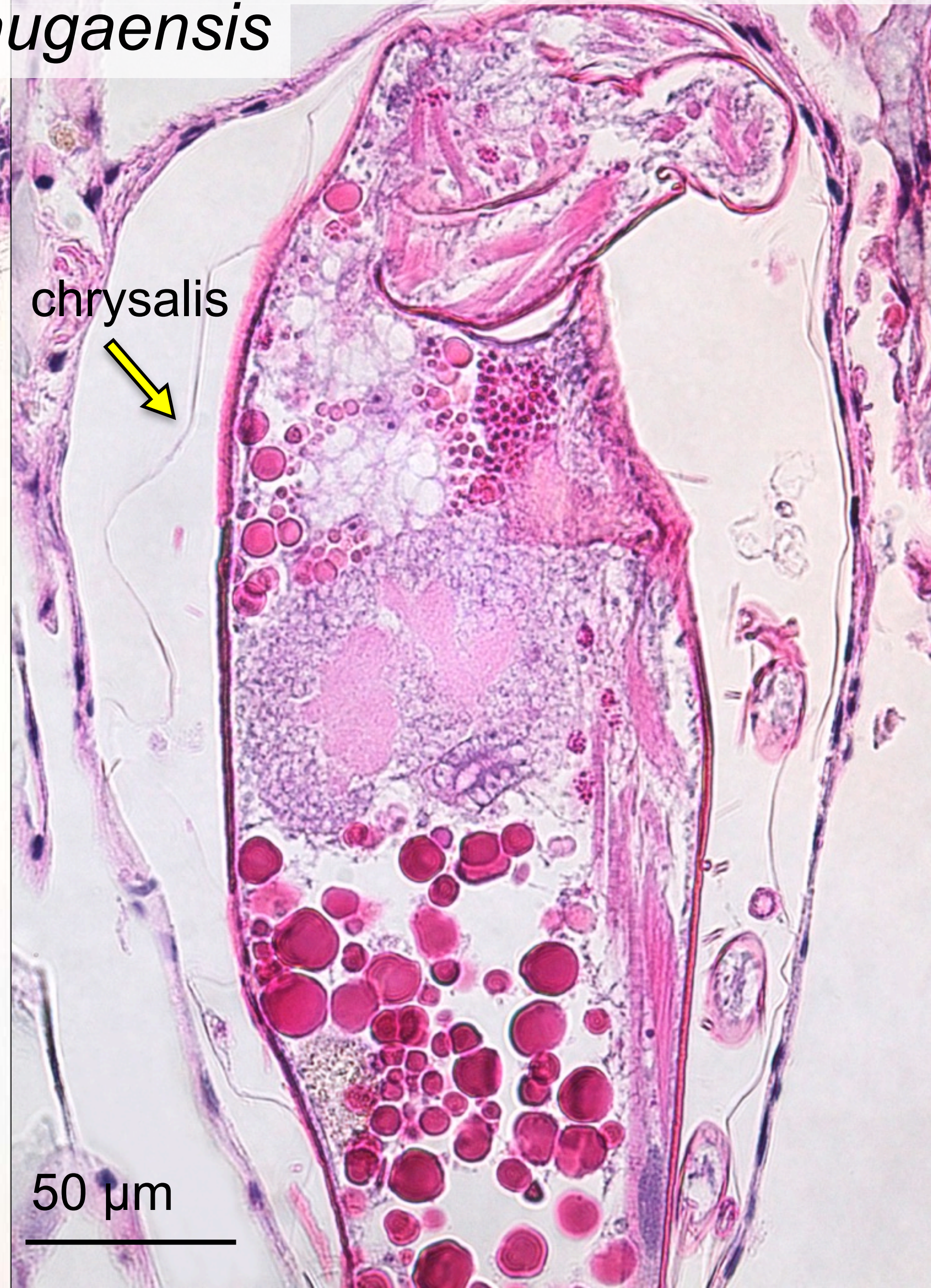


From: Curran and Benz (1996)

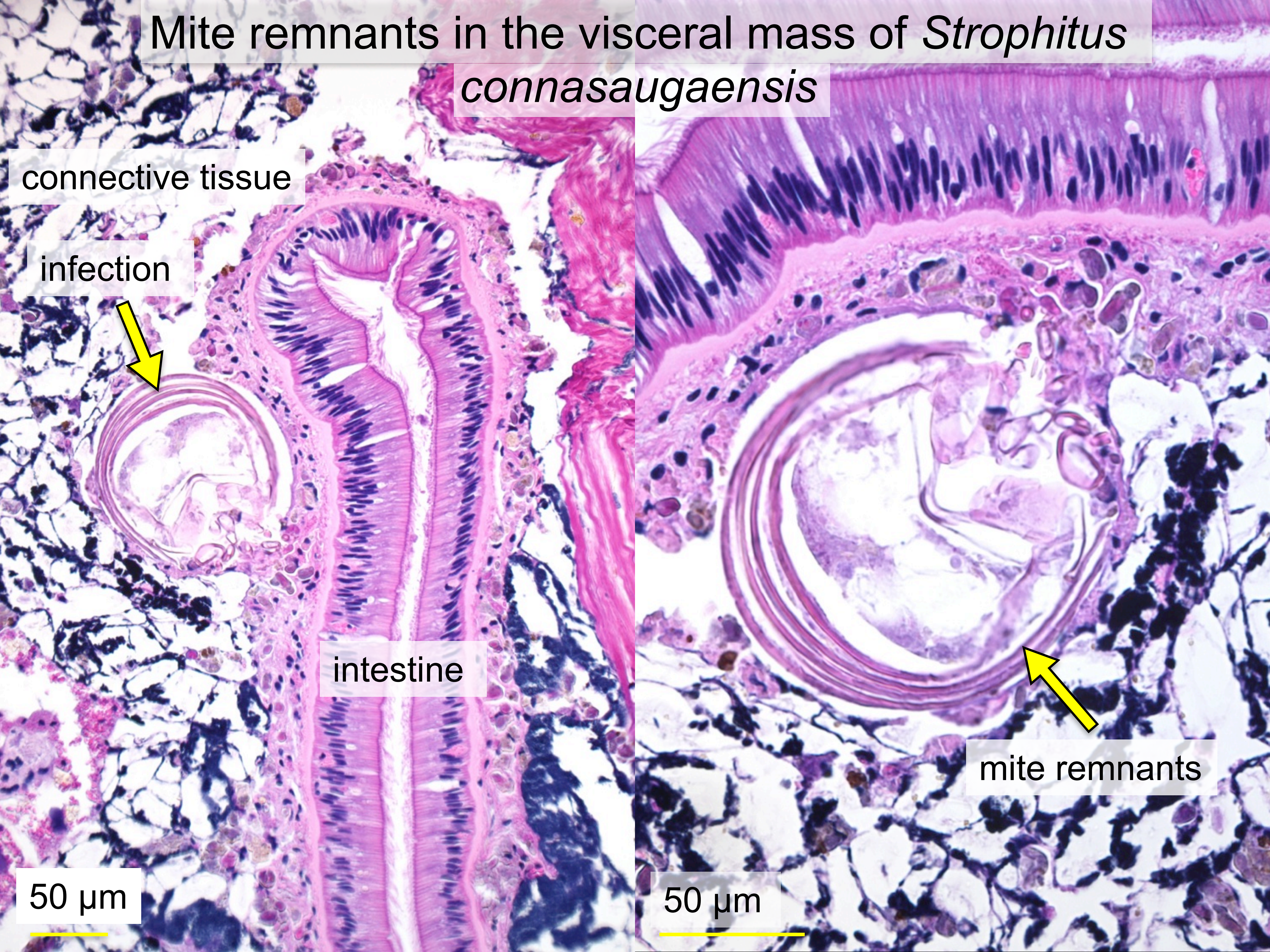
Eggs of *Unionicola* sp. in the gill of *Strophitus connasaugaensis*

A nymph and an egg of *Unionicola* sp. in the gill of *Strophitus connasaugaensis*

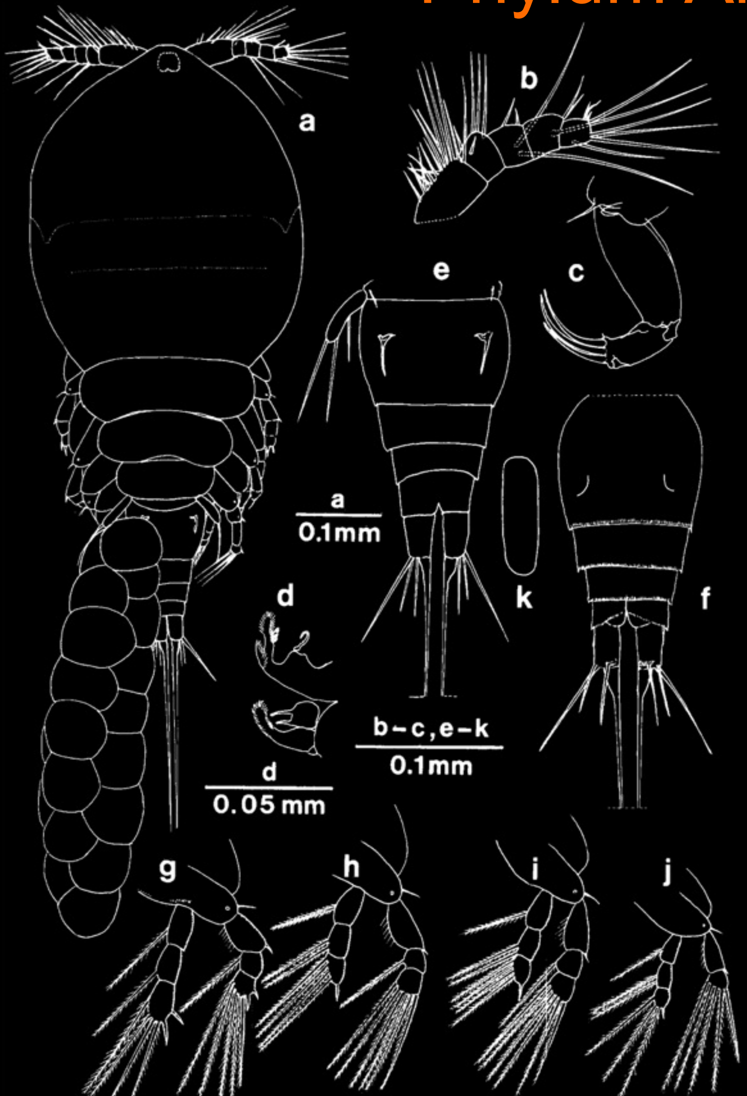




Mite remnants in the visceral mass of *Strophitus connasaugaensis*



Phylum Arthropoda: Copepoda

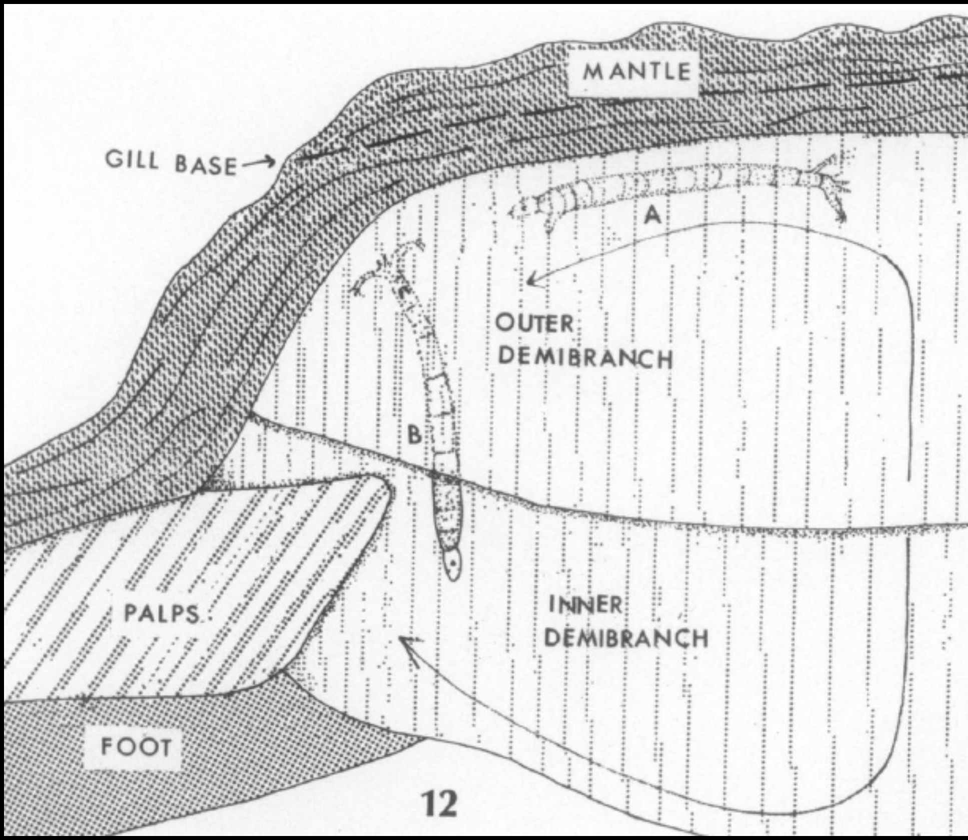


Paraergasilis rylovi from *Anodonta piscinalis* (Chernysheva and Purasjoki, 1991)

- Copepoda contains many free-living and parasitic species
- Parasitic copepods best known from gills and skin of fishes
- Direct life cycle with egg, nauplius, copepodid stages, adult
- *Paraergasilis rylovi* reported from gills of *Anodonta* spp. and olfactory sacs of fishes from Europe (Chernysheva and Purasjoki, 1991; Pekkarinen, 1993)
- May attach to mussel gills, but the relationship is unclear

Phylum Arthropoda: Insecta

- Many records of chironomids (Diptera, Chironomidae) from North American unionids (e.g., Roback et al. 1979; Vidrine 1990)
- Probably more common and widely distributed than literature indicates (Forsyth and McCallum, 1978; Roback et al. 1979; Pekkarinen, 1993)
- Chironomid spp. may occur between mantle and gill, *Ablabesmyia* sp. (*A. janta*?) most frequently reported (Roback et al. 1979; Roback 1982; Vidrine, 1990)
- Chironomids may get between mantle and shell whether the shell is breached or not (Beedham 1971; Forsyth and McCallum, 1978; Cichy et al. 2016)



Diagrammatic representation of Ablabesmyia sp. attached to unionid gills (Roback et al. 1979)

Injuries associated with insect larvae

Diptera, Chironomidae:

- *Glyptotendipes* sp. (*G. paripes*?) from between mantle and shell of *Anodonta cygnea* (Unionidae). Histopathological changes including damage to mantle and influx of amoebocytes reported (Beedham, 1971).

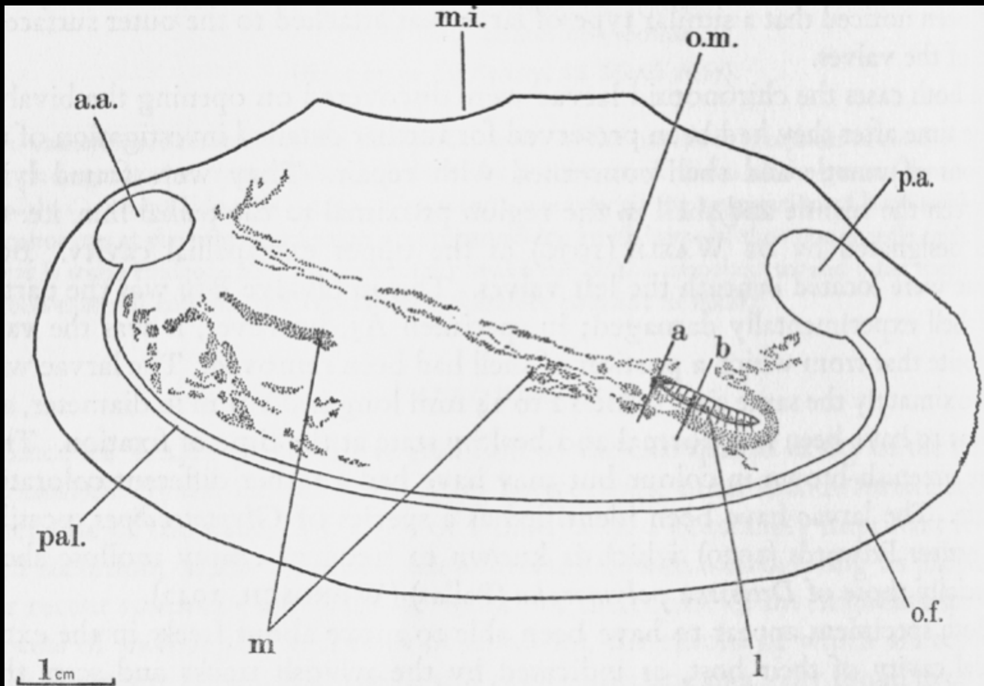
- *Baeoctenus bicolor* larvae and pupae inhabit tubes of particulate matter attached to gills near labial palps of *Anodonta cataracta* (Unionidae). Larvae feed on gill tissue, as much as 50% of gill missing in some mussels (Gordon et al. 1978).

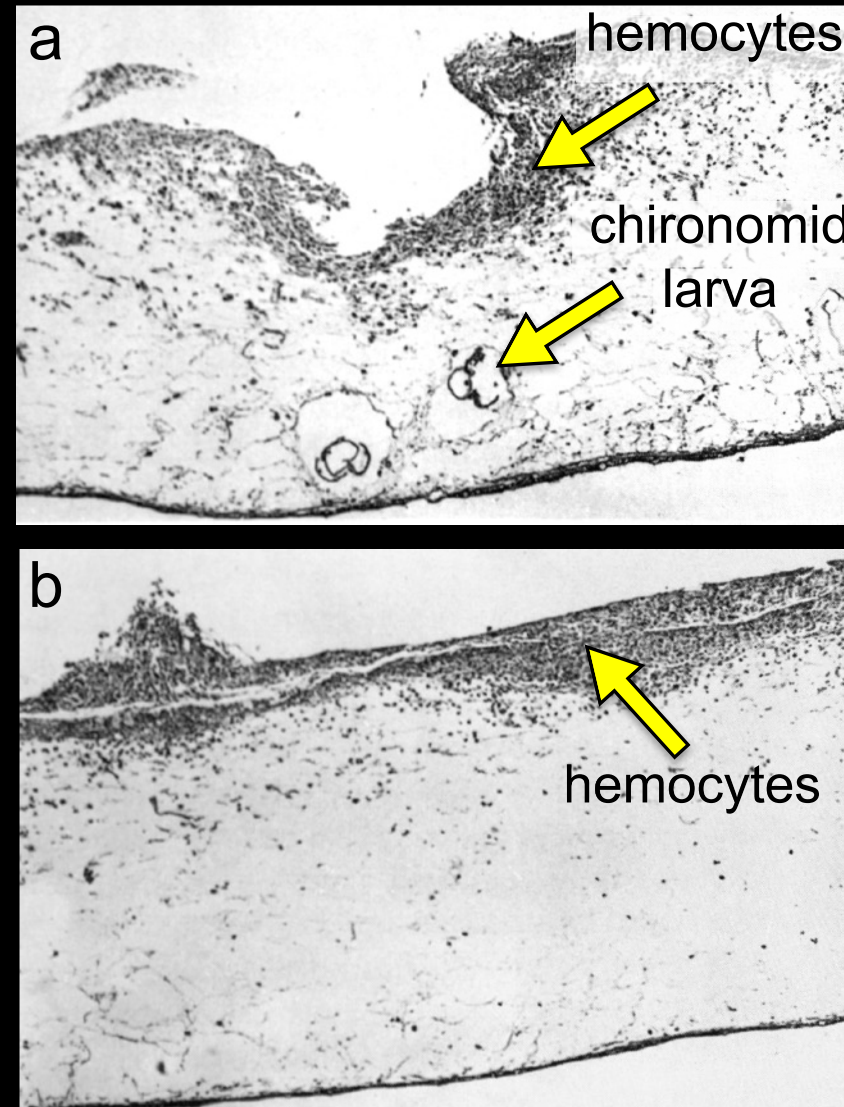
- *Xenochironomus canterburyensis* from of *Hyridella menziesi* (Hyriidae). Chironomid larvae occurred between old shell growth and new shell growth, in mantle cavity, and between mantle and shell. Chironomids associated with blister pearls (Forsyth and McCallum, 1978).

Odonata, Gomphidae:

- *Gomphus miliataris* fed on gills of *Poponaias popeii* (Unionidae), some individuals were missing the entire outer gills or all four gills (Levine et al. 2009).

Histopathological changes associated with *Glyptotendipes* sp. in *Anodonta cygnea*





Above: Diagrammatic representation of the outer mantle of *Anodonta cygnea* showing marks made by *Glyptotendipes* sp.

Right: Histology of the outer mantle of *Anodonta cygnea* showing damage and hemocytes associated with *Glyptotendipes* sp.

From: Beedham (1971).

Phylum Chordata: Actinopterygii

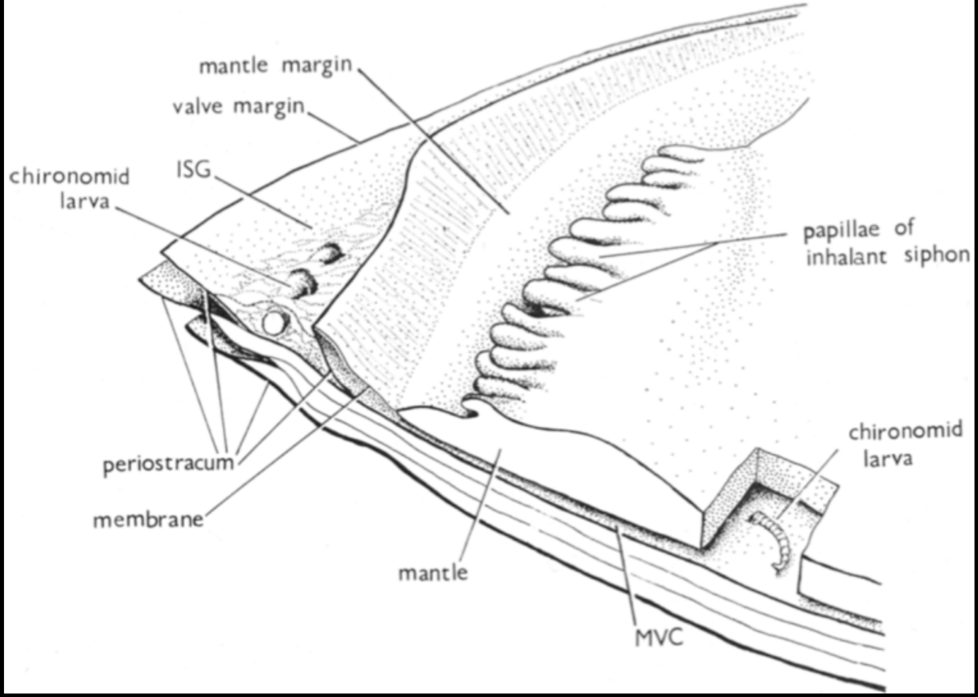
- European bitterling, *Rhodeus sericeus* (Cyprinidae) oviposits into the mantle cavity of mussels in Unionidae and Margaritiferidae in Europe, Asia and North America (For a review, see Smith et al. 2004)
- Bitterling embryos may become lodged between interlamellar spaces in the gill, may compress gill tissue, obstruct water flow through gills of *Unio rostratus* (Stadnichenko and Stadnichenko, 1980)
- Bitterling embryos compete with developing glochidia for oxygen (Smith et al. 2001)
- Bitterling embryos may reduce growth rates of mussels (Reichard et al. 2006)

Parasite-induced pearl formation

Records of parasite-pearls in mussels:

- Digeneans: Clark and Wilson (1912), Wilson and Clark (1912), Genter and Hopkins (1934), Hopkins (1934); all records from Unionidae
- Mites: Kelaart and Möbius (1856), Baker (1928); Edwards and Vidrine (2013); all records from Unionidae
- Midge larvae:

  Forsyth and McCallum (1978), Pekkarinen (1993)



Right: Diagrammatic representation of chironomids between mantle and shell and chironomid-induced pearls from Forsyth and McCallum (1978).

Blister pearls on the nacre (left) and pearls from the mantle (right)

Shell anomalies or deformities

Anomalies or deformities reported include:

- Protuberances
- Infoldings
- Erosion
- Misshapen shells
- For a review, see Strayer (2008)

Fig. 9. Mussel shell deformities. *A–F.* examples of freshwater mussel valves exhibiting various types of deformities, most often the result of trauma or physical damage to the mantle.

Examples of shell deformities. From: Parmalee and Bogan (1998).

Normal and truncated right valves of *Elliptio complanata*

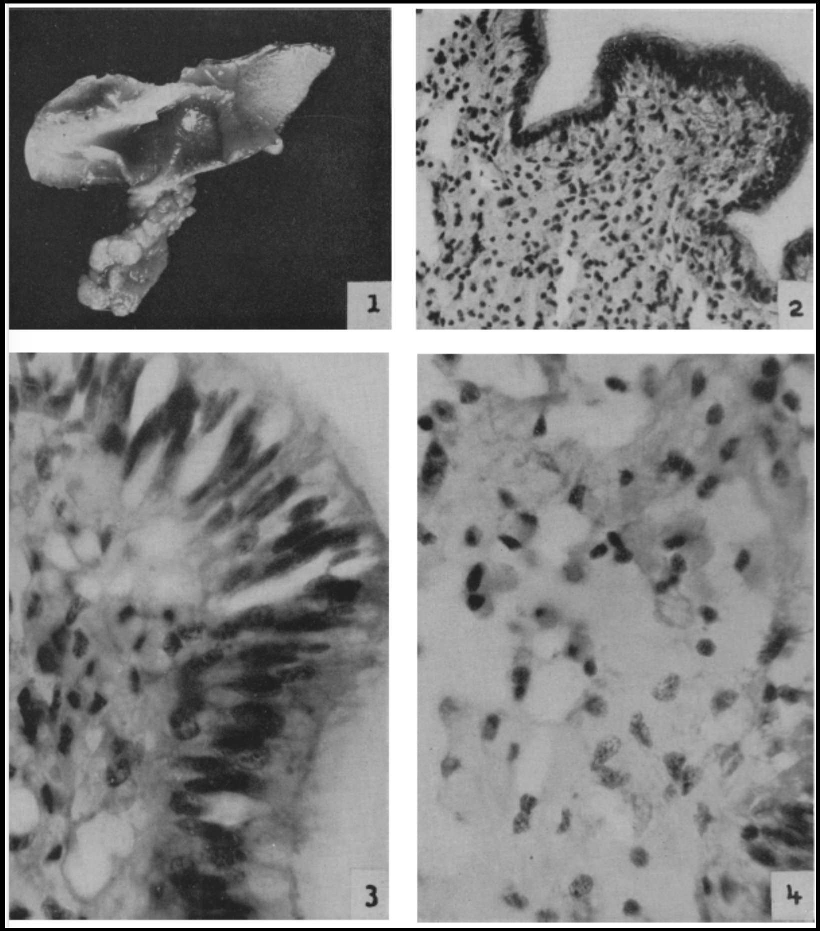
Normal | Slightly truncated | Moderately truncated | Severely truncated

- Occurs among 3 species representing Unionidae as well as *Margaritifera margaritifera* in several rivers in Massachusetts
- Reported from 5 unionid species among rivers in the Southern Tier and Hudson River Valley in New York (Strayer 2006)
- The cause of these deformities is presently indeterminate
- Impact of shell deformities on mussel physiology (feeding, reproduction) is poorly understood

Neoplasms or tumors

Records of tumors in mussels:

- Williams (1890): Adeno-myoma of the mantle of *Anodonta cygnea*
- Collinge (1891): Tumor arising from the mantle-outer gill junction in *A. cygnea*. This mussel lacked nacre in the posterior portion of the shell.
- Butros (1948): Connective tissue tumor arising from the labial palp of *A. implicata*
- Pauley (1967a, 1967b): Adenomas from the foot of *A. californiensis*
- Prevalence of tumors is 1% or less



A connective tissue tumor arising from the labial palp of *Anodonta implicata.* From: Butros (1948).

Are parasites and diseases associated with mussel declines?

- Some parasites such as digeneans, mites, insects can directly reduce fecundity by damaging gonad or by damaging or obstructing marsupial gill
- Prevalence of high infections tends to be low (<20%)
- Are parasitized mussels more susceptible to environmental stress?
  - Jokela et al. (2005) found that *Anodonta piscinalis* may be more susceptible to *Rhipidocotyle* spp. (Digenea) under anoxic conditions (eutrophication and ice cover)
  - Choo's dissertation work (2015) suggests rising water temperatures expected with global climate change may increase *Rhipidocotyle* cercarial shedding, and unionid host mortality
- Are parasitized mussels more susceptible to contaminants?
  - Heionen et al. (2001) found that *Pisidium amnicum* infected with *Bundodera luciopercae* (Digenea) were more likely to survive exposure to pentachlorophenol than uninfected clams
  - NOAA Sentinel Bivalve Program [e.g. Kim et al. (1998)] inconsistent results/typically no correlation to parasites in marine bivalves and specific contaminants; correlations that were observed were usually negative