Chapter 1
Fungi in Antarctica: Diversity, Ecology, Effects of Climate Change, and Bioprospection for Bioactive Compounds

Luiz Henrique Rosa, Carlos Leomar Zani, Charles Lowell Cantrell, Stephen Oscar Duke, Patrick Van Dijck, Alessandro Desideri, and Carlos Augusto Rosa

1.1 Taxonomy, Diversity, and Ecology of Antarctic Fungi

In Antarctica, microorganisms dominate food chains in several different pristine ecosystems. In these ecosystems, fungi occur as two known basic forms (i) filamentous fungi and (ii) yeasts, which display colonies with different morphologies and colours (Fig. 1.1). Such colonies demonstrate a high degree of genetic plasticity that allows them to survive under extreme conditions of low temperatures, high UV irradiation, freeze-thaw cycles, different pH levels, strong winds, dehydration, osmotic stress, and low nutrient concentrations (Fell et al. 2006).

The fungal assemblages of Antarctica include taxa that belong to the major fungal groups, which were reported by Kirk et al. (2008) to be *Ascomycota*, *Basidiomycota*, traditional *Zygomycota*, *Chytridiomycota*, and *Glomeromycota*;

L. H. Rosa (✉) · C. A. Rosa
Departamento de Microbiologia, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brasil
e-mail: lhrosa@icb.ufmg.br

C. L. Zani
Instituto René Rachou, FIOCRUZ-MS, Belo Horizonte, Minas Gerais, Brasil

C. L. Cantrell · S. O. Duke
United States Department of Agriculture, Agricultural Research Service, Natural Products Utilization Research Unit, University, MS, USA

P. Van Dijck
VIB-KU Leuven Center for Microbiology, Leuven, Belgium

Laboratory of Molecular Cell Biology, KU Leuven, Leuven, Belgium

A. Desideri
Department of Biology, University of Rome "Tor Vergata", Rome, Italia

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Fig. 1.1 Antarctic fungi and their diverse colony macro-morphologies

some assemblages also include the stramenopiles (*Oomycota*) and slime moulds (*Mycetozoa*) traditionally studied by mycologists (Bridge and Spooner 2012). However, as modern taxonomic studies consider phylogenetic analysis and the characterisation of uncultivable taxa, this taxonomic hierarchy is changing. Tedersoo et al. (2018) proposed, using phylogenies and divergence time estimates, the following 18 phyla for fungi: *Ascomycota*, *Aphelidiomycota*, *Basidiobolomycota*, *Basidiomycota*, *Blastocladiomycota*, *Calcarisporiellomycota*, *Chytridiomycota*, *Glomeromycota*, *Entomophthoromycota*, *Entorrhizomycota*, *Kickxellomycota*, *Monoblepharomycota*, *Mortierellomycota*, *Mucoromycota*, *Neocallimastigomycota*, *Olpidiomycota*, *Rozellomycota*, and *Zoopagomycota*. In contrast to fungi from tropical and temperate environments, the fungi present in Antarctica still represent an unknown proportion of diversity and potentially new phyla that may yet be discovered. Bridge and Spooner (2012) estimated that over 1000 fungal species (without lichens) have been previously recorded in Antarctica and suggested that the true diversity of Antarctic fungi may be far greater than currently estimated.

Most taxonomic studies of Antarctic fungi have included the use of molecular biology techniques. DNA is extracted from mycelia using protocols similar to those proposed by de Hoog et al. (2005) and Rosa et al. (2009), followed by sequencing of the internal transcribed spacer (ITS) region according to protocols established by White et al. (1990). The ITS represents the most common and accepted DNA barcoding marker for the identification of fungi, and ITS sequencing has been frequently used to identify fungi (Gazis et al. 2011). However, some fungal species of the genera *Penicillium*, *Aspergillus*, and *Cladosporium*, which represent abundant cosmopolitan cold-adapted taxa living in Antarctica, are genetically very similar, and the ITS region is not sufficiently variable to separate them at the species level. For this reason, other more variable DNA regions such as partial β-tubulin II (TUB2), γ-actin (ACT), translation elongation factor 1-α (TEF1α), RNA polymerase II (partial RPB2), elongation factor 3 (TEF3), topoisomerase I (TOPI), and phosphoglycerate kinase (PGK) can be sequenced to identify these fungi at the species level (Stielow et al. 2015). Although yeasts are also fungi, they are identified using different protocols. Yeasts are morphologically and physiologically characterised using standard methods (Kurtzman et al. 2011), followed by an analysis of the DNA region spanning the ITS-5.8S and rRNA gene D1/D2 domains according to protocols established by White et al. (1990) and Lachance et al. (1999).

However, such molecular biology taxonomy procedures are dependent on the parameters used by each mycologist. For these reasons, Godinho et al. (2013) proposed uniform criteria to interpret sequences from the GenBank database: for query coverage and sequence identities ≥99%, the genus and species were accepted; for coverage and sequence identities = 98%, the genus and species were accepted, but the term ‘cf.’ (Latin for confer = compares with) is used to indicate that the specimen resembles, but has certain minor features not found in the reference species; for query coverage and sequence identities between 95% and 97%, only the genus was accepted; for query coverage and sequence identities ≤95%, the isolates were labelled with the order or family name or as ‘unknown’ fungi. Additionally, phylogenetic analyses can be conducted to estimate the evolutionary distance between the sequences of Antarctic fungi and those sequences of type species deposited in the GenBank database. Molecular biology methods are also recommended for those fungi that do not produce conidia or spores when cultured on common mycological media.

Although molecular biology methods represent the main taxonomic tool used to identify Antarctic fungi, classical macro- and micro-morphological and physiological methods can be necessary in some cases. Some cosmopolitan cold-adapted fungi show the same query coverage and identities percentage, so they have been assigned to two or more species when compared with sequences deposited in GenBank. For these cases, it is necessary to characterise fungal macro- and micro-morphological structures and perform a physiological characterisation on different mycological media, such as potato dextrose, cornmeal, malt extract, potato dextrose, Sabouraud dextrose, and yeast extract sucrose agars, to define the species level.

Those studies conducted to date show that fungal diversity differed between the Antarctica Peninsula and continental Antarctica environments. The extreme conditions of the Antarctic Peninsula are milder than those of the continental regions. Additionally, the Antarctic Peninsula has more life forms, such as plants, macroalgae, invertebrates, and vertebrates, supplying this region with organic matter and nutrients and, consequently, creating several ecological niches and microenvironments for different fungal webs to survive. In contrast, in continental Antarctica, organic matter and nutrients are extremely scarce because of the near absence of life forms; moreover, the soils, rocks, snow, and ice are ultra-oligotrophic. According to Rao et al. (2012), life in continental Antarctica is restricted to the rare occurrence of some species of lichens, mosses, invertebrates, and soil microbial communities. Fungi in continental Antarctica have been more often described in lichen symbioses, while the occurrence of free-living fungi in soils remains poorly understood (Godinho et al. 2015).

Cold habitats are dominated by cold-adapted (psychrophilic) and cold-tolerant (psychrotolerant) microorganisms (Harding et al. 2011). Mycological studies in Antarctica have reported the occurrence of few endemic, psychrophilic species, with the majority being cosmopolitan psychrotolerant taxa. According to Ruisi et al. (2007), the endemic Antarctic fungal species are characterised as true psychrophilic fungi that are only able to actively grow and reproduce in specific Antarctic environments. The cosmopolitan psychrotolerant fungi are ecotypes with mesophilic-psychrotolerant behaviour resulting from an adaptation to the cold Antarctic climate (Zucconi et al. 1996). According to these criteria, species like *Metschnikowia australis*, *Antarctomyces psychrotrophicus*, *Antarctomyces pellizariae*, *Cryomyces antarcticus*, *Friedmanniomyces simplex*, *Friedmanniomyces endolithicus*, *Mortierella antarctica*, *Penicillium antarcticum*, *Penicillium tardochrysogenum*, *Thelebolus globosus*, *Thelebolus ellipsoideus*, *Thelebolus balaustiformis*, and *Thelebolus spongiae* are considered to be endemic psychrophilic species. By contrast, different species of *Penicillium* (e.g. *P. chrysogenum*), *Aspergillus* (*A. fumigatus*), *Cladosporium* (*C. sphaerospermum)*, *Colletotrichum* (*Co. gloeosporioides*), and *Rhodotorula* (*R. mucilaginosa*) are considered to be cosmopolitan cold-tolerant taxa that have adapted to the cold Antarctic climate. Additionally, some psychrophilic taxa of polar or temperate occurrence occur in Antarctica such as *Pseudogymnoascus destructans* and *Mortierella alpina*. The ecological, biochemical, physiological, and genetic peculiarities of certain endemic, cosmopolitan cold adapted and polar fungi have been studied. Among them are *M. australis*, *A. psychrotrophicus* and *A. pellizariae* (endemic), *P. destructans* (cold regions), and *P. chrysogenum* (cosmopolitan cold adapted).

The yeast *M. australis* is always reported in marine ecosystems (Fell and Hunter 1968; Gonçalves et al. 2017), similar to *Euphausia superba*, as species that colonise the stomach of Antarctic krill (Donachie and Zdanowski 1998) and macroalgae (Loque et al. 2010; Godinho et al. 2013; Furbino et al. 2014) in lakes next to the sea that have influence on marine spray (Vaz et al. 2011; Gonçalves et al. 2012). The isolation of *M. australis* in abundant association with several Antarctic macroalgae from different areas of the Antarctic Peninsula supports the possibility that this yeast may have a specific ecological association with Antarctic macroalgae in the marine environment.

The genus *Antarctomyces* has only two species reported to be endemic for Antarctica: *Antarctomyces psychrotrophicus* (isolated for the first time from the soil) and *A. pellizariae* (from snow) in the South Shetland Islands, King George Island (Stchigel et al. 2001; de Menezes et al. 2017). *Antarctomyces psychrotrophicus* produces an antifreeze protein, similar to those produced by polar fish, with potential uses in biotechnological processes (Xiao et al. 2010). *Antarctomyces pellizariae* (Fig. 1.2) produces a rare, blue pigment with possible uses in the food industry (de Menezes et al. 2017).

Pseudogymnoascus species are abundant in Antarctica and occur in different substrates and environments, including the soils (Mercantini et al. 1989), mosses (Tosi et al. 2002), leaves of *Colobanthus quitensis* (Rosa et al. 2010), thalli of macroalgae (Loque et al. 2010), freshwater lakes (Gonçalves et al. 2012), and lichens

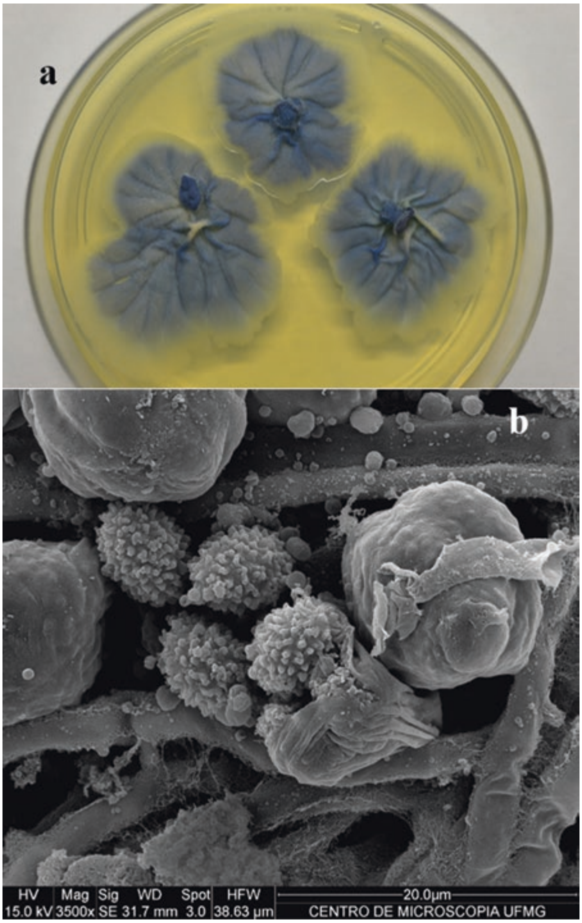

Fig. 1.2 (**a**) Blue colony of A*ntarctomyces pellizariae* and (**b**) a scanning electron microscopic image of its ascospores and ascus. (Photos Credits: LH Rosa)

(Santiago et al. 2015). Several published studies have reported several *Pseudogymnoascus* taxa identified only at the genus level. Moreover, many of these unidentified taxa may represent new species, different from those reported from the northern hemisphere, resulting from a lack of a critical taxonomic evaluation of the diversity of *Pseudogymnoascus*. Within the genus *Pseudogymnoascus*, *P. destructans*, which is characterised as a psychrophilic pathogenic fungus that has led to a reduction in bat populations as the causative agent of white-nose syndrome (WNS) in temperate regions (Lorch et al. 2011), is abundantly found in different substrates and regions of Antarctica. Zukal et al. (2016) reported that symptoms caused by *P. destructans* in the bats of North America and Europe/Palearctic Asia are different. However, no data about the virulence of *P. destructans* strains from Antarctica is yet available, which represents a major gap in knowledge owing to concern about their pathogenic potential (Gomes et al. 2018). Since Lorch et al. (2013) and Minnis and Lindner (2013) suggested that the diversity of *Pseudogymnoascus* seems to be greater than previously reported, those species found in Antarctica may represent new endemic species that play a previously unknown ecological role in Antarctic environments.

1.2 Effects of Climate Changes on Fungi that Are Resident to Antarctica

In recent years, concerns about global climate change have increased worldwide. Several studies demonstrated that Arctic regions and the Antarctic Peninsula represent two of the regions on Earth with the fastest changing climates, and the warming of these regions is likely to have a profound influence on terrestrial and marine environments (Clarke et al. 2006). Consequently, all biota living in these ecosystems are subject to varying effects of climate change. Another concern about Antarctica is the introduction of alien species owing to both climate changes and tourism, which can affect the resident Antarctic biota in terms of distribution and ecological roles.

Mycological studies have demonstrated that the fungal assemblages of different environments of Antarctica are composed of both cold-adapted and endemic taxa, which display interesting dynamics of richness, dominance, and similarity patterns. According to Fell et al. (2006), the different types of soils of Antarctica offer an interesting opportunity to investigate the regional to global environmental effects of microbial webs on community structures.

Godinho et al. (2013) and Furbino et al. (2014) observed that algicolous fungi assemblages, associated with endemic Antarctic macroalgae of the Antarctic Peninsula, are composed of few endemic and many cosmopolitan cold-adapted fungi. Based on these taxonomic and ecological observations, they proposed that the reduction of endemic or cold-adapted fungal species, associated with an increase of mesophilic cosmopolitan taxa within the fungal assemblages associated with endemic macroalgae, may reflect the influence of climate change in the maritime

Antarctic Peninsula. They also proposed that analyses of the balance and dynamics of richness, dominance, and distribution among endemic, cold-adapted, or cosmopolitan fungal taxa could be used as model to understand the influence of climate change on maritime Antarctica.

However, since Antarctica represents one of the most pristine extreme environments of the planet, there is a consensus that several new, undescribed microorganism taxa or strains may occur in its different regions, which could display novel physiological, biochemical, and genetic characteristics. Since the discovery of *Bacillus anthracis* in thawing permafrost of Siberia in Russia (Revich and Podolnaya 2011), different studies have focused on the microorganisms present in pristine environments under the effects of global climate change and their potential capabilities to cause diseases in animals or crop plants.

In Antarctica, few studies have been published to date on the pathogenic potential of resident microbiota, especially resident fungi. However, published studies on Antarctic fungal diversity have shown the presence of taxa phylogenetically near to fungi that are capable of causing diseases in plants and animals.

The first studies of fungi associated with Antarctic plants (mosses and the angiosperms *Deschampsia antarctica* and *Colobanthus quitensis*) and lichens were published by Pugh and Allosopp (1982), Fletcher et al. (1985), Gamundi and Spinedi (1988), Onofri and Tosi (1989), Del Frante and Caretta (1990), Baublis et al. (1991), and Möller and Dreyfuss (1996). All of these studies detected taxa of the genera *Alternaria*, *Botrytis*, *Cladosporium*, *Fusarium*, *Penicillium*, *Phaeosphaeria*, and *Phoma* but reported no correlation with potential plant pathogens. Additionally, the endophytes most frequently recovered from the angiosperms *D. antarctica* (Rosa et al. 2009) and *Colobanthus quitensis* (Rosa et al. 2010) are strains of *Alternaria*, *Fusarium*, *Microdochium*, *Mycocentrospora*, and *Phaeosphaeria*, which represent genera that can cause diseases in important crop plants worldwide (Prasada and Prabhu 1962; Thomma 2003). Species of *Microdochium* have been described as pathogens able to cause diseases in cereal and turf grasses of cold regions (Mahuku et al. 1998), *Fusarium* spp. are well-known plant pathogens (Zhong-shan et al. 2008), and *Mycocentrospora* spp. have widespread distribution that can be pathogenic in several plant species (Ananda and Sridhar 2002).

Recently, Gonçalves et al. (2017), Sousa et al. (2017), and Alves et al. (2019) studied fungal diversity in rocks and ornithogenic soils of Antarctica and the physiological opportunistic virulence potential in vitro of the fungi for animals. Gonçalves et al. (2017) recovered from rocks of continental Antarctica the fungal taxa *Acremonium* sp., *Debaryomyces hansenii*, *P. chrysogenum*, *P. citrinum*, *P. tardochrysogenum,* and *R. mucilaginosa*, which are able to grow at 37 °C. Additionally, different isolates of *P. chrysogenum*, *P. citrinum*, and *P. tardochrysogenum* could produce partial haemolysis on blood agar at 37 °C; *Acremonium* sp., *P. citrinum*, and *P. tardochrysogenum* had spore sizes ranging from 2.81 to 5.13 μm in diameter at 37 °C; and *P. chrysogenum* and *P. tardochrysogenum* displayed macro- and micro-morphological dimorphism. Additionally, from 50 rock samples of the Antarctic Peninsula, Alves et al. (2019) obtained 155 fungi able to grow at 37 °C, which were identified as *P. chrysogenum*, *Fusarium* sp., and *R. mucilaginosa*.

Additionally, 103 fungi exhibited haemolytic activity, 81 produced proteinase and 9 phospholipase, and 25 were dimorphic with spore diameters ≤4 μm.

Sousa et al. (2017) recovered 50 fungi that were able to grow at 37 °C, from the ornithogenic soil nests of bird species *Phalacrocorax atriceps*, *Macronectes giganteus*, *Pygoscelis antarcticus*, and *P. papua* in the Antarctic islands. Among the different species, *A. fumigatus*, *P. chrysogenum*, *Cryptococcus laurentii*, and *R. mucilaginosa* were the most abundant. Isolates of *A. fumigatus* and *Cr. laurentii* were able to grow at different pH values. *Aspergillus fumigatus* (Fig. 1.3) produced spores ≤1 μm, and the amphotericin B minimum inhibitory concentration (MIC) for this species varied from 0.5 and 1 μg mL^{-1}. *Cryptococcus laurentii* produced phospholipase and had haemolytic activities; they also produced a capsule, and the

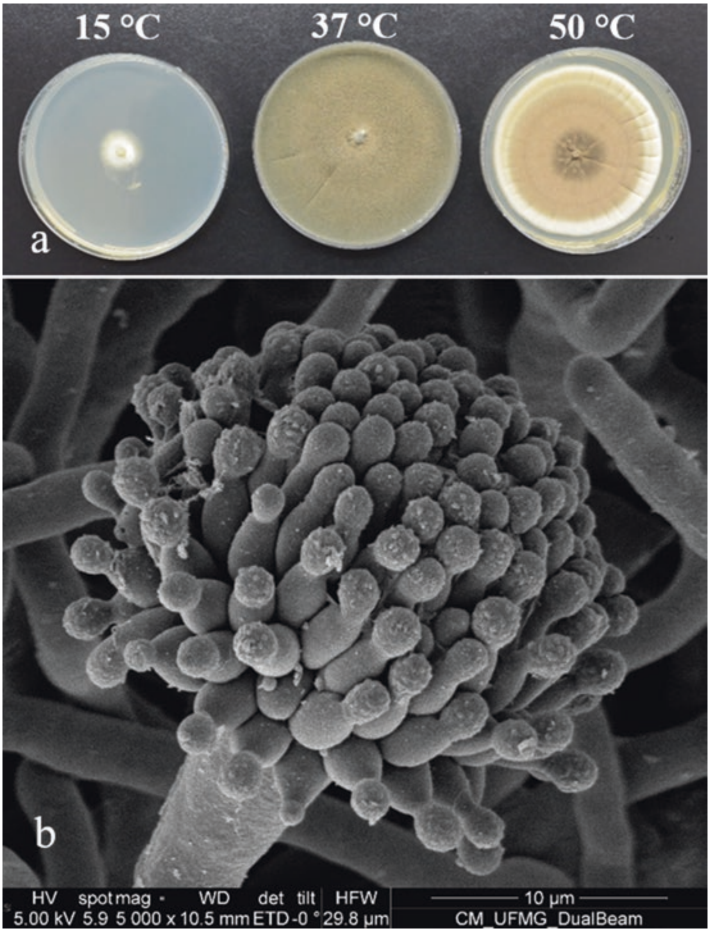

Fig. 1.3 *Aspergillus fumigatus* isolated from ornithogenic soil of Antarctica. (**a**) Colonies at different growth temperatures and (**b**) details of asexual reproductive structures are revealed by scanning electron microscopy. (Photos Credits: LH Rosa)

amphotericin B MIC for this species was 2 μg mL^{-1}. Additionally, isolates of *P. chrysogenum* could grow at 37 °C at different pH ranges, cause partial haemolysis and display polymorphism of its colonies and macro- and micro-morphologies. The spores were ≤3.07 μm, and the amphotericin B MIC for this species was 2 μg mL^{-1}.

These studies demonstrate that the Antarctic environments shelter different fungi that are phylogenetically close to species pathogenic to plants and animals. Since Antarctica is subject to the effects of the global climate changes, unreported and cryptic fungi, including those with innate pathogenic potential, may disperse from Antarctica by animals (birds), air, and tourists and then mainly spread to South America and Oceania.

1.3 Potential of Antarctic Fungi as a Pipeline to New Drugs and Agrochemicals

Microorganisms, including fungi, are promising sources of useful, new pharmaceuticals and agrochemicals. Some Antarctic bioprospecting studies have been conducted, and different organisms with potential uses in biotechnological processes have been identified. According to Santiago et al. (2012), the ability of Antarctic fungi to survive in extreme conditions suggests that they may display unusual biochemical pathways that allow them to generate new compounds. Within the Antarctic fungal communities, some taxa were detected as promising producers of bioactive secondary metabolites with potential uses as prototypical structures to develop new drugs and agrochemicals. Among them, we can report species of *Aspergillus*, *Cladosporium*, *Penicillium*, *Pseudogymnoascus*, *Phaeosphaeria*, *Microdochium*, *Mortierella*, and *Purpureocillium*.

Recently, different screening studies have been conducted with Antarctica fungi in recent years that have demonstrated their great potential in drug discovery programmes. Santiago et al. (2012) studied the capabilities of Antarctic endophytic fungi recovered from *D. antarctica* to produce bioactive secondary compounds against neglected tropical diseases and tumour cells. They discovered that extracts of the endophytic fungus *Phaeosphaeria herpotrichoides* showed selective leishmanicidal activity with an IC_{50} value equivalent to that of amphotericin B. Additionally, *Microdochium phragmitis* extracts had specific cytotoxic activity against the UACC-62 human cancer cell line. In addition, extracts from solid fermentation processes derived from cultures of *Pseudogymnoascus* strains displayed selective antifungal activities against *Candida albicans*, *Candida krusei*, and *C. sphaerospermum* (Furbino et al. 2014). An extract of *Purpureocillium lilacinum*, isolated from Antarctic soil, exhibited high trypanocidal, antifungal, and antibacterial activities, with moderate toxicity over normal human cells. Proton nuclear magnetic resonance (^{1}H NMR) spectral analysis indicated the presence of compounds containing a highly functionalised aromatic ring system (Gonçalves et al. 2015) (Fig. 1.4).

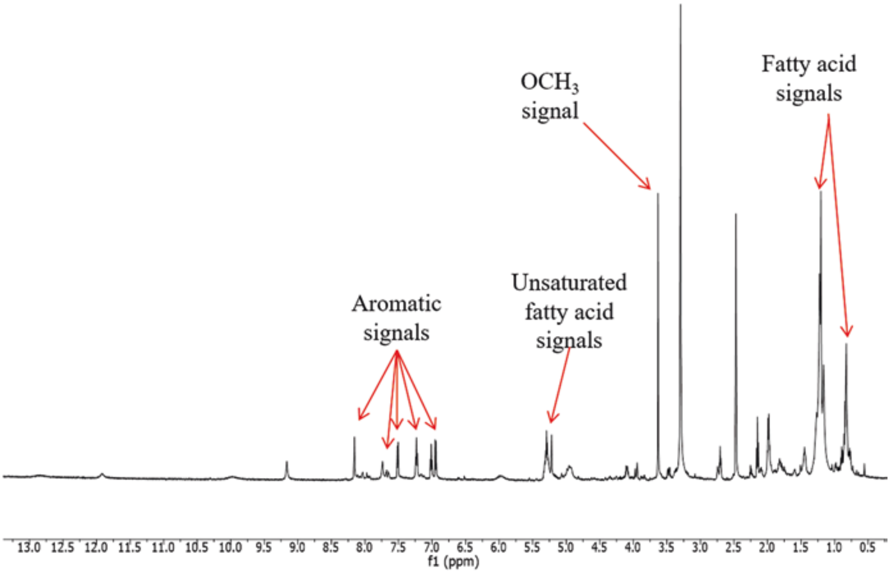

Fig. 1.4 ^{1}H NMR spectrum (600 MHz, DMSO-d_6) of methylene chloride bioactive extracts from freeze-dried culture medium of the Antarctic fungus *Purpureocillium lilacinum*, isolated from soil of the Antarctic Peninsula. Regions of interest are labelled above the corresponding signals

Gomes et al. (2018) assayed 218 fungal extracts to detect the presence of antiviral activity against dengue and Zika viruses, antiparasitic activity against *Trypanosoma cruzi* and *Leishmania amazonensis*, and herbicidal activity. Among them, extracts of *P. destructans*, *Mortierella parvispora*, and *P. chrysogenum* inhibited the growth of the trypomastigote and amastigote forms of *T. cruzi* to a similar degree as the control drug. Extract of *P. destructans* and *P. tardochrysogenum* showed strong and selective herbicidal activity against *Allium schoenoprasum* and *Lactuca sativa*. *Penicillium tardochrysogenum* (Fig. 1.5) is an endemic species of Antarctica producing penicillin, secalonic acids D and F (Fig. 1.6) (Houbraken et al. 2012). Different fungal strains of *Pseudogymnoascus*, *Penicillium*, *Cadophora*, *Paraconiothyrium*, and *Toxicocladosporium*, obtained from soil and marine sediments of Antarctica, could produce antimicrobial inhibitory compounds against the phytopathogen bacteria *Xanthomonas citri* (Vieira et al. 2018).

Among the fungi living in Antarctica, *Penicillium* are likely the most abundant and widespread in different environments and substrates in Antarctica. *Penicillium* are producers of bioactive compounds, but few species found in Antarctica have been investigated at the chemical level for this potential application. Brunati et al. (2009) showed that *P. chrysogenum*, obtained from Antarctic lakes, produces selective antimicrobial activities against *Staphylococcus aureus*, *Enterococcus faecium*, and *Escherichia coli*. Extracts of *P. chrysogenum* recovered from the endemic Antarctic macroalgae *Palmaria decipiens* displayed high and selective antifungal and/or trypanocidal activities (Godinho et al. 2013). *Penicillium steckii*, obtained

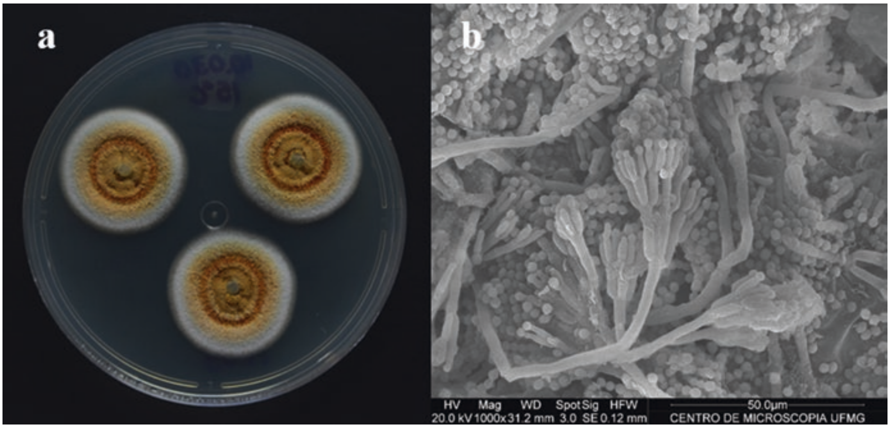

Fig. 1.5 (**a**) Colonies and (**b**) scanning electron microscopic images of the asexual reproductive structures of *Penicillium* sp. isolated from Antarctica. (Photos Credits: LH Rosa)

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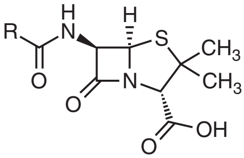

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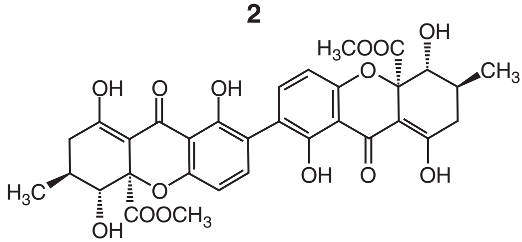

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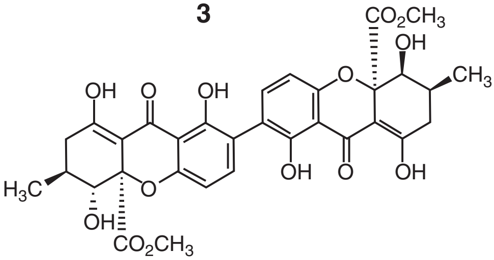

Fig. 1.6 Chemical structures of (**1**) penicillin, (**2**) secalonic acid D, and (**3**) secalonic acid

from the Antarctic macroalgae *Monostroma hariotti*, was reported as a producer of compounds with antiviral activity against yellow fever virus (Furbino et al. 2014). Extracts of different wild and pristine isolates of *A. sydowii*, *P. allii-sativi*, *P. brevicompactum*, *P. chrysogenum*, and *P. rubens* displayed antiviral, antimicrobial (antibacterial and antifungal), anticancer, antiprotozoal, and herbicidal activities, with equal or greater activity compared to control drugs (Godinho et al. 2015). The bioactive extracts of these fungi were examined by ^{1}H NMR spectroscopy, and the presence of highly functionalised secondary metabolites was found as indicated by

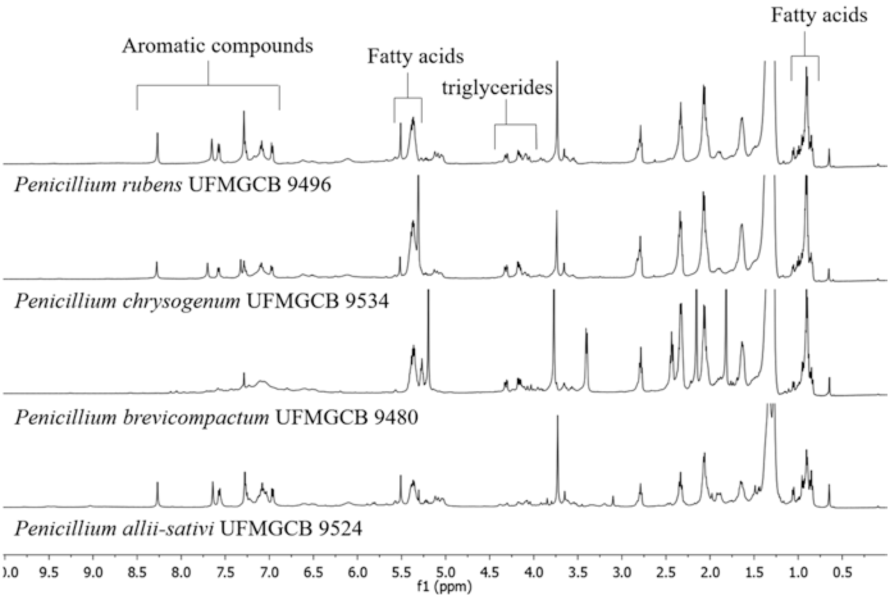

Fig. 1.7 ^{1}H NMR spectrum (500 MHz in $CDCl_3$) of representative crude extracts from wild *Penicillium* sp. isolated from soil of continental Antarctica. Labels indicate regions indicative of protons belonging to specific compounds

the presence of protons in the aromatic and olefinic regions (Fig. 1.7). *Penicillium* spp. are well known to be cosmopolitan, and some of them are abundant and adapted to the extreme conditions of Antarctica. *Penicillium* species are known to produce important bioactive compounds; however, few Antarctica *Penicillium* have been investigated at chemical level.

The number of bioactive compounds identified from strains of Antarctic fungi is increasing. Li et al. (2008) isolated geomycins B and C from *Pseudogymnoascus* sp., obtained from Antarctic soil that displayed antifungal activity against *A. fumigatus* and antibacterial activity against *S. aureus*, *Escherichia coli*, and *Streptococcus pneumonia*. *Pseudogymnoascus pannorum* from leaf litter produces pannomycin (Fig. 1.8), a cis-decalin secondary metabolite with potential antibacterial activity against *S. aureus* (Parish et al. 2009).

The compounds (pyrrolo[1,2-a]pyrazine-1,4-dione, hexahydro-3-(2-methylpropyl) and pyrrolo[1,2-a]pyrazine-1,4-dione, hexahydro-3-(phenylmethyl)) produced by *Mortierella alpina* strains and recovered from the Antarctic moss *Schistidium antarctici* displayed strong antibacterial activity against *E. coli*, *Pseudomonas aeruginosa*, and *Enterococcus faecalis* with low MIC values (Melo et al. 2014). The Antarctic soil fungus *Aspergillus ochraceopetaliformis* produced the antiviral secondary metabolites ochraceopone A, isoasteltoxin, and asteltoxin (Fig. 1.9) with activities against the H1N1 and H3N2 influenza viruses (Wang et al. 2016). Liu et al. (2019) isolated a secondary compound from *Penicillium crus-*

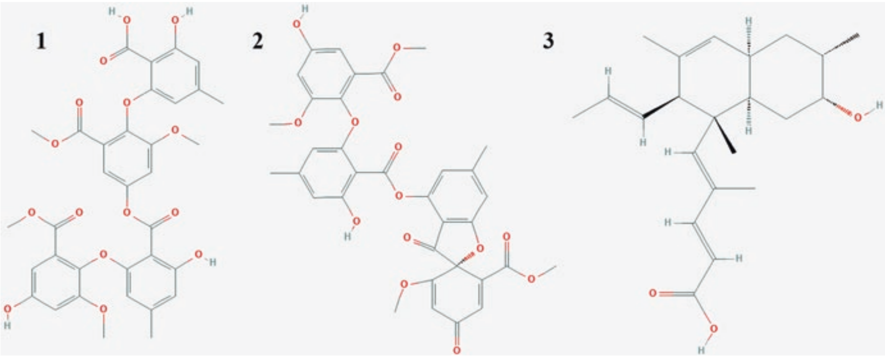

Fig. 1.8 Bioactive compounds (**1**) geomycin B, (**2**) geomycin C, and (**3**) pannomycin produced by *Pseudogymnoascus* species from Antarctica

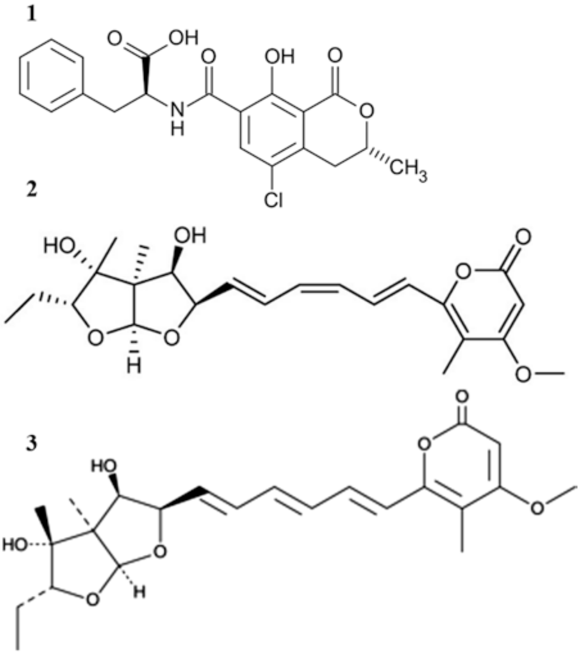

Fig. 1.9 Antiviral secondary metabolites (**1**) ochraceopone A, (**2**) isoasteltoxin, and (**3**) asteltoxin produced by the Antarctic soil fungus *Aspergillus ochraceopetaliformis*

tosum, found in Antarctic marine sediments, that was a new diketopiperazine showing cytotoxicity towards K562 human cancer cells. Lin et al. (2014) purified, from a crude extract of Antarctic deep-sea fungus *Penicillium* sp., the cytotoxic compounds eremophilane-type sesquiterpene and eremofortine C (Fig. 1.10), which exhibited cytotoxicity activities against HL-60 human cells with IC_{50} values of 45.8 and, 28.3 μM, respectively.

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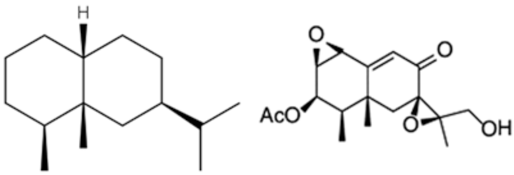

Fig. 1.10 Eremophilane-type (**1**) sesquiterpene and (**2**) eremofortine C cytotoxic compounds produced by *Penicillium* sp.

1.4 Conclusions and Perspectives

Recently, interest in studying the fungal communities from different Antarctic environments has increased. Published data have revealed the presence of fungi in all of the studied substrate/host microhabitats, demonstrating that fungi may occur in virtually all regions of Antarctica. Additionally, all of the studies conducted to date demonstrate that Antarctic fungal diversity is relatively high, which is remarkable considering the different extreme conditions to which they are constantly exposed. Antarctic fungal assemblages are predominantly composed of cosmopolitan cold-adapted taxa, but many endemic species have been newly described, suggesting that Antarctica remains yet to be fully characterised source of fungal and microbial diversity. Different Antarctic fungal assemblages fit a variety of ecological niches and roles, such as mutualists, decomposers, or pathogens of plants and animals. Additionally, several Antarctic fungi can produce secondary metabolites with various biological activities. These fungi represent potential biological "factories" that can produce compounds with great potential for direct use in medicine and agriculture or as prototypical molecules that can be chemically modified for pharmaceutical and agrochemical applications.

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