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Review

Marine pharmacology in 2005–2006: Antitumour and cytotoxic compounds

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ABSTRACT

During 2005 and 2006, marine pharmacology research directed towards the discovery and development of novel antitumour agents was reported in 171 peer-reviewed articles. The purpose of this article is to present a structured review of the antitumour and cytotoxic properties of 136 marine natural products, many of which are novel compounds that belong to diverse structural classes, including polyketides, terpenes, steroids and peptides. The organisms yielding these bioactive marine compounds included invertebrate animals, algae, fungi and bacteria. Antitumour pharmacological studies were conducted with 42 structurally defined marine natural products in a number of experimental and clinical models which further defined their mechanisms of action. Particularly potent *in vitro* cytotoxicity data generated with murine and human tumour cell lines were reported for 94 novel marine chemicals with as yet undetermined mechanisms of action. Noteworthy is the fact that marine anticancer research was sustained by a global collaborative effort, involving researchers from Australia, Belgium, Benin, Brazil, Canada, China, Egypt, France, Germany, India, Indonesia, Italy, Japan, Mexico, the Netherlands, New Zealand, Panama, the Philippines, Slovenia, South Korea, Spain, Sweden, Taiwan, Thailand, United Kingdom (UK) and the United States of America (USA). Finally, this 2005–2006 overview of the marine pharmacology literature highlights the fact that the discovery of novel marine antitumour agents continued at the same active pace as during 1998–2004.

1. Introduction

This article reviews the 2005–2006 research literature in the field of marine antitumour pharmacology using a format similar to the one used in our previous five reports, which covered 1998–2004.[1–5] The pharmacology of marine compounds with anthelmintic, antibacterial, anticoagulant, antidiabetic, antifungal, anti-inflammatory, antimalarial, antiplatelet, antiprotozoal, antituberculosis and antiviral activities, and those affecting the cardiovascular and nervous systems, and other miscellaneous mechanisms of action has been reviewed elsewhere.[6–10]

Consistent with our previous five reviews, only those articles reporting on antitumour pharmacology or cytotoxicity of marine compounds with well-defined chemical structures (Figs. 1 and 2) were included in the present review, and are presented in alphabetical order in Tables 1 or 2. The literature reporting novel information on the preclinical

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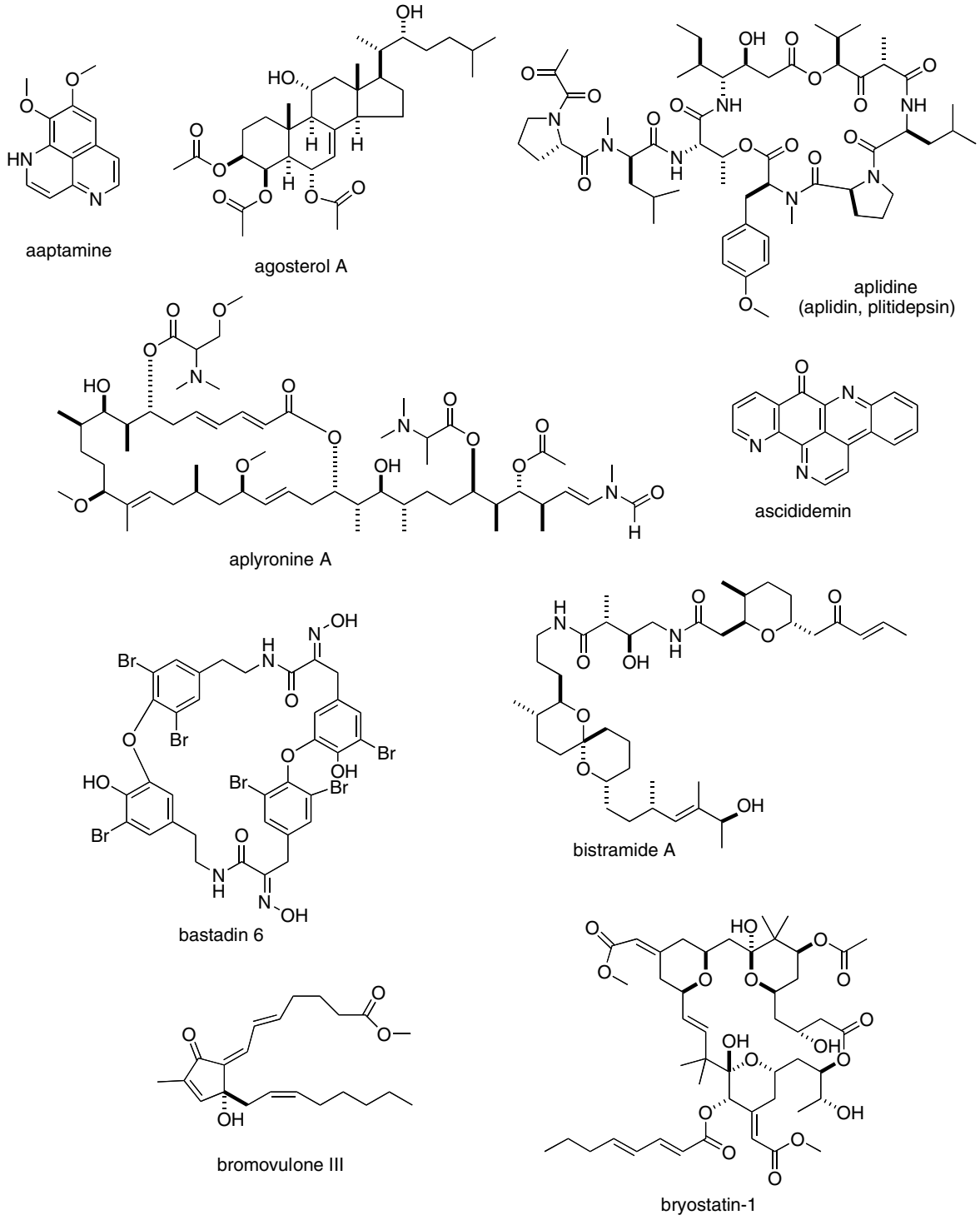


Fig. 1 – Structures of marine natural products reported in 2005 and 2006 with established mechanisms of action.

and/or clinical pharmacology of marine chemicals with previously *determined* mechanisms of action has been summarised in Table 1, and is further discussed in the text of this review. On the other hand, reports on novel marine chemicals, which demonstrated significant cytotoxicity but with as yet *undetermined* mechanisms of action, are shown in Table 2. With few exceptions, studies on the preclinical antitumour pharmacology of synthetic analogues of marine metabolites as well as reports on research with marine extracts or as yet structurally *uncharacterised* marine chemicals are not included in this review.

2. 2005–2006. Antitumour pharmacology of marine natural products with established mechanisms of action

Table 1 summarises novel mechanism of action research from preclinical studies of 42 marine compounds (selected struc-

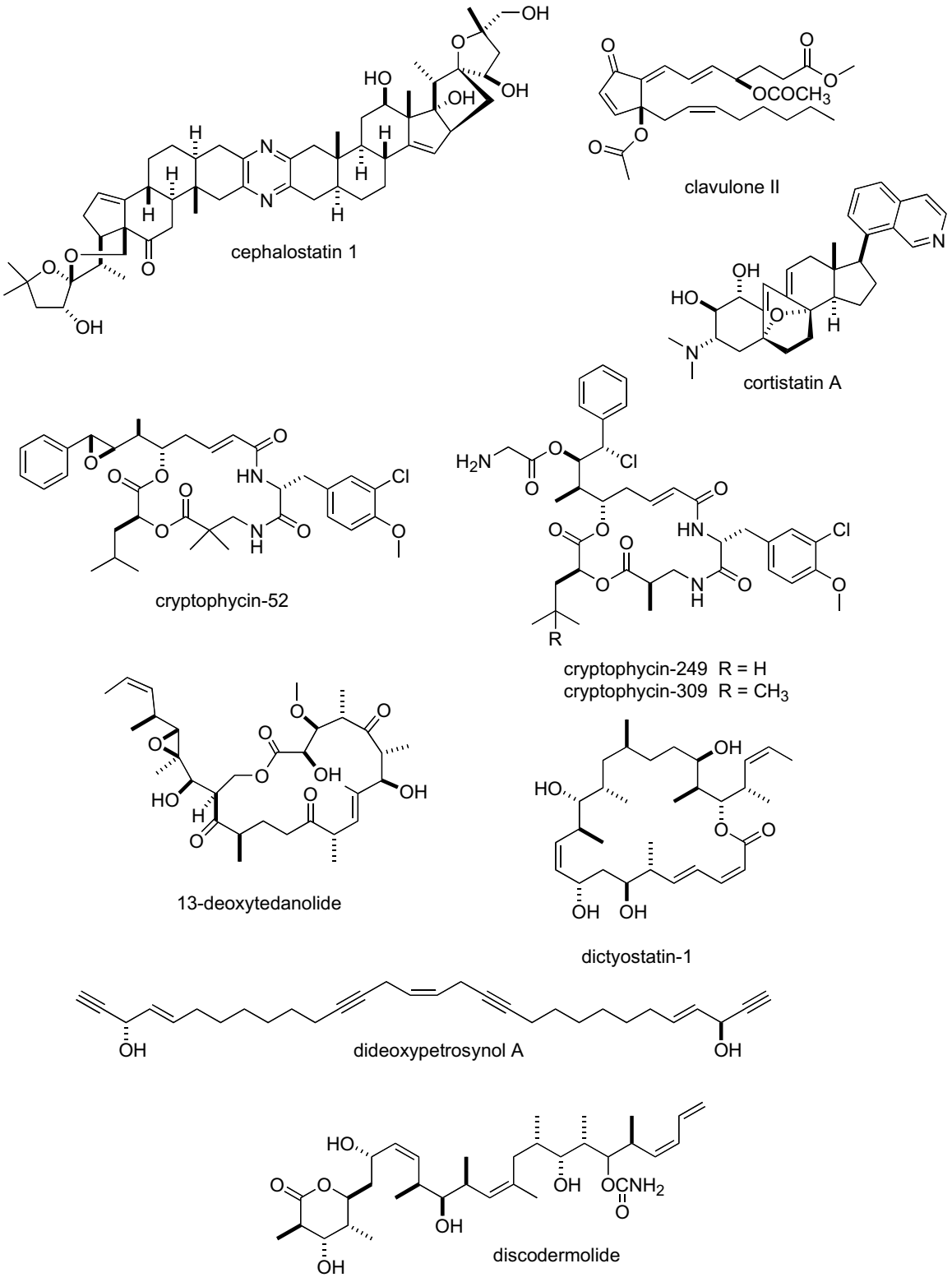
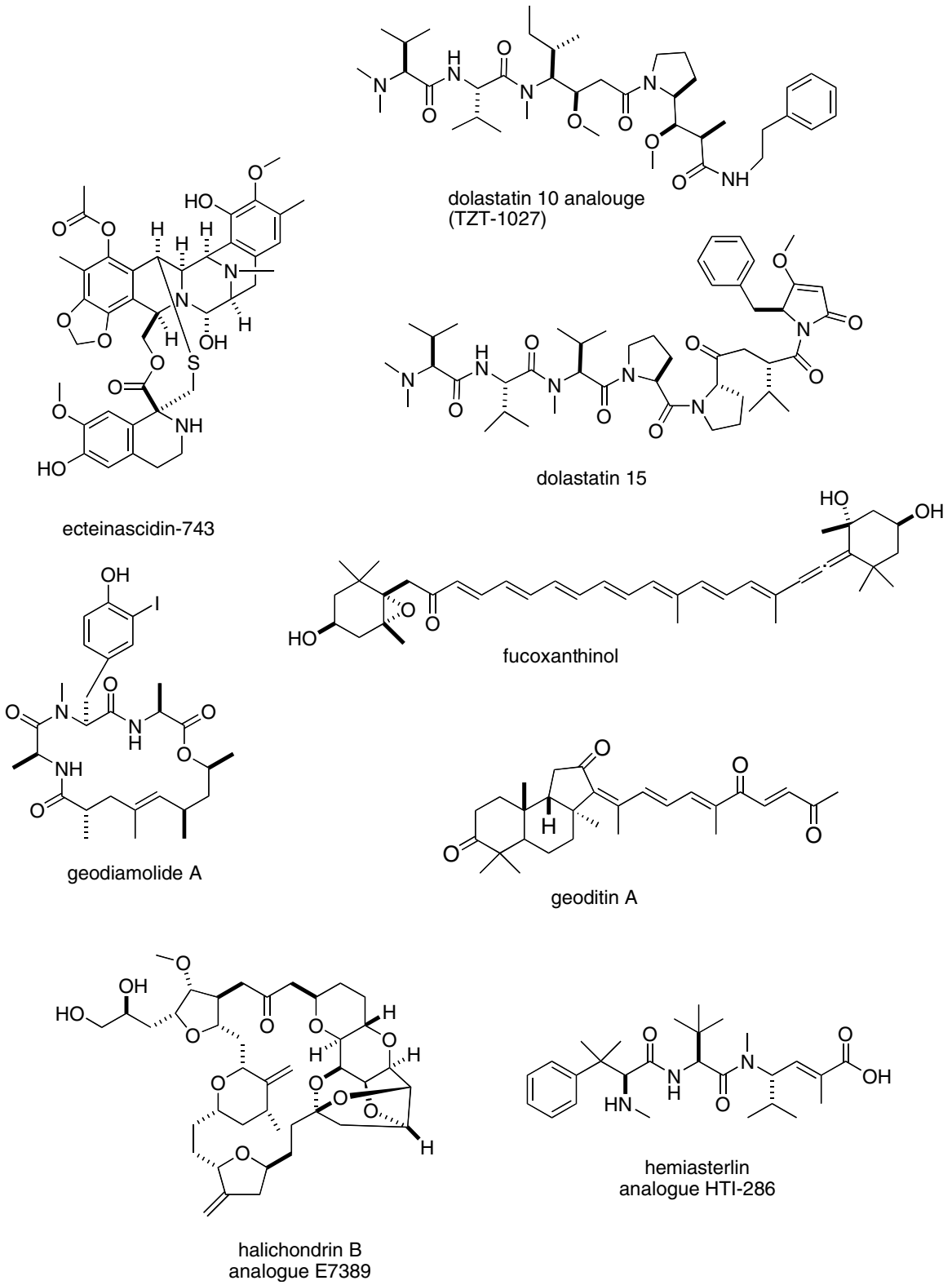


Fig. 1 – (*continued*)

tures are shown in Fig. 1). Reports on clinical trials with some of these marine compounds are excluded from Table 1, but discussed in this section of the article.

New information was published during 2005–2006 on the preclinical and clinical pharmacology of 24 marine compounds which we have previously reviewed:[1–5] agosterol A, aplidine, ascididemin, auristatin, bistramide A, bromovulone III, bryostatin-1, cephalostatin-1, cryptophycins, dictyostatin-1, didemnin B, dideoxypetrosynol A, discodermolide, dolastatins, ecteinascidin-743, fascaplysin, halichondrin B, hemiasterlin, jasplakinolide, kahalalide F, lamellarin D, pateamine A, peloruside A and psammaplin A.



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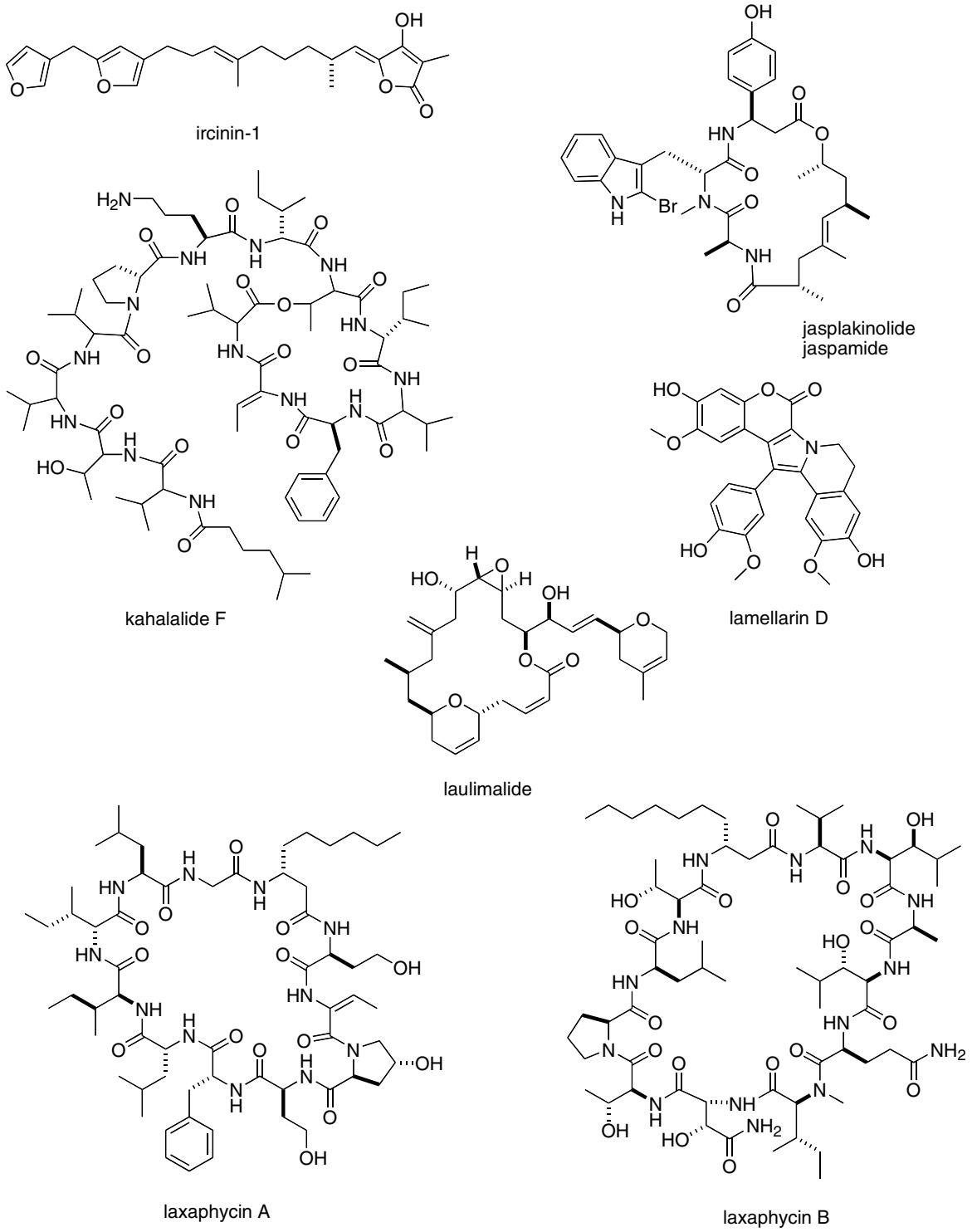
One study was published on the preclinical pharmacology of **agosterol A**, a polyhydroxylated sterol acetate isolated from the marine sponge *Spongia* sp. Ren and colleagues[11] determined the functional role of intracellular loops (ICL) on the 190 kDa human membrane multidrug resistance protein 1 (MRP1), a transporter in non-P-glycoprotein-mediated multidrug resistance in tumour cells. Interestingly, mutations of the ICL5 or ICL7 domains directly affected ATP and azido agosterol A binding to MRP1, demonstrating the role of both ICL domains on the drug-binding properties of MRP1 and its concomitant drug transporter function.



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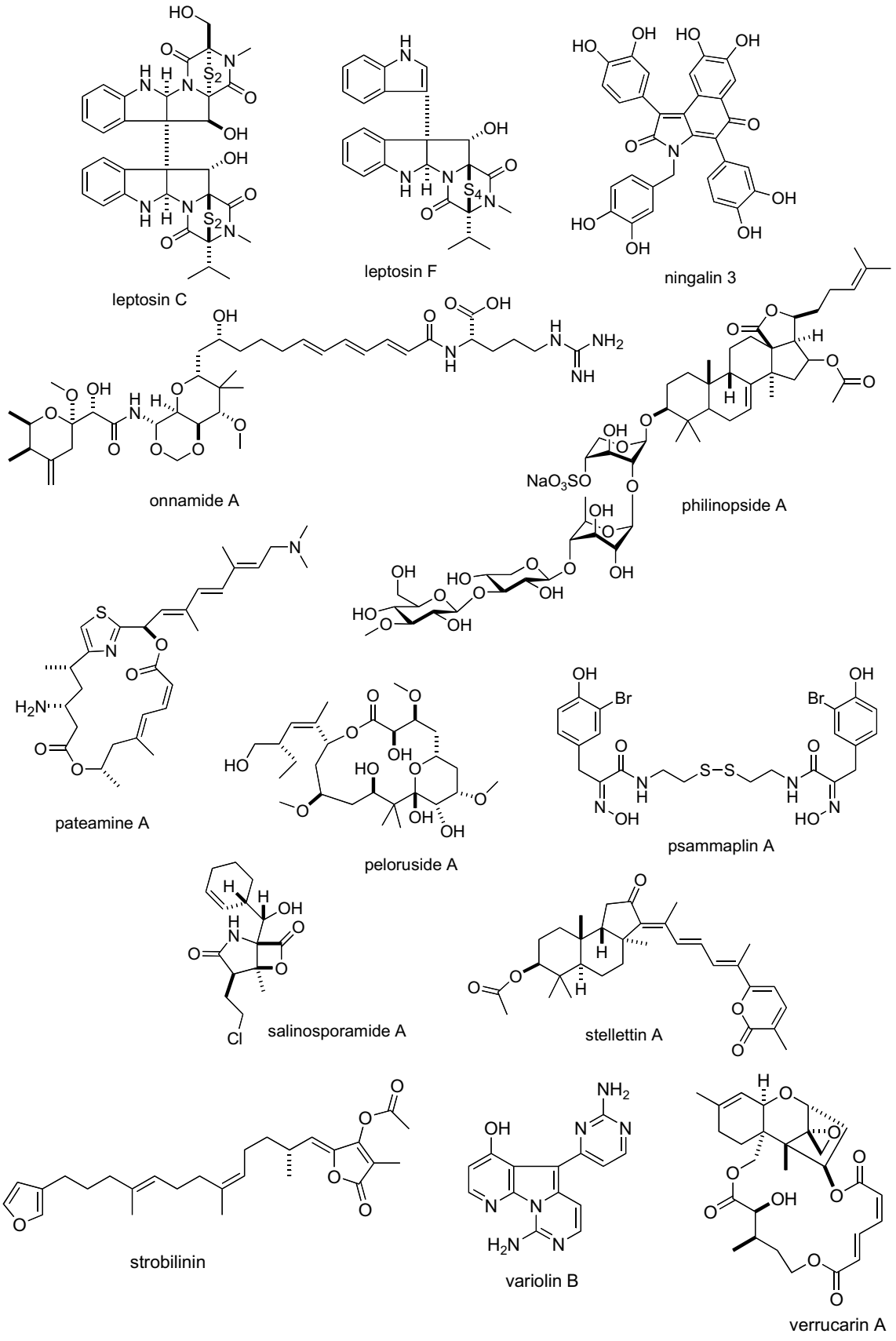
Research on the cyclic depsipeptide **aplidine**, a second-generation didemnin analogue also known as aplidin or dehydrodidemnin B, and isolated from the Mediterranean marine tunicate *Aplidium albicans* continued at an active pace. Seven preclinical studies, which characterised the cellular and molecular pharmacology of aplidine, and two clinical articles were published during 2005–2006. Taddei and colleague[12] demonstrated that aplidine's cytotoxic activity in NIH3T3 cells involved the production of mitochondrial reactive oxygen species that induced oxidation and inactivation of low molecular weight protein–tyrosine phosphatase activity, an enzyme that appears to play a role in both tumour onset and development. Bravo and colleagues[13] investigated the actions of aplidine in human thyroid cancer cells. Aplidine blocked *in vitro* cell progression into the G1 phase of the cell cycle, with markedly reduced levels of cyclin D1, cdk4 and p21 protein levels, at plasma concentrations similar to those observed *in vivo* in Phase I/II clinical studies. Biscardi and



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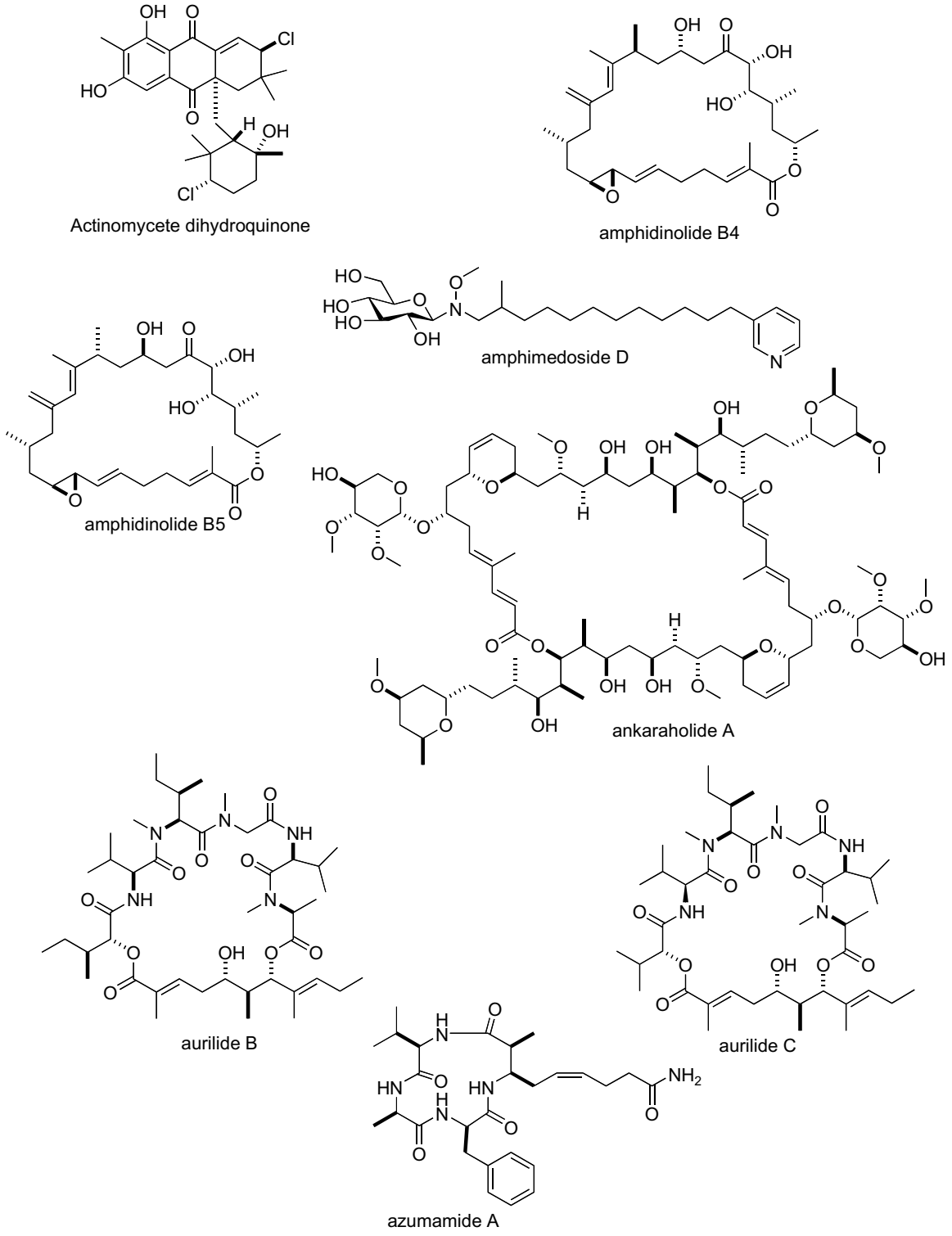
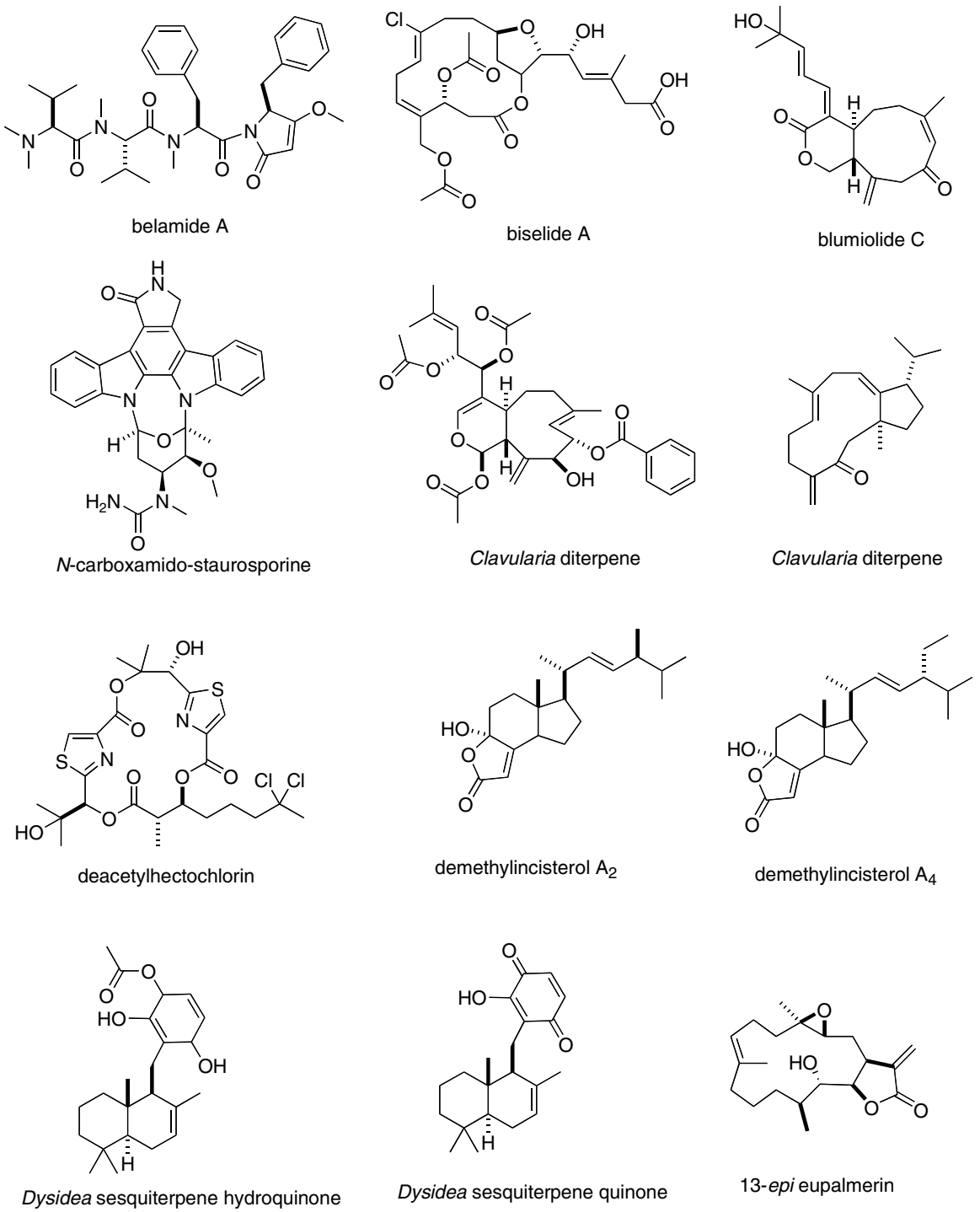


Fig. 2 – Structures of new marine natural products reported in 2005 and 2006 with undetermined mechanisms of action.

colleagues[14] confirmed aplidine's cytotoxic and apoptotic activity in three human myeloid leukaemia cell lines and in cells derived from patients with acute myeloid leukaemia. At *in vitro* concentrations achievable in patients (100 nM) aplidine induced G1 cell cycle arrest and vascular endothelial growth factor inhibition. Gajate and Mollinedo[15] discovered that the mechanism of aplidine-induced apoptosis involved a novel and potent cell-killing mechanism that required Fas activation and clustering of additional death receptors, membrane-bound FasL and downstream signalling molecules into 'aggregated lipid rafts' through a cytoskeleton-mediated process. The observation that aplidine was rapidly incorporated into lipid rafts highlighted the significance of these lipid aggregates in the regulation of apoptosis and cancer



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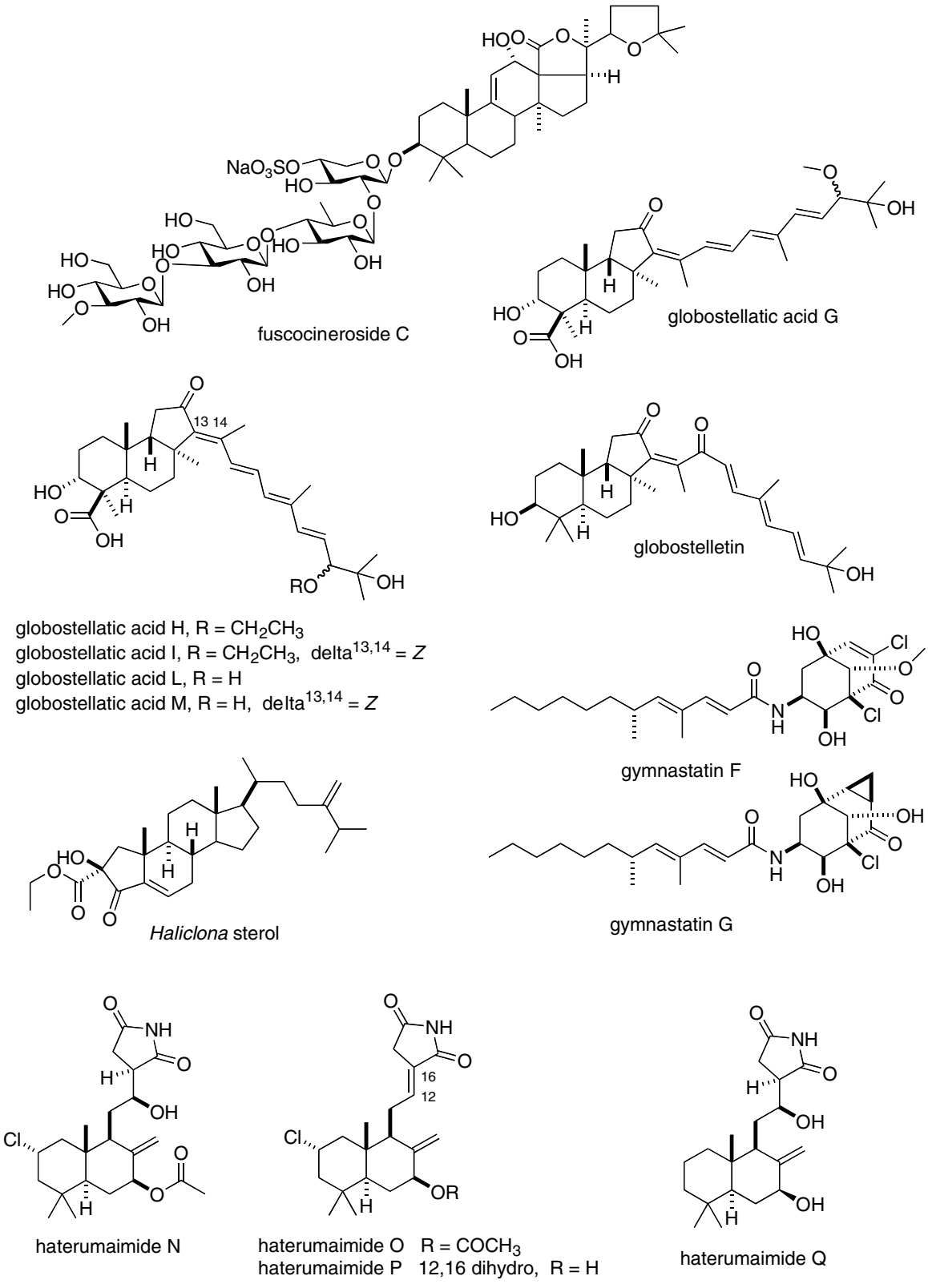
chemotherapy. Tognon and colleagues[16] found that aplidine-induced resistance in a human ovarian cancer cell line over a period of several months, was related to the expression of the multidrug transporter Pgp, 'potentially useful pharmacological information' that may have clinical relevance. Gonzalez-Santiago and colleagues[17] examined the molecular mechanism of apoptosis induction by aplidine in human breast cancer cells. They demonstrated that aplidine disrupted glutathione homeostasis by increasing the ratio of oxidised to reduced forms, thus leading to increases in reactive oxygen species and oxidative stress. Furthermore, aplidine caused rapid activation of Rac1 small GTPase resulting in Jun *N*-terminal kinase (JNK) phosphorylation, which was considered critical for aplidine-induced apoptosis. There was a concomitant decrease of MKP-1 phosphatase, an enzyme overexpressed in human breast cancer and considered a 'viable target for therapeutic intervention' by enabling the expression of pro-apoptotic activity of JNK. Straight and colleagues[18] tested the hypothesis that aplidine would reduce the growth of anaplastic thyroid xenografts in mice. Interest-



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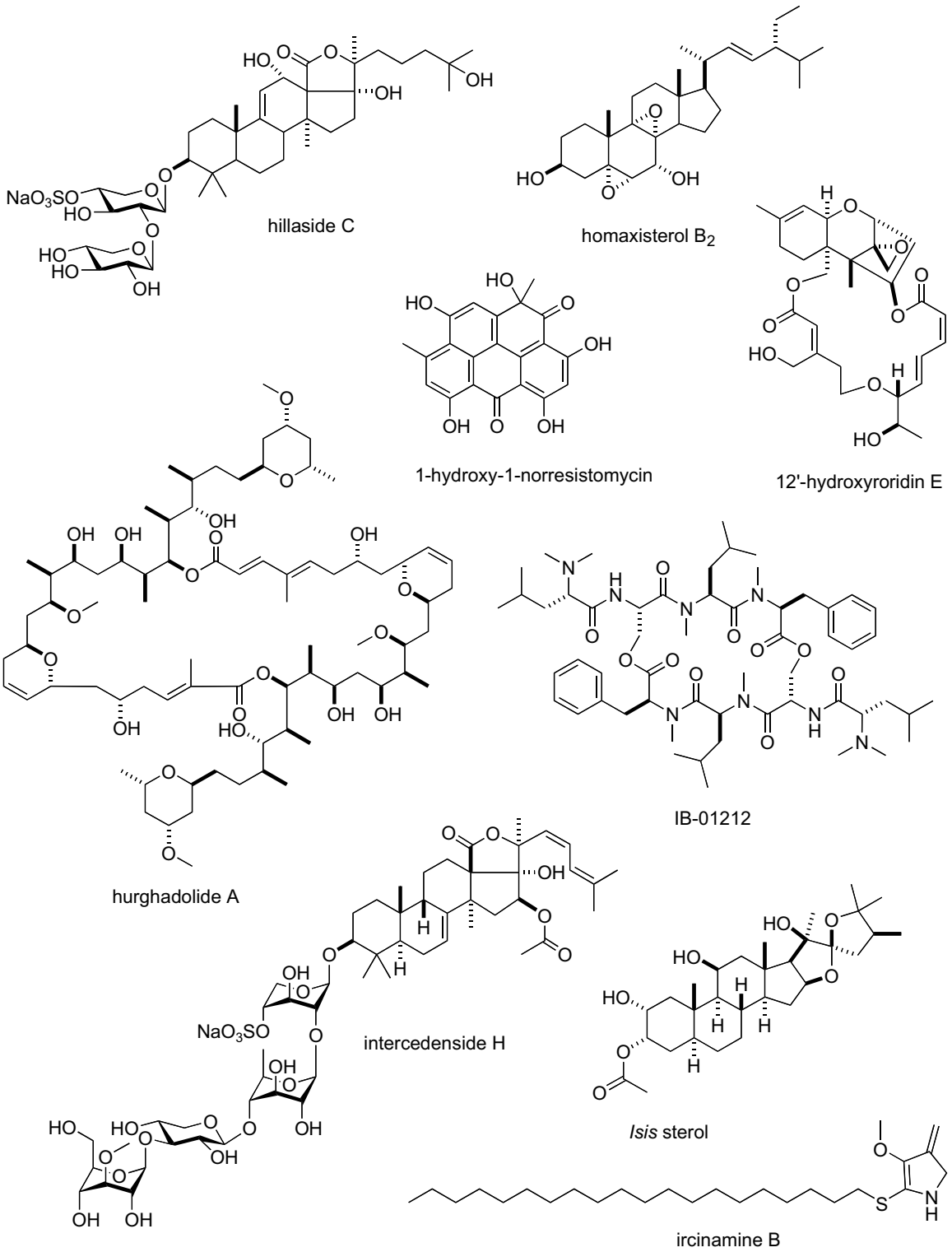
ingly, aplidine reduced tumour growth as well as the expression of 16 of 20 angiogenic genes investigated, suggesting that aplidine might be an effective adjunctive therapy for anaplastic thyroid cancer, an aggressive and highly lethal cancer.

Two Phase I trials evaluated the clinical pharmacology of aplidine during 2005–2006. Faivre and colleagues[19] completed a Phase I and pharmacokinetic study on 67 patients who received aplidine as a 24-h intravenous (i.v.) infusion for



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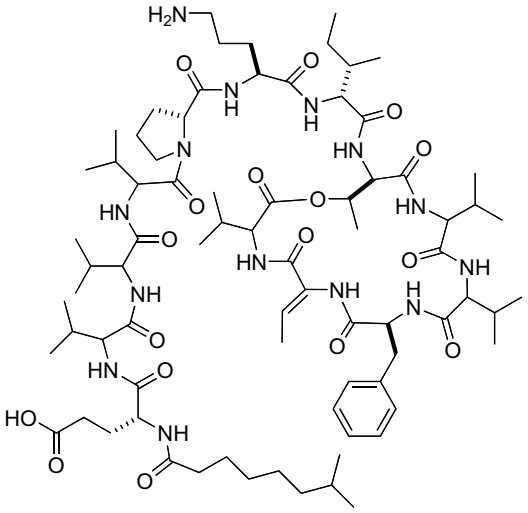
advanced malignancies. Although muscle toxicity was noted as dose limiting at doses $\geqslant 5$ mg/m^2, aplidine induced minor responses and tumour stabilisations in eight patients, and clinical benefit in six patients with endocrine tumours. Maroun and colleagues[20] conducted a Phase I study in 37 patients with refractory solid tumours in which a 1-h infusion of aplidine was given for 5 d every 3 weeks. Even though the regimen was well tolerated, only nine patients with progressive disease at study entry had stable disease, whilst two patients with non-small cell lung cancer and one with colorectal cancer evidenced minor responses.

A preclinical study by Guittat and colleagues[21] reported that **ascididemin**, a pyridoacridine alkaloid isolated from the marine sponge *Amphimedon* sp., inhibited telomerase



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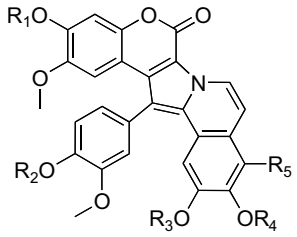

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lamellarin-*eta* R_1 = H, R_2 = Me, R_3 = Me, R_4 = Me, R_5 = H
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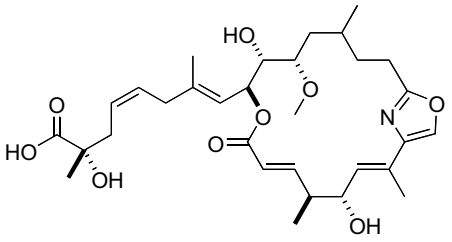

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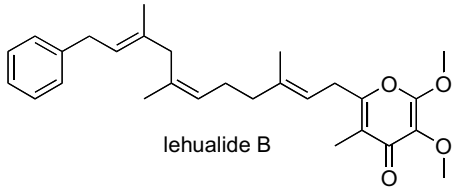

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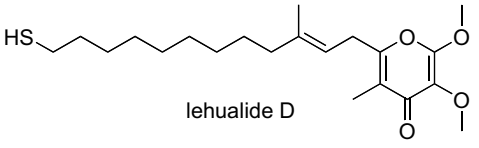

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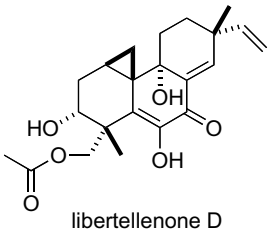

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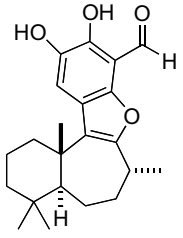

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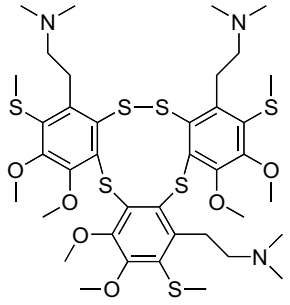

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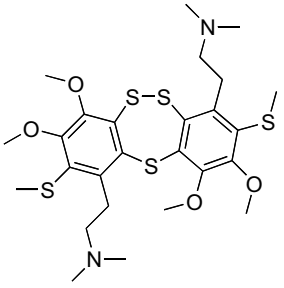
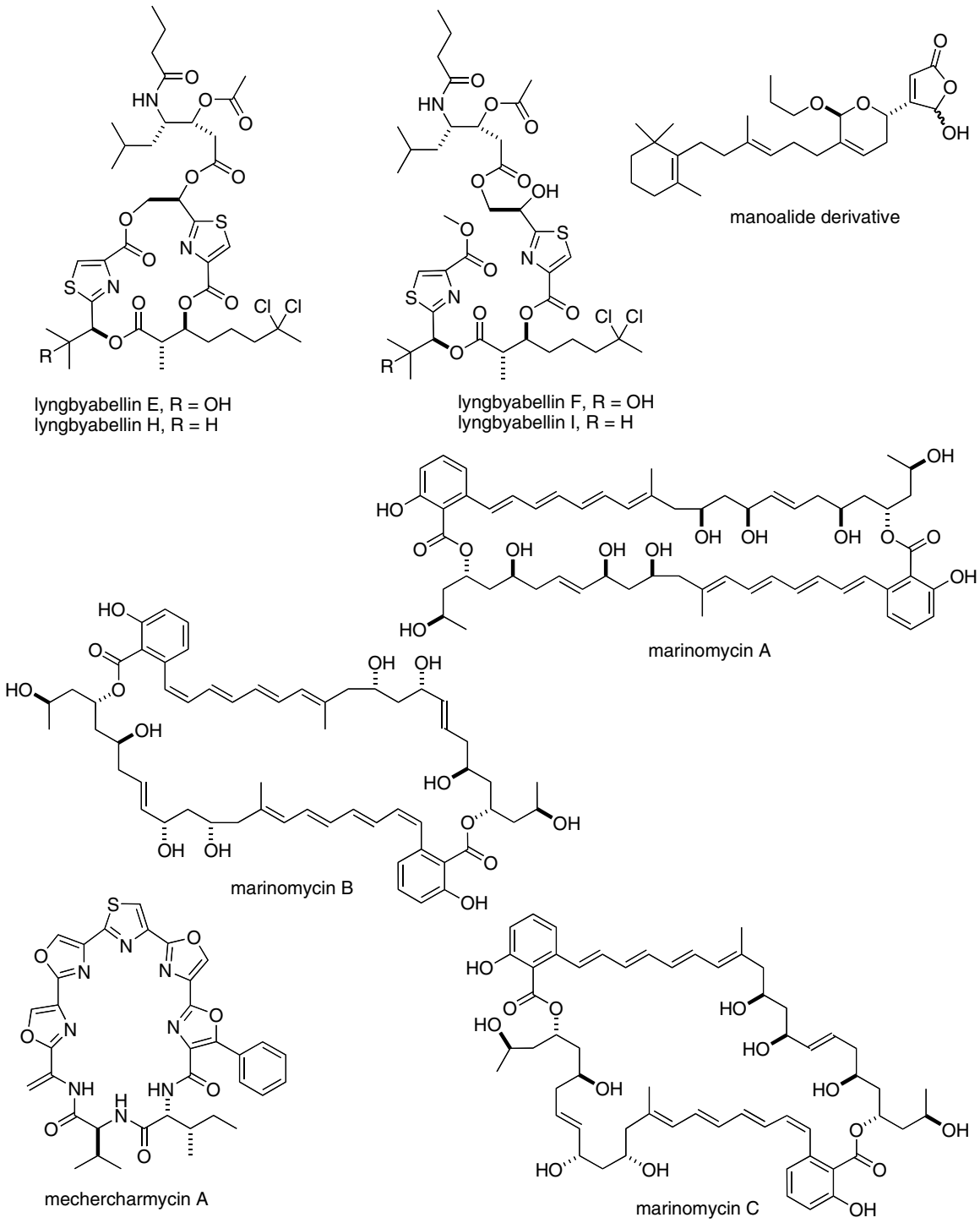


lissoclibadin 2

Fig. 2 – (*continued*)

function (IC_{50} = 87 μM) by preferentially binding to G-quadruplex DNA structures, thus potentially affecting telomere structure and cancer cell replication.

Five studies in 2005–2006 described the preclinical pharmacology of **auristatin,** a synthetic antitubulin agent related to the marine natural product dolastatin 10 (see below). Sutherland and colleagues[22] demonstrated that lysosomal trafficking and cysteine protease metabolism enabled the target-specific cellular cytotoxicity by valine-citrulline linked anti-CD 30-auristatin conjugates, which were previously shown by Sanderson and colleagues[23] to have the 'longest reported drug-linker half-life to date' in plasma and cell culture. Taken together these findings provide the basis for pronounced specificity and antitumour activity of anti-CD30 monoclonal antibody-monomethylauristatin E conjugates towards $CD30^+$ tumour cells. Using a similar antibody-drug conjugate approach, Ma and colleagues[24] evaluated the antitumour activity of auristatin-conjugated to a human monoclonal antibody to prostate-specific membrane antigen (PSMA), a membrane glycoprotein which is highly up-regulated in



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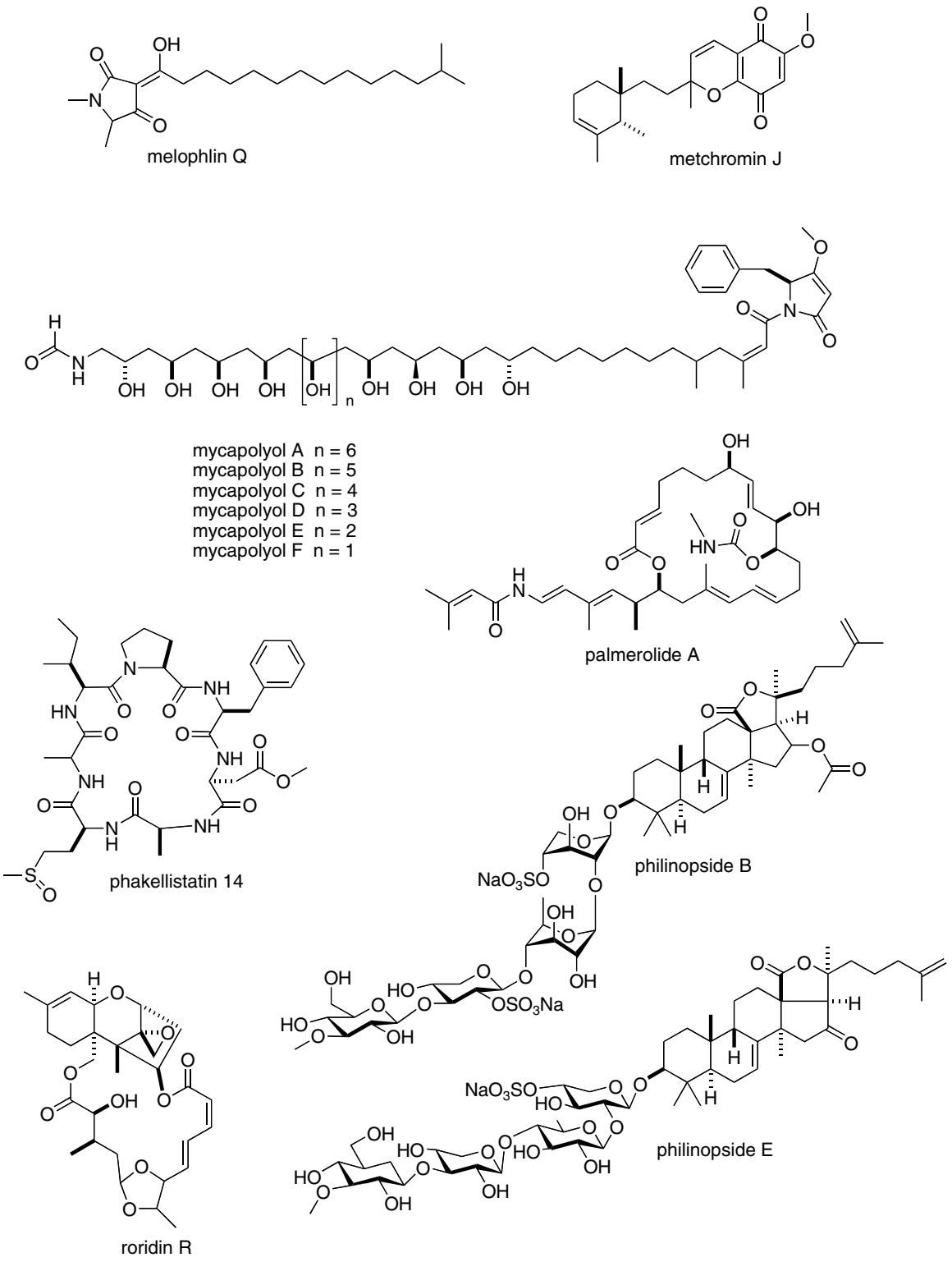
prostate cancer. The novel conjugate eliminated PSMA-expressing cells with picomolar efficiency *in vitro* as well showed therapeutic efficacy in a mouse xenograft model of androgen-independent human prostate cancer. These findings suggested that this approach merits further development as a molecularly targeted therapy of hormone-refractory prostate cancer, the second leading cause of death in men in the United States. Smith and colleagues[25] as well as Tse and colleagues,[26] reported encouraging *in vitro* and *in vivo* results with auristatin-containing antibody-drug conjugates to target melanoma cells expressing either melanotransferrin/p97 or glycoprotein NMB, respectively. Their studies indicated that these agents may provide a new type of selective and efficient treatment for late stage malignant melanoma, for which current therapeutic options are limited.

Two studies extended the preclinical pharmacology of **bistramide A**, a polyketide derivative isolated from the marine ascidian *Lissoclinum bistratum*. In a detailed mechanistic



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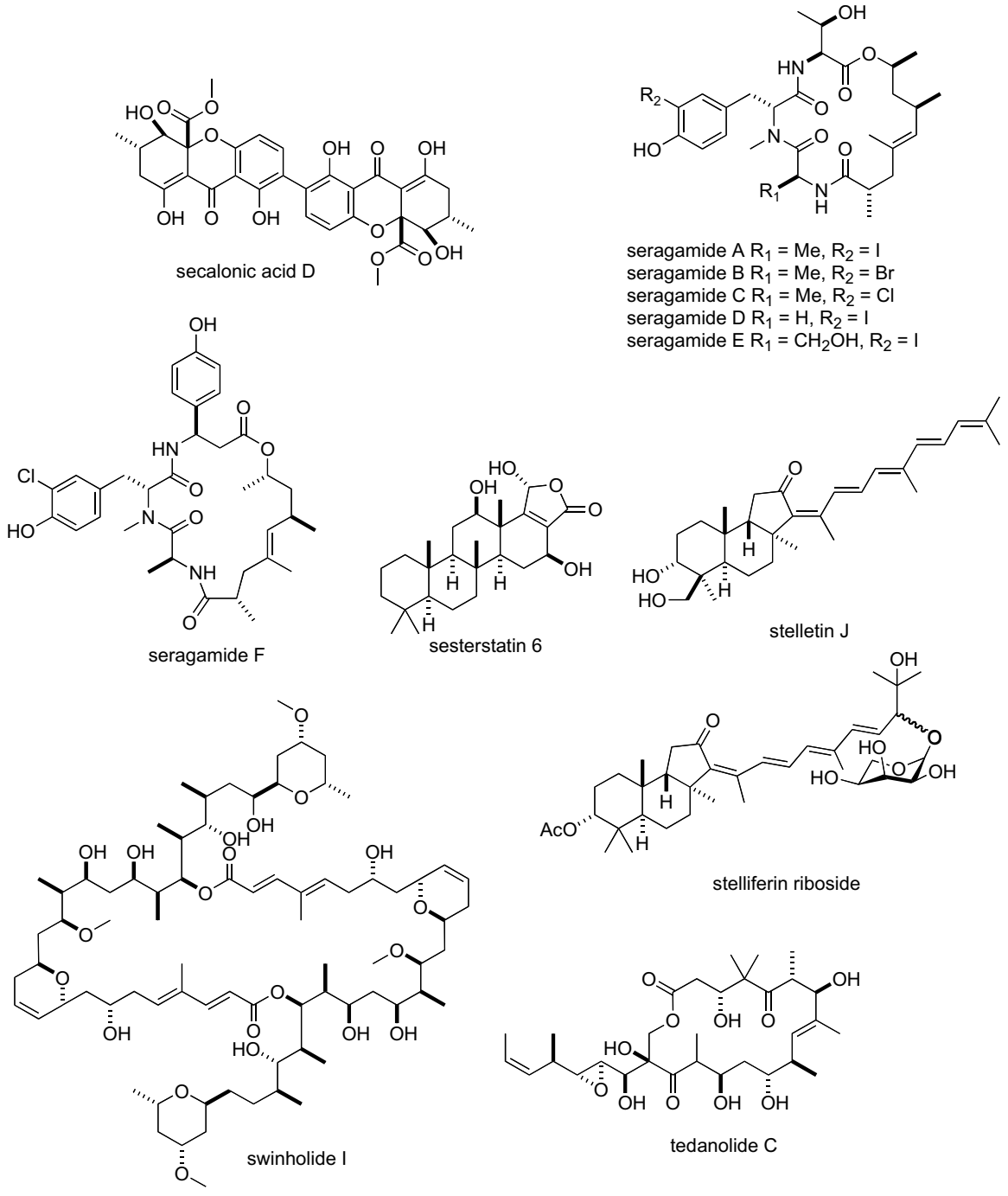
study Statsuk and colleagues[27] identified actin as the cellular receptor for bistramide A, and reported that this marine compound disrupted the actin cytoskeleton, depolymerised F-actin *in vitro* and bound directly to monomeric G-actin in a 1:1 ratio with a $K_d = 7$ nM. Furthermore, the discovery by Rizvi and colleagues[28] that bistramide A spans the entire deep binding cleft between actin's subdomains 1 and 3, whilst forming a network of extensive hydrogen-bonding contacts, has provided the required structural information for the rational development of novel bistramide analogues for studying the actin cytoskeleton and as potential therapeutic leads.



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Two preclinical studies were described for the cyclopentenone prostanoid **bromovulone III,** which was isolated from the soft coral *Clavularia viridis*. In 2005, Chiang and colleagues[29] reported that bromovulone III induced apoptosis in hepatocellular carcinoma cells through a mechanism that involved endoplasmic reticulum stress as well as activation of the transcription factor CHOP/GADD153 and caspase-12. Then in 2006, this same research group[30] reported that bromovulone III induced apoptosis in human hormone-resistant prostate cancer cells by a mechanism that required the rapid redistribution and clustering of Fas, as well as activation of the caspase-9/Bid/caspase-9 signalling cascades.

Several preclinical and clinical studies published during 2005–2006 extended the pharmacology of **bryostatin-1,** a macrocyclic lactone derived from the marine bryozoan *Bugula neritina* that continued to receive considerable attention in view of its demonstrated antineoplastic activity *in vitro* and *in vivo*. Five studies contributed new information on the molecular pharmacology of bryostatin-1 at both the cellular leval and the molecular level. Powell and Yin[31] discovered that overexpression of PKCε sensitised human prostate cancer cells to the induction of apoptosis by bryostatin-1, an observation that may have implications for therapy because overexpression of PKCε has been reported in human prostate

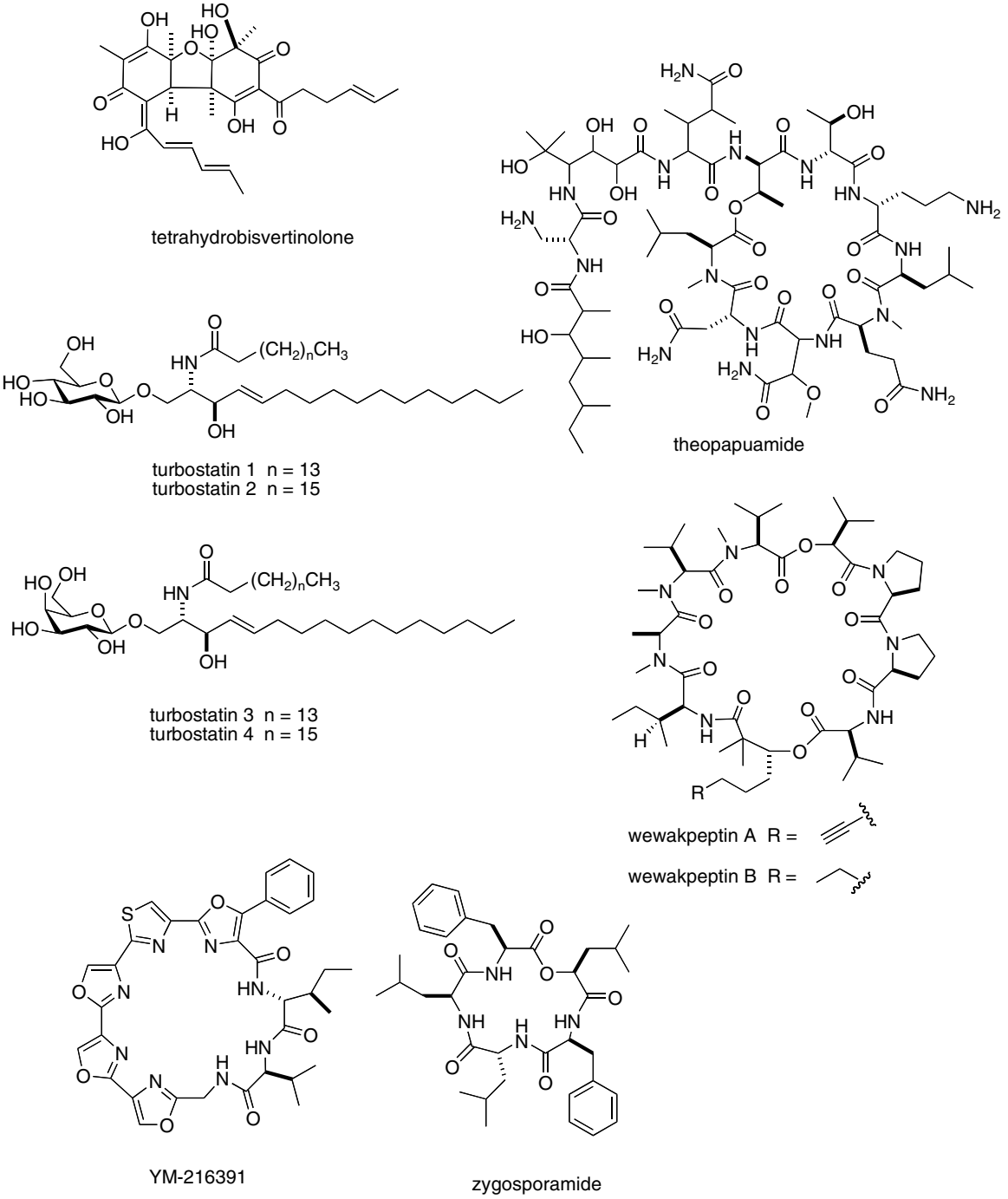

Fig. 2 – (*continued*)

cancer. Mohanty and colleagues[32] investigated bryostatin-1's influence on protein kinase Cδ in human cervical carcinoma HeLa cells and its cisplatin-resistant variants. The observation that modulation of PKCδ by bryostatin-1 enhanced sensitivity to cisplatin in both HeLa cells and cisplatin-resistant HeLa cells 'could be used to enhance cellular sensitivity to cisplatin' as well as to increase the molecular understanding of bryostatin-1's effect on PKCδ regulation. Interestingly, Choi and colleagues[33] also noted that bryostatin-1 down-regulation of PKCδ was associated with enhanced proliferation of a non-small cell lung cancer cell line. Taken together, these observations may help identify systems in which bryostatin-1 has a rational therapeutic application. Tuthill and colleagues[34] examined the effect of bryostatin-1 on the regulation and activation of mouse epidermal keratinocyte RasGRP1, an exchange factor for the Ras small GTPases which also activates three classic Ras proteins both *in vitro* and *in vivo*. These results support the hypothesis that non-PKC receptors are also involved in the molecular mechanism of action of bryostatin-1, and further the molecular understanding of the antitumour effects in the skin. Garcia and colleagues[35] demonstrated for the first time that bryostatin-1

Table 1 – 2005–2006 Antitumour pharmacology of marine natural products with established mechanisms of action

Compound	Organism	Chemistry	Experimental or clinical model[a]	Mechanism of action[b]	Country[c]	Refs.
Aaptamine	Sponge	Alkaloid	HU osteosarcoma cell line	Induction of p21 gene and G2/M cell cycle arrest	INDO, JAPN	90
Agosterol A	Sponge	Steroid	Insect cell expression of MRP1 wild type or mutants	[I^{125}]-azido agosterol A binding to MRP1 abolished by ICL5 and ICL7 domain mutations	JAPN	11
Alkylpyridinium salts	Sponge	Alkaloid	HU adenocarcinoma cell lines	Induction of apoptosis and reduced cell adhesion	ITA, SLO	91
Aplidine	Ascidian	Depsipeptide	MU fibroblast cell line	Oxidation and inactivation of low molecular weight-protein tyrosine phosphatase activity	ITA, SPA	12
			HU thyroid cancer cells	Cytostatic, blocks G1 phase of cell cycle, reduction of cyclin D1, cdk4 and p21 protein levels	SPA	13
			Fas-positive and deficient HU leukaemia cell line	Apoptosis promoted by concentration of death receptors, adaptors and signalling molecules in lipid rafts	SPA	15
			HU-breast cancer cell line	JNK-dependent apoptosis affected by glutathione homeostasis, Rac1 GTPase activation and MKP-1 phosphatase	GER, SPA	17
Aplyronine A	Sea hare	Macrolide	Synchrotron radiation method	Binding to hydrophobic cleft in actin molecule involving trimethylserine moiety	JAPN	92
Ascididemin	Ascidian	Alkaloid	Assessment of DNA binding	Enhanced binding to telomeric DNA quadruplex	FRA, BEL	21
Bastadin 6	Sponge	Alkaloid	HU epidermoid carcinoma and leukaemia cell lines	Inhibition of angiogenesis *in vitro* and *in vivo* involves apoptosis	JAPN	93
Bistramide A	Ascidian	Polyketide		Depolymerisation of F-actin, inhibition of G-actin polymerisation, binding to actin subdomains 1 and 3	USA	27,28
Bromovulone III	Soft coral	Prostanoid	HU hepatocarcinoma cell line	Apoptosis and endoplasmic reticulum stress, activation of caspase-12	TAIW	29
			Hormone-resistant prostate cancer cell line	Apoptosis *via* induction of Fas clustering and caspase-8/Bid/caspase-9 cascade	TAIW	30
Bryostatin-1	Bryozoan	Macrolide	HU prostate cancer cell lines	Apoptosis induction enhanced by PKCε overexpression	USA	31
			HU cervical carcinoma cells	Enhanced cisplatin sensitivity associated to PKCδ regulation	USA	32
			HU monocytic cell lines	Transcriptional and posttranscriptional regulation of IFNγ receptor 2	USA	35
			MU keratinocytes	Modulation of RasGRP1 receptor	USA	34
Cephalostatin 1	Tube worm	Steroid	HU Jurkat T cell line	Bcl-2 hyperphosphorylation independent of M-phase arrest and DNA damage	GER	39
			HU Jurkat T cell line	Apoptosis induction *via* ER stress response signalling and caspase -4 and -9 activations	USA, GER	40
Clavulone II	Soft coral	Prostanoid	HU leukaemia cell line	G1 cell cycle arrest and apoptosis	TAIW	94
Cortistatin A	Sponge	Alkaloid	HU normal and tumour cell lines	Selective inhibition of angiogenesis	JAPN, INDO	95
Cryptophycins 52, 53, 249 and 309	Bacterium	Depsipeptide	HU and MU glutathione metabolism	Cytosolic GSTs metabolise C52 and C53	USA	41
13-Deoxytedanolide	Sponge	Macrolide	Ribosomal binding and polypeptide synthesis	Binding to 80S ribosome and 60S subunit; inhibition of polypeptide elongation	JAPN	96
Dictyostatin-1	Sponge	Macrolide	HU ovarian adenocarcinoma cell lines	Tubulin binding, taxoid site binding and antiproliferative effects comparable to discodermolide	USA	44
Dideoxypetrosynol A	Sponge	Polyacetylene fatty acid	HU monocytic leukaemia	Induction of Cdk inhibitor p16 expression and down-regulation of pRB phosphorylation	S. KOR	46
Discodermolide	Sponge	Polyketide	Direct photoaffinity labelling	Binding to amino acid residues 305-359 in the S9-S10 loop in β-tubulin	USA	47
			HU tumour cell lines	Inhibition of hypoxia-inducible factor 1α	SPA, USA	48
			HU lung, colon, breast and cervical carcinoma	Induction of accelerated senescence	USA	49

Dolastatins 10 and 15	Mollusk	Peptide	HU tumour panel and MU cell line	Antitumour action and DNA fragmentation time-dependent and less affected by P-gp	JAPN	52
Ecteinascidin-743 (ET-743)	Ascidian	Isoquinoline alkaloid	NIH 3T3 fibroblasts and HU hepatoma cell lines	Cell cycle promoters are selectively affected	ITA	62
			Lipo-, leio-, osteo- and chondrosarcoma cell lines	Up-regulation of 86 genes, down-regulation of 244 genes, cDNA microarray analysis with 6,700 cancer genes	SPA	69
			S. pombo yeast model system	ET-743 binding to Arg314 in a 46-amino acid region of DNA-binding domain of human nuclease FEN-1	SPA	66
Fucoxanthinol	Ascidian	Carotenoid	HU leukaemia, breast and colon tumour cell lines	Induction of apoptosis and decrease in Bcl-2 protein	JAPN	97
Geodiamolides	Sponge	Peptide	HU breast cancer cell lines	Disorganisation of actin filaments	BRA, JAPN	98
Geoditin A	Sponge	Triterpene	HU leukaemia cell line	Reactive oxygen species generation and caspase-3 mediated apoptosis	CHI	99
Halichondrin B analogue E7389	Sponge/ Synthetic	Macrolide derivative	HU breast tumour cell line	Suppression of microtubule dynamics both *in vitro* and *in vivo*	USA	80
			HU tumour cell lines, molecular modelling	Proposed binding site on tubulin results in unstable, aberrant tubulin polymers	USA, NZEL	81
Hemiasterlin analogue HTI-286	Sponge/ synthetic	Tripeptide	Molecular docking experiments	Binding to specific residues in the β-tubulin	USA	82
Ircinin-1	Sponge	Sesterterpene	HU melanoma cell line	G1 phase inhibition and apoptosis induction	S. KOR	100
Jasplakinolide	Sponge	Depsipeptide	HU breast and lung cancer cell lines	Enhanced motility of A549 lung cancer cells but not MCF7 breast tumour cells	BEL	83
Kahalalide F	Mollusk	Depsipeptide	HU vulval, hepatic, colon and breast carcinoma cell lines	ErbB3 protein and PI3K-Akt pathway involved in necrosis induction	SPA,NETH	84
Lamellarin D	Mollusk	Alkaloid	HU and MU tumour cell lines	Apoptosis induced by effect on mitochondria at μM concentrations	FRA, SPA	86
Laxaphycins A and B	Bacterium	Cyclic peptides	HU lymphoblastic cell lines	Increased polyploidy by putative topoisomerase II alterations	FRA, BEN	101
Leptosins C and F	Fungus	Alkaloid	HU lymphoblastoid cell line	DNA topoisomerase I and II inhibition, apoptosis induction and Akt/PKB inactivation	JAPN	102
Ningalins	Ascidian/ synthetic	Alkaloid	HU leukaemia and breast cancer cell lines	Inhibition of PgP and MDR-reversing activity	USA	103
Onnamide A	Sponge	Polyketide	HU leukaemia cell line	Protein synthesis inhibition, activation of stress-activated protein kinases and apoptosis	JAPN	104
Pateamine A	Sponge	Macrolide	HU T cell leukaemia	Sequestration of RNA helicase elF4A inhibiting translation initiation	CAN, NZEL, USA	87
Peloruside A	Sponge	Macrolide	HU breast cancer cell line	Synergistic effect with taxoid site drugs but not with laulimalide	NZEL, UK, USA	88
Philinopside A	Sea cucumber	Saponin	HU adenocarcinoma cell lines	Inhibition of angiogenesis and receptor tyrosine kinases	CHI	105
Psammaplin A	Sponge	Alkaloid	HU tumour cell lines	Activation of PPARγ and apoptosis induction	USA	89
Salinosporamide A	Bacterium	Alkaloid	HU tumour cell lines	SAR studies revealed importance of chloroethyl group	USA	106
Stellettin A	Sponge	Triterpene	HU leukaemia cell line	Induction of oxidative stress and FasL-caspase-3 apoptotic pathway	CHI	107
Strobilinin–felixinin	Sponge	Sesterterpene	HU tumour cell line	Cell cycle S phase arrest and inhibition of topoisomerase I and pol α-primase	S.KOR	108
Variolin B	Sponge	Alkaloid	HU colon, leukaemia and ovarian cell lines	Inhibition of cyclin-dependent kinases and apoptosis induction	FRA, ITA, SPA	109
Verrucarin A	Fungus	Macrolide	HU leukaemia cell lines	Inhibition of MAP kinase, enhanced p38 and JNK phosphorylation	JAPN	110

a Experimental or clinical model: HU: human; MU; murine.
b Mechanism of action: SAR: Structure–activity relationship.
c Country: BEL: Belgium, BEN: Benin, BRA: Brazil, CAN: Canada, CHI: China, FRA: France, GER: Germany, INDO: Indonesia, ITA: Italy, JAPN: Japan, NETH: The Netherlands, NZEL: New Zealand, S.KOR: South Korea, SLO: Slovenia, SPA: Spain, TAIW: Taiwan, UK: United Kingdom.

Table 2 – 2005–2006 Antitumour pharmacology of marine natural products with undetermined mechanism of action

Compound	Organism	Chemistry	Preclinical tumour cell line model[a]	50% growth inhibition or cytotoxicity	Country[b]	Refs.
Actinomycete dihydroquinone	Bacterium	Terpene	HU	0.97 μg/ml	MEX, USA	127
Amphidinolides B4 and B5	Alga	Macrolide	HU and MU	0.1–4 ng/ml	JAPN	128
Amphimedoside D	Sponge	Alkaloid	MU	0.45 μg/ml	JAPN, NETH	129
Ankaraholides A and B	Bacterium	Macrolide	HU and MU	8.9–262 nM	USA	119
Aurilides B and C	Bacterium	Depsipeptide	HU and MU	0.01–0.13 μM	USA	130
Belamide A	Bacterium	Peptide	HU	0.74–1.6 μM	PAN, USA	131
Biselide A	Ascidian	Polyketide	HU	0.513–9.35 μg/ml	JPAN	132
Blumiolide C	Soft coral	Diterpene	HU and MU	0.2–0.5 μg/ml	EGPT, TAIW	133
N-carboxamido-staurosporine	Bacterium	Alkaloid	37-cell line panel	0.016 μg /ml	GER, CHI	134
Clavularia inflata diterpenes	Soft Coral	Diterpene	MU	0.5–0.6 μg/ml	TAIW	135
Deacetylhectochlorin	Sea hare	Lipopeptide	HU	0.31–1.03 μM	THAI, JAPN	136
Sesquiterpene	Sponge	Sequiterpene	HU	0.34–0.37 μM	N. ZEL	137
13-*Epi*palmerin	Soft coral	Diterpene	HU	0.5–5 μg/ml	SPA, USA	138
Fuscocineroside C	Sea cucumber	Triterpene glycoside	HU	0.58–0.88 μM	CHI	139
Gymnastatins F and G	Fungus	Polyketide	MU	0.03–0.13 μg/ml	JAPN	140
Globostelletin and globostellastic acids G, H, J, L and M	Sponge	Triterpene	MU	0.31–0.92 nM	CHI, GER	141
Haliclona sterol	Sponge	Steroid	HU	0.33–0.73 μg/ml	CHI, GER	142
Haterumaimides N–Q	Ascidian	Alkaloid	MU	3.4–50 ng/ml	JAPN	143
Hillaside C	Sea cucumber	Triterpene	HU	0.15–3.20 μg/ml	CHI	144
Homaxisterol B_2	Sponge	Steroid	HU	0.55–1.51 μg/ml	S. KOR	145,146
Hurghadolide A	Sponge	Macrolide	HU	0.36 μM	EGPT, USA	111
Hydroxy-norresistomycin	Bacterium	Polyketide	HU	9–14 ng/ml	IND	147
IB-01212	Fungus	Depsipeptide	HU	10 nM	SPA	148
Intercedenside D–I	Sea cucumber	Triterpene glycoside	HU	0.96–5 μg/ml	CHI, USA	149
Ircininamine B	Sponge	Fatty acid	MU	0.28 μg/ml	JAPN	150
Isis sterol	Soft coral	Steroid	HU	0.21–1.07 μg/ml	TAIW	151
Kahalalide R	Mollusk	Depsipeptide	HU and MU	0.14–4.3 μM	CHI, GER	152
Lamellarins	Ascidian	Alkaloid	HU	0.2–178 nM	IND	153
Lehualides B and D	Sponge	Polyketide	HU	0.23–0.83 μM	NZEL, USA	154
Leiodolides A and B	Sponge	Macrolide	HU 60-cell line panel	0.25–0.26 μM	NZEL, USA	155
Libertellone D	Fungus	Diterpene	HU	0.76 μM	USA	156
Liphagal	Sponge	Sesquiterpene	HU	0.58–1.58 μM	CAN, NETH, USA	116
Lissoclibadins 1 and 2	Ascidian	Alkaloid	HU	0.21–5.5 μM	JAPN	157
Lyngbyabellins E–I	Bacterium	Lipopeptide	HU and MU	0.2–4.8 μM	USA	118
Manoalide derivative	Sponge	Sesterterpene	HU	0.32 μg/ml	CHI, USA	158
Marinomycins A–C	Bacterium	Macrolide	HU 60-cell line panel	0.005–2.7 μM	USA	159
Mechercharmycin A	Bacterium	Cyclic peptide	HU	0.04 μM	JAPN	160
Melophlin Q	Sponge	Fatty acid	MU	0.85 μM	JAPN	161
Metachromins J	Sponge	Sesquiterpene	HU and MU	1–9.9 μg/ml	JAPN, AUS	162
Mycapolyols A–F	Sponge	Polyketide	HU	0.06–0.90 μg/ml	THAIL, JAPN	163
Palmerolide A	Tunicate	Macrolide	HU	18 nM	USA	114
Phakellistatin 14	Sponge	Peptide	HU and MU	0. 75–5 μg/ml	USA	164
Philinopsides A and B	Sea cucumber	Triterpene	HU	0.75–3.5 μg/ml	CHI, USA	112
Philinopside E	Sea cucumber	Triterpene	HU and MU	0.62–5.53 μg/ml	CHI	165
Roridin R and 12′-hydroxyroridin E	Fungus	Macrolide	MU	0.19–0.45 μM	JAPN, INDO	166
roseotoxin B	Fungus	Depsipeptide	HU	0.14–1.30 μg/ml	BRA, USA	167

Table 2 – *continued*

Compound	Organism	Chemistry	Preclinical tumour cell line model[a]	50% growth inhibition or cytotoxicity	Country[b]	Refs.
Secalonic acid D	Fungus	Polyketide	HU and MU	0.03–5.76 μM	CHI	120
Seragamides A–E	Sponge	Depsipeptide	MU	0.064–0.58 μM	JAPN, USA	117
Sesterstantin 6	Sponge	Sesterterpene	HU and MU	0.17–4.9 μg/ml	USA	168
Stellettin J	Sponge	Triterpene	HU	0.28–1.2 μM	USA	115
Stelliferin riboside	Sponge	Triterpene	MU	0.22 nM	CHI, GER	141
Streptomyces nobilis peptide	Bacterium	Cyclic peptide	HU	14 nM	JAPN	169
Swinholide I	Sponge	Macrolide	HU	5.6 nM	EGPT, USA	111
Tedanolide C	Sponge	Macrolide	HU	0.057 μM	USA	113
Tetrahydrobisvertinolone	Fungus	Polyketide	HU and MU	0.52–1.7 μM	CHI	170
Theopapuamide	Sponge	Depsipeptide	HU	0.5–0.9 μM	USA	171
Turbostatins	Mollusk	Fatty acid	HU and MU	0.15–2.6 μg/ml	USA	172
Wewakpeptins A and B	Bacterium	Depsipeptide	HU and MU	0.2–0.65 μM	USA	173
Zygosporamide	Fungus	Depsipeptide	NCI 60-cell line panel	5.0–6.5 nM	USA	174

a HU: human, MU: murine.

b Country: AUS: Australia, BRA: Brazil, CAN: Canada, CHI: China, EGPT: Egypt, FRA: France, GER: Germany, IND: India, INDO: Indonesia, JAPN: Japan, MEX: Mexico, NETH: the Netherlands, NZEL: New Zealand, PAN: Panama, S. KOR: South Korea, SPA: Spain, SWE: Sweden, THAI: Thailand, TAIW: Taiwan.

enhanced expression of the IFN-γ receptor 2 in human monocytic cells and primary human monocytes, by a dual mechanism involving transcriptional and post-transcriptional events that did not require protein synthesis. The authors speculated that their observations might help 'overcome some of the immune defects observed in cancer patients', and thus proposed *in vivo* preclinical research of the combination of bryostatin-1 and IFN-γ in murine tumour models.

Two clinical trials with bryostatin-1 were reported during 2005–2006. El-Rayes and colleagues[36] completed a Phase I study with bryostatin-1 and gemcitabine with 36 patients who had non-haematologic cancer that was refractory to conventional treatment. Based on the preclinical data and the tolerability of this combination, the authors suggested that a Phase II trial in breast and pancreatic cancer represented a rational approach for the development of this regimen. Ajani and colleagues[37] reported a multi-centre Phase II study of sequential paclitaxel and bryostatin-1 in 35 patients with untreated, advanced gastric and gastroesophageal adenocarcinoma. Although the sequential use of paclitaxel plus bryostatin-1 resulted in a 29% response as compared to paclitaxel alone (17% response), further development of this synergic combination will require the amelioration or prevention of myalgia. Peterson and colleagues[38] reported a Phase II trial of interleukin-2 in combination with four different doses of bryostatin-1 in 33 patients with renal cell carcinoma, a type of cancer that in the US has an estimated incidence of 319,000 new cases per year. Although the addition of bryostatin-1 to IL-2 was well tolerated, and four patients demonstrated evidence of tumour shrinkage, the overall rate of response was low (3.2%), leading this group of researchers to state that they did not 'recommend further studies investigating this combination'.

Two studies extended the preclinical pharmacology of **cephalostatin 1**, a bis-steroidal marine natural product isolated from the Indian Ocean hemichordate *Cephalodiscus gilchristi*. Müller and colleagues[39] discovered that cephalostatin 1 inactivated the antiapoptotic mitochondrial protein Bcl-2 by hyperphosphorylation which was independent of M-phase arrest and DNA damage, a finding that could potentially help treatment of drug-resistant cancers. Lopez-Antón and colleagues[40] reported that cephalostatin 1 activated an endoplasmic reticulum (ER) stress response which was accompanied by caspase-4 activation and apoptosis induction without the requirement of the classical mitochondrial pathway. The fact that cephalostatin 1 appears to enable the ER stress signalling pathway may be advantageous for the treatment of chemoresistant tumours with potential defects in the mitochondrial pathway.

Two preclinical and one clinical study were reported during 2005–2006 with the **cryptophycins**, macrocyclic depsipeptides isolated from the marine cyanobacterium *Nostoc* sp. Cannady and colleagues[41] examined the enzyme kinetics of glutathione conjugation of cryptophycins 52 and 53 by cytosolic glutathione *S*-transferases (GST) and epoxide hydrolases, and discovered that human, rat and mouse cytosolic GSTs are responsible for the metabolism of cryptophycin 52 to the GSH conjugate. Their results provide firm support for the ongoing Phase II metabolism studies. Liang and colleagues[42] reported extensive preclinical evaluation of the synthetic and formulation-stable glycinate esters of cryptophycins 309 and 249, as well as other analogues in mouse and human tumours. Based on the expectation that these second-generation analogues will produce 100–1000-fold greater activity than the first clinical candidates (e.g. cryptophycin 52), and their formulation stability advantage compared to cryptophycin C-52, the authors noted that both 'C-309 and C-249 are being considered as second-generation clinical candidates'. D'Agostino and colleagues[43] described a multicentre Phase II study of a synthetic cryptophycin analogue LY355703 in 26 patients with platinum-resistant ovarian cancer, a leading cause of death from gynaecological tumours

in Western countries. Although only a modest level of activity was observed, the lack of severe side-effects in this poor-prognosis population suggested that this compound might deserve further investigation.

One study during 2005–2006 described the pharmacology of **dictyostatin**, a 22-membered macrolactone isolated from the sponge *Spongia* sp. collected in the Republic of Maldives. Madiraju and colleagues[44] observed that dictyostatin's induction of tubulin polymerisation, taxoid site binding and antiproliferative activity against human ovarian carcinoma cells was comparable to that of discodermolide, and thus concluded that the macrocyclic structure of dictyostatin might represent a template for the bioactive conformation of discodermolide.

Didemnin B, a cyclic depsipeptide produced by ascidians of the family *Didemnida*e, was the focus of one pharmacologic investigation in 2005–2006. Beasley and colleagues [45] completed a study of the excretion and tissue concentrations of [^{3}H] didemnin B in mice after intraperitoneal administration. Interestingly, they found that the pancreas had the greatest concentration of radiolabel at both the high and the low doses 7 d after administration, which suggested possible efficacy in animal models for the treatment of pancreatic cancer.

Park and colleagues[46] examined the pharmacology of **dideoxypetrosynol A**, a polyacetylene from the marine sponge *Petrosia* sp., by investigating the molecular mechanism involved in cell cycle arrest at the G1 to the S phase transition in human monocytic leukaemia cells. A careful study of G1/S transition regulatory proteins revealed an enhanced expression of the Cdk inhibitor p16/INK4a with a concomitant decrease of retinoblastoma protein phosphorylation, thus suggesting that both p16 and pRB proteins play an important role in G1 cell cycle arrest induced by this compound in human leukaemia cells.

There were four studies of **discodermolide**, a compound originally isolated from the sponge *Discodermia dissoluta* that suppresses microtubule dynamics. Xia and colleagues[47] using a photoaffinity-labelled analogue to investigate and define the drug binding pocket in tubulin observed that whilst the analogue had no hypernucleation effect in an *in vitro* microtubule polymerisation assay, it labelled amino acid residues 305–359 in the S9–S10 loop in β-tubulin. This sequence is very close to the Taxol binding site, thus enabling the construction of a computationally derived binding model of both the discodermolide analogue and the native discodermolide binding to β-tubulin. Escuin and colleagues[48] observed that discodermolide, as well as other microtubule-disrupting agents, down-regulated hypoxia-inducible factor-1α (HIF-1α) protein levels, but not mRNA, in a dose-dependent manner. This study directly linked β-tubulin drug binding with HIF-1α protein inhibition, a discovery of considerable clinical significance because HIF-1α overexpression is present in over 70% of all human tumours and their metastasis, thus making HIF-1α 'a prime target for anticancer therapies'. Klein and colleagues[49] evaluated discodermolide in several human cancer cell lines and determined that it induced accelerated senescence with a potency similar to doxorubicin with concomitant Erk1/2 activation and up-regulation of two markers of senescence, namely the p66Shc and PAI-1 proteins. These findings provide the first demonstration of a microtubule stabilising agent that inhibits tumour cell growth by the mechanism of accelerated senescence. Huang and colleagues[50] investigated the combination of discodermolide and taxol in human ovarian cancer cells and an *in vivo* model of ovarian carcinoma, and reported that both agents interacted synergistically at drug concentrations that resulted in aneuploidy rather than mitotic arrest. Although the mechanism for the synergistic efficacy of these two agents was not determined, the data supported concurrent use of low doses of these two compounds for the treatment of epithelial ovarian carcinoma, a leading cause of death from gynaecologic malignancies. In an effort to develop novel therapies for poorly vascularised and hypoxic tumours, a 'longstanding problem in clinical oncology', Smith and colleagues[51] tested discodermolide analogues as potent chemical components of combination bacteriolytic therapy. Interestingly, a single i.v. injection of (+)-2,3 anhydrodiscodermolide plus genetically modified *Clostridium novyi*-NT spores into mice bearing colorectal cancer xenografts caused rapid and complete obliteration of the tumours.

Nine studies were published during 2005–2006 on the preclinical and clinical evaluation of the **dolastatins,** a family of modified peptides originally isolated from the marine mollusk *Dolabella auricularia* that induce actin assembly *in vivo*. Watanabe and colleagues[52] investigated the antitumour activity of TZT-1027 (Soblidotin), a newly synthesised dolastatin 10 derivative, using a panel of human tumours that included Pgp overexpressing sublines. They concluded that TZT-1027 antitumour activity was superior to that of paclitaxel, docetaxel and vincristine, and thus anticipated that TZT-1027 would provide benefit in the chemotherapy of tubulin inhibitor-unresponsive tumours.

Five Phase I trials were conducted with TZT-1027 and a third-generation dolastatin-15 analogue, tasidotin hydrochloride (ILX651). Jonge and colleagues[53] in the Netherlands completed a Phase I and pharmacokinetic study with TZT-1027 in 17 patients with advanced solid tumours. In this trial, one patient with a refractory metastatic liposarcoma demonstrated a response, and eight patients experienced stabilisation of their tumour, and the study defined a dose of TZT-1027 that was 'well tolerated', with the main dose-limiting toxicities being reversible neutropaenia and infusion arm pain. A three-institution Phase I study with TZT-1027 in 18 Japanese patients with advanced solid tumours was reported by Tamura and colleagues.[54] The researchers noted that one patient with metastatic oesophageal cancer achieved a partial response, and that TZT-1027 was 'active at a tolerable dose' with neutropaenia and infusion reaction (phlebitis) the most frequent toxicities that were observed. Greystoke and colleagues[55] published data of a Phase I study with TZT-1027 administered in combination with carboplatin in 14 patients with advanced solid tumours, which resulted in one patient with pancreatic adenocarcinoma achieving a partial response. Although peripheral reversible neuropathy was observed in 36% of the patients, the combination of TZT-1027 and carboplatin appeared to be 'relatively well tolerated'. Cunningham and colleagues[56] conducted a Phase I and pharmacokinetic study with the pentapeptide tasidotin hydrochloride (ILX651), a third-generation dolastatin-15 analogue, in 32 patients with advanced solid tumours refractory to

standard treatment. Whilst the best antitumour response consisted of stable disease in 10 patients, in contrast to TZT-1027, tasidotin's neurotoxicity and cardiovascular toxicity were diminished, with neutropaenia observed as the principal dose-limiting toxicity. Mita and colleagues[57] reported a Phase I and pharmacokinetic study with tasidotin hydrochloride in thirty patients with advanced solid tumours. Although neutropaenia was observed as the principal toxicity, the researchers concluded that the mild myelosuppression and manageable non-haematologic toxicities observed concomitant to antitumour activity in three patients with lung, hepatocellular and renal cell carcinoma 'warranted further disease-directed evaluations' with this agent.

Three Phase II trials of dolastatin-10 and TZT-1027 were described during 2005–2006. Perez and colleagues[58] reported a Phase II study in 22 patients with advanced breast cancer who were treated with dolastatin-10 as a single agent. Whilst the observed haematological toxicity was moderate and one patient had a partial response, the study was terminated due to the lack of tumour response. The results of this Phase II study were judged to be 'disappointing', probably a result of dolastatin 10′s 'true lack of activity'. Kindler and colleagues[59] completed a Phase II trial of dolastatin-10 in 16 patients with advanced hepatobiliary cancer and 12 patients with metastatic pancreatic adenocarcinoma, malignancies that are known to be refractory to most chemotherapy and for which novel therapeutic agents are needed. Due to the lack of tumour response, and only a slight increase in patient survival, the authors concluded that unfortunately further evaluation of 'dolastatin-10 in pancreaticobiliary malignancies is not warranted'. Patel and colleagues[60] reported the results of a Phase II study of i.v. TZT-1027 in 28 patients with advanced or metastatic soft-tissue sarcomas with prior exposure to anthracycline-based chemotherapy, usually doxorubicin. Whilst no confirmed responses were observed in any of the patients enroled in this study, TZT-1027 was found to be safe and well tolerated, with the most common haematologic toxicity being neutropaenia.

Ten preclinical and seven clinical articles contributed to the preclinical and clinical pharmacology of the tetrahydroisoquinoline alkaloid **ecteinascidin-743 (ET-743;** Trabectedin, Yondelis®), an antitumour agent originally isolated from the Caribbean sea squirt *Ecteinascidia turbinata*.[61]

New insights into the *molecular* pharmacology of ET-743 were provided by several studies during this period. Minuzzo and colleagues[62] tested the hypothesis that ET-743 specifically targeted cell cycle genes involved in transcription. Their data demonstrated that ET-743 was not a general inhibitor of inducible genes, but its effects were downstream from transcription factor binding, and that histone acetylation was largely unaffected. David-Cordonnier and colleagues[63] carried out the first structure–activity study with ET-743 analogues, and demonstrated that the DNA-interacting activity of this molecule is dependent on the C21-hydroxyl group, and that changes in the C ring of ET-743 can affect the DNA binding affinity. The data also suggested the existence of an additional non-DNA target for ET-743, probably a protein, 'located close to DNA', that would cause the formation of a ternary complex that would trigger apoptosis and cell cycle arrest. Marco and Gago[64] used unrestrained molecular dynamics simulations to investigate the interaction of two ET-743 molecules with a self-complementary dodecanucleotide d(GTATGGCCATAC). These simulations revealed that it was possible for two ET-743 molecules to bind in a tail–tail arrangement to two adjacent TGG sites placed on opposite DNA strands. This interaction led to structural distortions in the DNA oligonucleotide that could affect the binding of transcription factors acting as activators or repressors of gene transcription. Dziegielewska and colleagues[65] determined the effects of ET-743 on DNA helicase/nuclease activity of RecBCD from *Escherichia coli*, an enzyme involved in unwinding the DNA helix, and used as a model to study the DNA-damaging agents. They reported that ET-743 significantly inhibited unwinding, enhanced degradation of DNA, and completely disrupted the RecBCD's enzyme, thus resulting in inhibition of repair, replication and transcription processes. Herrero and colleagues[66] tested the hypothesis that ET-743 induced lethal DNA strand breaks by interacting with the nucleotide exchange excision repair proteins, which are involved in DNA damage repair caused by several anticancer drugs, e.g. cisplatin. Specifically, the researchers discovered that ET-743-induced DNA cytotoxicity depended on the interaction of this agent with an arginine residue (Arg314) in the DNA-binding region in human nuclease FEN-1, and the putative formation of a DNA-ET-743 ternary complex which caused tumour cell death.

Preclinical *cellular* pharmacology of ET-743 was described in several studies during 2005–2006. Brandon and colleagues[67] reported on the cytotoxicity of ET-743 in a human hepatic carcinoma cell line growing *in vitro*. The results demonstrated that because ET-743 is metabolised by cytochromes (CYP) P450 3A4, and 2C9, 2C19 and 2E1, and by Phase II enzymes, combination therapy with other CYP inhibitors (e.g. cisplatin, paclitaxel and doxorubicin) may result in hepatotoxicity due to drug–drug interactions. More recently, Brandon and colleagues [68] examined the human biotransformation and cytochrome P450 reaction phenotype of ET-743, and confirmed that CYP3A4 has a major role in the metabolism of ET-743 *in vitro* with lesser involvement of CYP2C9, 2C19, 2D6 and 2E1 isozymes. Clearly assessment of the biotransformation and CYP reaction phenotype is important for interpreting pharmacokinetic data from clinical trials and predicting potential ET-743-drug interactions, in particular hepatic toxicity. In an effort to correlate gene expression profiles with *in vitro* sensitivity to ET-743, Martinez and colleagues[69] investigated a panel of 11 chemonaïve, low-passage soft-tissue sarcoma cell lines established from patient biopsies using a cDNA microarray containing 6700 cancer-related genes. Although the gene expression profile revealed that 244 genes were down-regulated and 86 genes up-regulated in 8 of the 11 sarcoma cell lines in this study, a noteworthy finding was the up-regulation of genes related to cell cycle control, stress, DNA-damage response and apoptosis. Confirmation of these results in patient tumour specimens will be necessary to help identify subsets of soft-tissue sarcomas that may show increased sensitivity to ET-743. To investigate the mechanism of *in vitro* resistance, Marchini and colleagues[70] evaluated microarray-based gene expression profiles in ET-743-sensitive and -resistant ovarian and chondrosarcoma cell lines. Microarray studies on a panel of 2400 cDNAs revealed that a subset

of 70 genes, 21 of which were up-regulated and 49 down-regulated, consistently showed differential expression in the ET-743-resistant cell lines, thus shedding new light on molecular pathways involved in chemoresistance to ET-743.

One study detailed the preclinical *in vivo* pharmacology of ET-743. Meco and colleagues[71] found that the combination of ET-743 and irinotecan, a water-soluble derivative of camptothecin that targets topoisomerase I, resulted in only weak cytotoxicity to human rhabdomyosarcoma *in vitro*, but this same drug combination produced a 'strong and long-lasting' effect on the growth of rhabdomyosarcoma tumour xenografts *in vivo*. Although the mechanism of the *in vivo* synergism of ET-743 and irinotecan was not investigated, the authors hypothesised that the discrepancy between *in vitro* and *in vivo* effects might result from a combination of direct cytotoxic and indirect anti-inflammatory effects of ET-743.

One Phase I and pharmacokinetic study as well as 6 Phase II trials extended the clinical pharmacology of ET-743 during 2005–2006. Lau and colleagues[72] conducted a Phase I and pharmacokinetic study with ET-743 given as a 3-h i.v. infusion every 21 d in 12 children with refractory solid tumours. ET-743 was generally well tolerated with reversible hepatotoxicity, the most common adverse effect (58% of patients). The observation that one patient with a recurrent Ewing sarcoma showed a complete response with resolution of pulmonary metastases has resulted in the development of a Phase II trial in children with refractory Ewing or soft tissue sarcomas. Garcia-Carbonero and colleagues[73] reported a Phase II and pharmacokinetic study with ET-743 in 36 previously untreated patients with advanced soft tissue sarcomas, mainly leiomyosarcoma and liposarcoma. ET-743 evidenced 'manageable' toxicity in this study, with one complete and five partial responses to ET-743 being observed (17.1% response rate). This led the investigators to state that ET-743 'demonstrates for the first time the safety, tolerability and antitumour activity' in chemotherapy-naïve patients with advanced soft tissue sarcomas when used as a single agent, and it justified 'some prudent optimism' for patients who fail doxorubicin or ifosfamide therapy. Huygh and colleagues[74] reported a retrospective Phase II study of 89 patients with advanced, pretreated soft tissue and bone sarcoma, who were treated with ET-743 as a 24-h continuous infusion. Whilst the toxicities were mainly an asymptomatic elevation of transaminases and neutropaenia, the treatment resulted in one complete remission, 5 partial remissions, one minimal response and 16 patients with disease stabilisation of 6 months or more, thus strongly suggesting that 'further evaluation of the activity of ET-743 in sarcomas is therefore warranted'. Le Cesne and colleagues[75] communicated a Phase II study with 104 patients from 8 European institutions with pretreated advanced soft tissue sarcomas that were provided with a 24-h continuous infusion every 3 weeks. The fact that 8 partial responses were observed in leiomyosarcomas, a tumour subtype usually considered to be resistant to doxorubicin and/or ifosfamide regimens, prompted the authors to 'demand(s) further evaluations' of ET-743 as a second-line agent and in combination studies. Sessa and colleagues[76] assessed the efficacy and toxicity of ET-743 in 59 patients with advanced ovarian cancer who had experienced treatment failure after platinum or taxane therapy. Using a Phase II 3-h infusion schedule every 3 weeks which allowed for outpatient administration, the study reported that ET-743 was tolerable with 'promising activity' in relapsed ovarian cancer, showing a 43% response rate in patients with platinum-insensitive disease. Zelek and colleagues[77] from 3 French institutions determined the activity of ET-743 in a Phase II study that investigated the use of this compound as a 24-h continuous i.v. infusion every 3 weeks in 27 patients with advanced breast cancer who were resistant or had relapsed after conventional chemotherapy. Although the partial response rate (14%) was judged to be modest, it was considered to be in the range of 'what can be expected for an active drug in this setting'. Tewari and colleagues[78] reported a remarkable case of activity of ET-743 when used as a single agent in one patient with refractory metastatic uterine leiomyosarcoma in whom 4 prior regimens had failed. The patient had a durable partial response lasting at least 8 months, and the authors concluded that ET-743's activity in uterine leiomyosarcomas definitely warrants further investigation.

One report in 2005–2006 examined the pharmacology of **fascaplysin**, an alkaloid obtained from the Papua New Guinea sponge *Fascaplysinopsis reticulata*. Subramanian and colleagues[79] showed therapeutic efficacy in a novel pharmacology paradigm designed to rapidly move prospective anticancer drugs from discovery phase through pharmacology testing and into therapeutic trial assessment, as well as complete proteomics analysis to reveal 'pathways involved in the drug's cytotoxicity'.

Two reports extended the preclinical pharmacology of **halichondrin B,** a large polyether macrolide found in a variety of marine sponges. Jordan and colleagues[80] observed that ET389, a synthetic macrocyclic ketone analogue that is currently in Phases I and II clinical trials, inhibited microtubule polymerisation in an *in vitro* human breast cancer cell line. It significantly suppressed microtubule growth rate, length and duration, thus resulting in the suppression of the metaphase/anaphase transition. A putatively novel mechanism of action involving E7389's ability to 'aggregate tubulin and selectively suppress microtubule growing events' was proposed by the authors. Dabydeen and colleagues[81] examined the biochemical mechanism of action of E7389 in direct comparison with halichondrin B. They found that ET389 was more potent than halichondrin B in all biochemical assays, and by extensive molecular modelling studies gained new insight into the interaction of both compounds with a cleft between αβ-heterodimers in tubulin. This interaction appeared to involve contacts with α-subunit residues Phe244, Ala247, Leu248, and Tyr257 and β-subunit residues Gli81, Pro82, Thr223 and Gly225.

One report extended the pharmacology of the peptidic antimitotic agent **hemiasterlin,** a compound isolated from numerous marine sponges. Ravi and colleagues[82] reported progress in the structure-based identification of the tubulin binding site for HTI-286, a synthetic analogue of hemiasterlin. They proposed a binding model of HTI-286 to key residues on β tubulin that appears to be supported by significant experimental data, including biophysical characterisation, photolabelling and NMR studies, and by biological activity data.

One report extended the pharmacology of **jasplakinolide** (jaspamide), a cyclic depsipeptide originally isolated from

Jaspis sponges, that induces actin polymerisation. Whilst investigating the anti-migratory potential of this agent, Hayot and colleagues[83] used an *in vitro* pharmacological strategy that included spectrofluorometry to monitor the kinetics of actin polymerisation, and videomicroscopy to investigate cell motility. They observed that jasplakinolide enhanced the motility of A549 lung cancer cells but not that of MCF7 breast tumour cells, and this led the authors to conclude that the use of 'multi-assays with different levels of sophistication' is required for the characterisation of anti-migratory and potentially novel antimetastatic agents.

During 2005–2006 two reports described the preclinical and clinical pharmacology of **kahalalide F,** a complex depsipeptide isolated from the Hawaiian marine mollusk *Elysia rufescens* that is currently under clinical investigation. Janmmat and colleagues[84] determined that kahalalide F induced cytotoxicity in breast, vulval, non-small-cell lung, and hepatic carcinoma cell lines *via* a necrosis-like cell death process. This process was positively correlated to ErbB3 (HER3) receptor protein levels and downstream in the PI3K-Akt pathway *in vitro*, findings that the investigators proposed 'may have important clinical relevance'. Lakhai and colleagues in the Netherlands [85] detailed a Phase I and pharmacokinetic study in 32 patients with androgen-refractory prostate cancer that received kalahalide F as a 1-h i.v. infusion for five consecutive days every three weeks. Whilst noting that kalahalide F dose-limiting toxicity was reversible, mainly an increase in transaminases, they observed that one patient had a partial response with a prostate-specific antigen declining by 50% for greater than four weeks, whilst five patients (16%) showed evidence of stable disease.

One report extended the pharmacology of the marine pyrrole alkaloid **lamellarin D**, a submicromolar inhibitor of topoisomerase I, that was isolated from the prosobranch mollusk *Lamellaria* sp. In an effort to find treatments for chemoresistant cancer, **Kluza** and colleagues[86] investigated the targets and pathways involved in apoptosis induced by lamellarin D. A detailed mechanistic study revealed that lamellarin D had an effect on the structural and functional integrity of cancer cell mitochondria at micromolar concentrations, which suggested that lamellarin D should be considered a 'bifunctional pharmacologic effector' agent.

During 2005–2006 one report described the preclinical pharmacology of **pateamine A**, a complex macrolide isolated from the marine sponge *Micale* sp. In an elegant molecular study, Bordeleau and colleagues[87] demonstrated that pateamine A is 'the first example of a chemical inducer of dimerisation that forces an engagement' between the RNA helicase eukaryotic initiation factor 4FA subunit (elF4A) and RNA. This interaction prevents elF4A from participating in the ribosome-recruitment of translation initiation, which is considered the rate-limiting step of protein synthesis in eukaryotes.

Preclinical research continued during 2005–2006 with the macrolide **peloruside A**, a microtubule-stabilising agent which is currently available both from synthetically and from aquaculture grown samples of the New Zealand marine sponge *Mycale hentscheli*. Hamel and colleagues[88] confirmed that peloruside A bound to the laulimalide site on tubulin which is distinct from the taxoid site. Furthermore, the researchers found that although peloruside A and laulimalide were unable to synergise with each other, both compounds could act synergistically on tubulin assembly with taxoid site-binding marine agents such as discodermolide, dictyostatin and eleutherobin. This finding led the authors to conclude that other combinations of these agents may be worth investigating both preclinically and clinically.

In an effort to identify novel natural product-derived peroxisome proliferator-activated receptor γ (PPRγ) activators for breast cancer treatment, Mora and colleagues [89] investigated the effects of **psammaplin A**, a known histone deacetylase inhibitor originally isolated from the marine sponge *Pseudoceratina rhax*. Psammaplin A activated PPRγ in a cell-based reporter assay and induced apoptosis in human breast cancer cells *in vitro*. This suggests that PPARγ activators may provide new molecularly targeted lead compounds for the design of novel classes of antitumour agents.

Table 1 also includes a number of marine natural products which were *not* previously reviewed:[2–4] aaptamine, polymeric alkylpyridinium salts, aplyronine A, bastadin 6, clavulone II, 13-deoxytedanolide, fucoxanthinol, geodiamolides, geoditin A, halocynthiaxanthin, ircinin-1, laxaphycins A and B, leptosins C and F, ningalins, onnamide A, philinopside A, salinosporamide A, stellettin A, strobilinin–felixinin and variolin B.

As a result of a screening effort to discover agents that target the cyclin-dependent kinase inhibitor Cip/Kip p21 protein, Aoki and colleagues[90] reported the isolation of a benzonaphthyridene alkaloid **aaptamine** from the Indonesian marine sponge *Aaptos suberitoides*. The *in vitro* studies demonstrated that aaptamine induced expression of p21 protein in a p53-independent manner, arresting the cell cycle at the G2/M phase. Paleari and colleagues[91] showed that polymeric **alkylpyridinium salts** isolated from the marine sponge *Reniera sarai* induced apotosis and cell–cell adhesion in non-small cell lung cancer cells. The selectivity of these polymeric alkylpyridinium salts, which were recently described as irreversible acetylcholinesterase inhibitors, towards cholinergic receptor-expressing tumours led the investigators to propose them as 'alternative inhibitors of lung cancer with low systemic toxicity'.

Hirata and colleagues [92] extended the molecular characterisation of the sea hare metabolite **aplyronine A**, which had previously been shown to inhibit polymerisation of globular actin to fibrous actin. Using synchrotron X-ray analysis, the crystal structure of the actin-aplyronine A complex was investigated. Aplyronine A was observed to bind to a hydrophobic cleft by intercalating its aliphatic tail into the actin molecule, an interaction shown to be essential to depolymerise actin and for cytotoxicity against human HeLa tumour cell lines.

Aoki and colleagues [93] described molecular pharmacology studies of **bastadin 6**, a macrocyclic and tetrameric bromotyrosine derivative isolated from the marine sponge *Lanthella basta*. Bastadin 6 was observed to inhibit angiogenesis and *in vivo* neovascularisation, probably by an apoptotic mechanism. It therefore shows potential for further development as an inhibitor of tumour angiogenesis, although the actual molecular target has not yet been determined.

Huang and colleagues [94] investigated the molecular pharmacology of the marine prostaglandin analogue **clavulone II**, originally derived from the Japanese soft coral *Clavularia*

viridis and previously shown to have antitumour and antiviral activity. Working with a human acute promyelocytic leukaemia, clavulone II induced down-regulation of cyclin D1 expression and G1 arrest of the cell cycle at lower concentrations (1.5 μM), whilst at higher concentrations (3 μM) clavulone II induced apoptosis with concomitant modulation of caspases and Bcl-2 family proteins.

Aoki and colleagues [95] reported the isolation of the steroidal alkaloids **cortistatins A–D** from the marine sponge *Corticium simplex*. Interestingly, cortistatin A exhibited highly selective anti-proliferative activity against human umbilical vein endothelial cells (IC_{50} = 0.0018–1.1 μM), in comparison with normal human dermal fibroblasts and several human tumour cell lines. Although the molecular mechanism of action of the cortistatins is currently under investigation, they clearly appear to be promising new inhibitors of angiogenesis and thus putative antitumour compounds.

Nishimura and colleagues [96] continued the characterisation of the antitumour macrolide **13-deoxytedanolide**, isolated from the marine sponge *Mycale adhaerens*. A high-affinity binding site on the *Saccharomyces cerevisiae* 60S large ribosomal unit was elegantly demonstrated to be the molecular target of 13-deoxytedanolide which caused potent inhibition of polypeptide synthesis (IC_{50} = 0.15 μM). The authors noted that this compound was the first macrolide that bound the eukaryotic ribosome, and therefore it represented 'an important tool for elucidating structure and function of eukaryotic ribosomes'.

Konishi and colleagues [97] investigated the carotenoids **fucoxanthinol** and **halocynthiaxantin** isolated from the sea squirt *Halocynthia* roretzi. Both carotenoids inhibited the growth of human leukaemia, breast and colon cancer cells *in vitro* in a dose- and time-dependent manner by a mechanism that required induction of apoptosis and the concomitant reduction of the apoptosis-suppressing protein Bcl-2.

Rangel and colleagues [98] reported new mechanistic information on the cyclic peptides **geodiamolides A, B, H** and **I** isolated from the marine sponge *Geodia corticostylifera* from Brazil. The researchers noted that peptides A and H had potent antiproliferative activity against two human breast cancer cell lines (IC_{50} = 18-90 nM) and disorganised F-actin filaments in a dose-dependent manner. Interestingly, normal cell lines did not show cytoskeleton alterations after treatment with the geodiamolides, thus suggesting a putative biomedical potential for these novel compounds.

As part of a research program to evaluate bioactive secondary metabolites of marine organisms, Liu and colleagues [99] compared the cytotoxicity of the isomalabaricane triterpenes **geoditins A** and **B** isolated from the marine sponge *Geodia japonica*. Geoditin A, which differs in an acetyl group at the C3 position with geoditin B, was found to be the most cytotoxic (IC_{50} = 5 μg/ml) to human HL60 promyelocytic leukaemia cells, probably due to a dose-dependent increase of reactive oxygen species, a decrease in mitochondrial potential and caspase-3 mediated apoptosis.

In an effort to find new agents for the treatment of melanoma, Choi and colleagues [100] completed a detailed mechanistic study of **ircinin-1**, isolated from the marine sponge *Sarcotragus* sp. Ircinin-1 inhibited the growth of a human melanoma cell line *in vitro*, by a dual mechanism that involved the arrest of cell cycle progression at the G1 phase and induction of apoptosis *via* the Fas/Fas-L pathway.

Gbankoto and colleagues[101] studied the cytotoxic effects of **laxaphycins A** and **B**, cyclic depsipeptides isolated from the marine cyanobacterium *Lyngbya majuscula*. Working with three established human lymphoblastic cell lines and a protocol of triple labelling with vital dyes and multifluorescence image analysis, both peptides were observed to act synergistically to produce an increase in the polyploid cell population. It was hypothesised that this effect 'could result from alteration of topoisomerase II activity'.

Yanagihara and colleagues[102] extended the molecular pharmacology of the sulphur-containing indole derivatives **leptosins C** and **F**, isolated from the marine fungus *Leptoshaeria* sp. Both compounds inhibited DNA topoisomerase II (IC_{50} = 3–10 μM), whilst only leptosin C inhibited topoisomerase I (IC_{50} = 10–30 μM) *in vitro* and *in vivo*. Furthermore, the compounds induced apoptosis *in vivo*, as measured by caspase-3 activation, whilst inactivating the survival Akt/protein kinase B pathway.

Chou and colleagues [103] evaluated the pharmacological properties of synthetic analogues of the **ningalins**, aromatic alkaloids originally isolated from the marine ascidian *Didemnum* sp. By a mechanism that involved a direct and dose-dependent interaction with the multidrug resistance drug transporter Pgp, the ningalins markedly enhanced the antitumour cytotoxicity of vinblastine, doxorubicin and taxol both *in vitro* and/or *in vivo*. This observation supported the proposition that these agents 'may allow the reduction in the dosage of anticancer drugs whilst enhancing or achieving a curative effect'.

Whilst screening 20,000 samples for agents that might activate the tumour-suppressing transforming growth factor-β (TGF-β) signalling cascade, Lee and colleagues[104] discovered that **onnamide A and theopederin B**, isolated from the marine sponge *Mycale* sp., induced activation of the PAI-1 promoter gene, a well-characterised TGF-β-responsive gene. Since both onnamide A and theopederin B potently inhibited protein synthesis (IC_{50} = 30 nM and 1.9 nM, respectively) and activated p38 kinase and c-Jun N-terminal kinase, as well as inhibited proliferation of several human cancer cell lines in the nanomolar range, the researchers concluded that these marine agents might serve as lead candidates for anticancer drug development.

During a screening effort for potential angiogenesis inhibitors, Tong and colleagues[105] discovered a novel sulfated saponin **philinopside A**, isolated from the sea cucumber *Pentacta quandrangulari*, that possessed dual antiangiogenic and antitumour effects. Philinopside A inhibited angiogenesis (IC_{50} = 0.98–1.4 μM) in human microvascular endothelial cells as well as tumour growth both *in vitro* (IC_{50} = 1.5–2.4 μM) and *in vivo* by a synergistic mechanism that appeared to involve inhibition of 4 receptor tyrosine kinases (IC_{50} = 2.6–4.9 μM).

Macherla and colleagues[106] contributed structure–activity relationship (SAR) studies of **salinosporamide A** (NPI-0052), a novel marine bacterium-derived alkaloid shown to potently inhibit the proteasome, a multicatalytic proteolytic complex that is involved in the regulation of cellular protein degradation. With 16 analogues of salinosporamide A generated by either fermentation or derivatisation, SAR studies were

completed using a variety of well-characterised cytotoxicity, proteasome inhibition and NF-κB activation assays. These studies demonstrated a marked reduction in potency resulting from the replacement of the chloroethyl group in salinosporamide A with nonhalogenated substituents.

Liu and colleagues[107] reported novel preclinical pharmacology for the isomalabaricane triterpene **stelletin A**, isolated from the marine sponge *Geodia japonica*. These investigators observed differential cytotoxicity of stelletin A between human leukaemia HL-60 cells (IC_{50} = 0.4 μg/ml) and human prostate cancer LNCaP cells (IC_{50} = 120 μg/ml) with the concomitant up-regulation of the pro-apoptotic marker proteins, FasL and caspase-3. Interestingly, in HL-60 cells stelletin A stimulated a dose-dependent increase of the NADPH oxidase components and generation of reactive oxygen radicals.

Jiang and colleagues[108] reported preclinical mechanism of action studies on the furanosesterterpene **strobilinin–felixinin**, which was isolated from the sponge *Psammocinia* sp. and was previously reported to display cytotoxicity towards several cancer cell lines. Cell cycle analysis revealed that the marine compounds arrested HeLa cells in the S phase, probably as a result of DNA synthesis inhibition, with topoisomerase I and polymerase α-primase, the 'two main target molecules'.

Simone and colleagues[109] extended the molecular pharmacology of **variolin B**, a guanidine alkaloid isolated from the Antarctican marine sponge *Kirkpatrickia variolosa*. Both variolin B and its analogue deoxy-variolin B, which has greater stability and solubility, were shown to activate apoptosis in a p53-independent fashion. They appeared to preferentially inhibit cyclin-dependent kinases (CDK) 1/cyclin B, CDK2/cyclin A and CDK2/cyclin E. Thus, variolin B may be effective against tumours with mutation or deletion of the *p*53 gene.

Oda and colleagues[110] extended the preclinical pharmacology of **verrucarin A**, isolated from a culture broth of the marine fungus *Myrothecium roridum*. Using human promyelocytic and erythroleukaemia cell lines, the investigators determined that verrucarin A's strong cytotoxicity against these cell lines was concomitant to inhibition of the p38 and C-Jun mitogen-activated protein kinases in the nanomolar range.

3. 2005–2006 Antitumour pharmacology of marine natural products with undetermined mechanisms of action

Table 2 encompasses 94 novel marine natural products published during 2005–2006 that demonstrated particularly potent activity in cytotoxicity assays (IC_{50} equal or less than 1.0 μg/ml), and whose structures are shown in Fig. 2. The preclinical pharmacology completed with these marine compounds consisted mainly of *in vitro* and/or *in vivo* cytotoxicity testing with panels of either human or murine tumour cell lines. In a few reports, cytotoxicity studies were more extensive and included the National Cancer Institute 60-tumour cell line screen. It is clear that additional pharmacological testing will be required to help determine if the potent cytotoxicity observed with these marine chemicals resulted from a specific pharmacologic effect rather than a general toxic effect on the tumour cells used in these investigations. Although contrasting with the extensive preclinical and clinical investigations completed with the marine compounds presented in Table 1, the mechanism of action research was reported for only a few of the compounds listed in Table 2: swinholide I and hurghadolide A caused disruption of the actin cytoskeleton at nM concentrations;[111] philinopside A inhibited proliferation, migration and tube formation of human microvascular endothelial cells;[112] exposure of human colorectal cancer cells to tedanolide C resulted in the accumulation of cells in S-phase;[113]; palmerolide A inhibited V-ATPase (IC_{50} = 2 nM);[114] stelletin J promoted binding of DNA with DNA polymerase β;[115] liphagal inhibited phosphatidylinositol-3-kinase α (IC_{50} = 100 nM);[116] seragamide A facilitated G-actin polymerisation (20–200 nM);[117] lyngbyabellin E (60 nM) and ankaraholide A caused disruption of cellular microfilament network and inhibition of cytokinesis[117,118] and secalonic acid D inhibited the cell cycle at the G_0/G_1 phase in a concentration-dependent manner.[120]

Although less potent than the marine natural products as included in Table 2, numerous additional reports were published during 2005–2006 describing novel structurally characterised molecules with cytotoxic activity (IC_{50}) mostly in the greater than 1–5.0 μg/ml range. Although only cytotoxicity against selected murine or human cancer cells was determined *in vitro* in the majority of these reports, mechanistic work was reported in a few of these studies, e.g. inhibition of Tie2 kinase, an enzyme that supports angiogenesis, by polybrominated diphenyl ethers;[121] inhibition of human telomerase by axinelloside A;[122] inhibition of FOX01a, a transcription factor, by psammaplysenes;[123] potent histone deacetylase inhibition and anti-angiogenic effects by the cyclic peptides azumamides A–E[124] and significant antimetastatic activity by the marine cembranoids sarcophine and 2-epi-16-deoxysarcophine.[125]

4. Conclusion

Antitumour marine pharmacology research in 2005–2006 consisted of a combination of preclinical research focused on the molecular and cellular pharmacology of marine cytotoxic agents, as well as clinical studies with a limited number of marine compounds, i.e. aplidine, bryostatin 1, cryptophycins, dolastatins and ecteinascidin-743 (Trabectedin, Yondelis®). Although during 2005–2006 no marine natural product was approved for cancer patient treatment by the US Food and Drug Administration (FDA), ecteinascidin-743 (Trabectedin, Yondelis®) has recently been granted Orphan Drug designation from the European Commission, and the FDA for soft tissue sarcomas and ovarian cancer. Our 2005–2006 overview of the antitumour and cytotoxic pharmacology of marine chemicals demonstrates that, more than 54 years after the discovery by Bergman and colleagues[126] of spongothymidine and spongouridine, global research aimed at the discovery of novel and clinically useful antitumour agents derived from marine organisms continues at a remarkably active pace.

Conflict of interest statement

None declared.

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