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Edward Mwenda

Development of a novel stereo-selective synthetic route towards Pumiliotoxin C, potent neurotoxin, *via* asymmetric Diels-Alder and sequential protonation-nucleophilic addition as key reaction steps

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An Abstract of
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Abstract:

The study towards the synthesis of the naturally occurring (-)-pumiliotoxin C of the dendrobatid alkaloid has been outlined. The bicyclic skeleton of the pumiliotoxin C was be rapidly assembled in one key reaction step using a novel regio- and enantiocontrolled asymmetric [4+2] cycloaddition of $TpMo(CO)_2$(3-alkenyl-η^3-4,5,6-pyridinyl) diene **39**. Diene **39** was formed from the $TpMo(CO)_2$(η^3-5-oxo-pyridinyl) scaffold **27** *via* a Grignard reaction and dehydration reaction. This was later followed by sequential protonation-nucleophilic addition as key reaction step for the introduction of the alkyl side chain.

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I like to thank all the past and present members of the Liebeskind group, Dong-Hyun Koo, Wenyong Chen, Greg Goschy, Biruk, Matt, Wenting, Ethel, Bryan, Zhihui, Hao Li, Reese, Tom, Emily, Bo. Finally, I would like to thank my family for their love and support.

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List of Abbreviations:

Å	Angstrom
Ac	acetate
Anal.	analysis
Ar	aryl
br	broard
Bu	butyl
°C	degrees Celsius
Calcd.	calculated
cat.	catalytic
cm^{-1}	wavenumber unit (IR)
δ	chemical shift (express in ppm for NMR)
d	doublet
DMF	*N*,*N*-dimethylformamide
DMSO	dimethylsulfoxide
equiv	equivalent
Et	ethyl
EtOAc	ethyl acetate
g	gram(s)
GC/MS	gas chromatography/mass spectrometry
h	hour(s)
HRMS	high-resolution mass spectrometry
HCl	hydrochloric acid
Hz	Hertz
IR	infrared spectroscopy
J	coupling constant in Hertz
L	ligand
M	molar
m	multiplet
Me	methyl
mg	milligram
MHz	megahertz
min	minute(s)
mL	milliliter(s)
mmol	millimole
mol	mole
mol%	mole percent
mp	melting point
NaH	sodium hydride
NMR	nuclear magnetic resonance spectroscopy
Ph	phenyl
ppm	part per million

i-Pr	isopropyl
q	quartet
R_f	retardation factor (TLC)
rt	room temperature
s	singlet
t	triplet
TFA	trifluoroacetic acid
TFAA	trifluoroacetic anhydride
THF	tetrahydrofuran
TLC	thin layer chromatography
Ts	*p*-toluenesulfonyl
w	weak

1. Introduction:

Dendrobatid Alkaloids: 2,5-Disubstituted Decahydroquinolines, (-)-Pumiliotoxin C

One of the major classes of dendrobatid alkaloids is the 2,5-disubstituted decahydroquinolines. Pumiliotoxin C (**1**) (**Figure 1**) was the first known member of this family. It was isolated from frog skin which was found in the Panamanian population of *Denbates pumilio*[1] and *Dendrobates auratus.*[2] The structural isolation and absolute configuration of the natural product were unambiguously confirmed by X-ray crystollagraphic analysis of the hydrochloride salt, which was reported in 1969 by Dale and co-workers.[3]

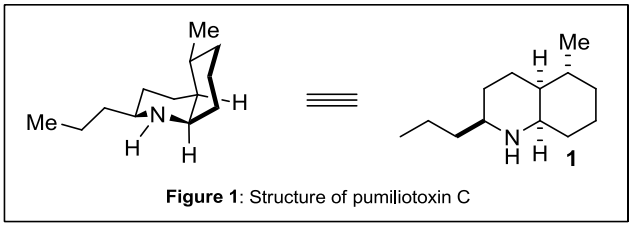

Figure 1: Structure of pumiliotoxin C

Pumiliotoxin C was noted to act as a reversible blocker of the nicotinic acetylcholine receptor channel,[4] making it a great candidate for biological studies of nerve and muscle systems. The unusual chemical structure and biological activity have prompted chemists to develop both chiral and non-chiral synthetic strategies toward this 2,5-disubstituted decahydroquinoline alkaloid in recent years. Owing to these interesting features, several approaches have been demonstrated towards the total synthesis of the dendrobatid alkolid (-)-pumiliotoxin C.

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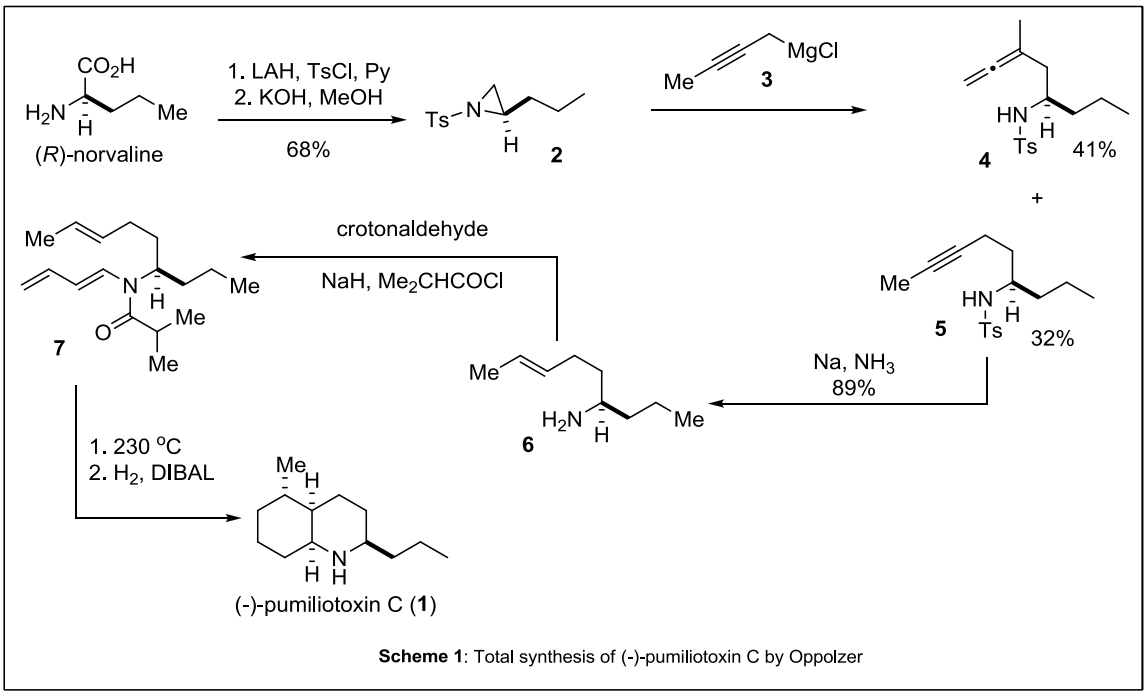
[1] Tokuyama, T.; Nishimori, N.; Shimada, A.; Edwards, M. W.; Daly, J. W. *Tetrahedron* **1987**, *43*, 643.
[2] a) Tokuyama, T.; Tsujita, T.; Shimada, A.; Garraffo, H. M.; Spande, T. F.; Daly, J. W. *Tetrahedron* **1991**, *47*, 5401. b) Daly, J. W.; Secunda, S. I.; Garraffo, H. M.; Spande, T. F.; Wisnieski, A.; Nishihira, C.; Cover, J. F., Jr. *Toxicon* **1992**, *30*, 887.
[3] Daly, J. W.; Tokuyama, T.; Habermehl, G.; Karle, I. L., Witkop, B. *Liebigs Ann. Chem.* **1969**, *729*, 198.
[4] a) Warnick, J. E.; Jessup, P. J.; Overman, L. E.; Eldefrawi, M. E.; Nimit, Y.; Daly, J. W.; Albuquerque, E. X. *Mol. Pharmacol*. **1982**, *22*, 565. b) Daly, J. W.; Nishizawa, Y.; Padgett, W. L.; Tokuyama, T.; McCloskey, P. J.; Waykole, L.; Schultz, A. G.; Aronstam, R. S. *Neurochem. Res*. **1991**, *16*, 1207.

The first total synthesis of (-)-pumiliotoxin C was reported by Oppolzer and co-workers.[5] They reported an efficient asymmetric synthesis of **1** *via* intramolecular Diels-Alder reaction as a key step (**Scheme 1**). The commercial enantiomerically pure starting material (*R*)-norvaline, was converted to the tosylated aziridine **2**, followed by nucleophilic attack with propargylmagnesium bromide **3** leading to ring opening which afforded acetylenic sulfonamide tosylamide **5** with allenic isomer **4** as a major side product.

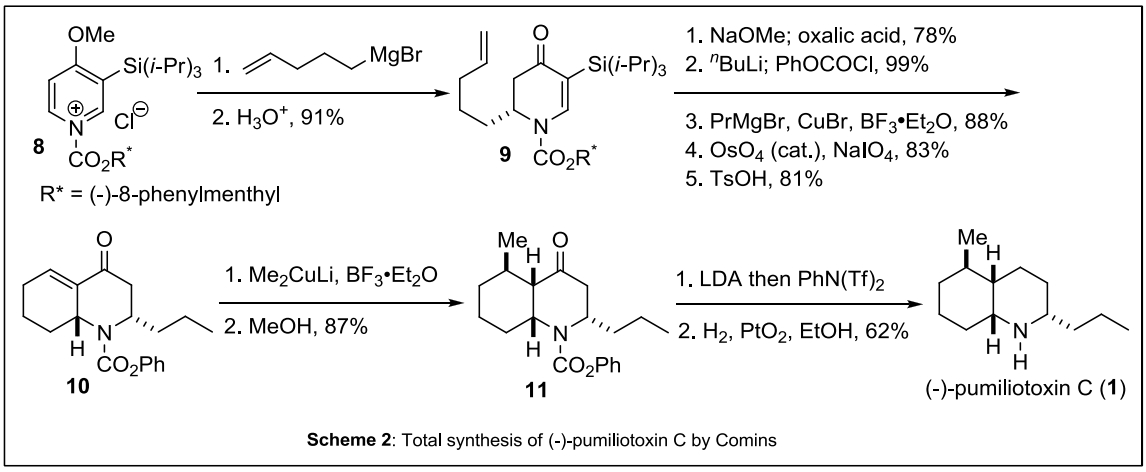


Scheme 1: Total synthesis of (-)-pumiliotoxin C by Oppolzer

Compound **5** was reduced and deprotected to furnish the desired unsaturated amine **6** (*E*)-configuration, which was further converted to isobutyramide **7** - the key intermediate for the IntraMolecular Diels-Alder reaction. IMDA, hydrogenation and cleavage of the amide protecting group afforded the natural product.

[5] a) Oppolzer, W.; Flaskamp, E. *Helv. Chim. Acta* **1977**, *60*, 204. b) Oppolzer, W.; Flaskamp, E.; Bieber, L. W. *Helv. Chim. Acta* **2001**, *84*, 141–145.

The asymmetric synthesis of **1** was also reported by Comins,[6] who achieved the nine steps synthesis starting from 4-methoxy-3-(triisopropylsilyl)pyridine **8**, a scaffold that has been developed in his lab. They carried out the synthesis using the intermediate *N*-acyldihydropyridone **9** as a key substrate (**Scheme 2**).



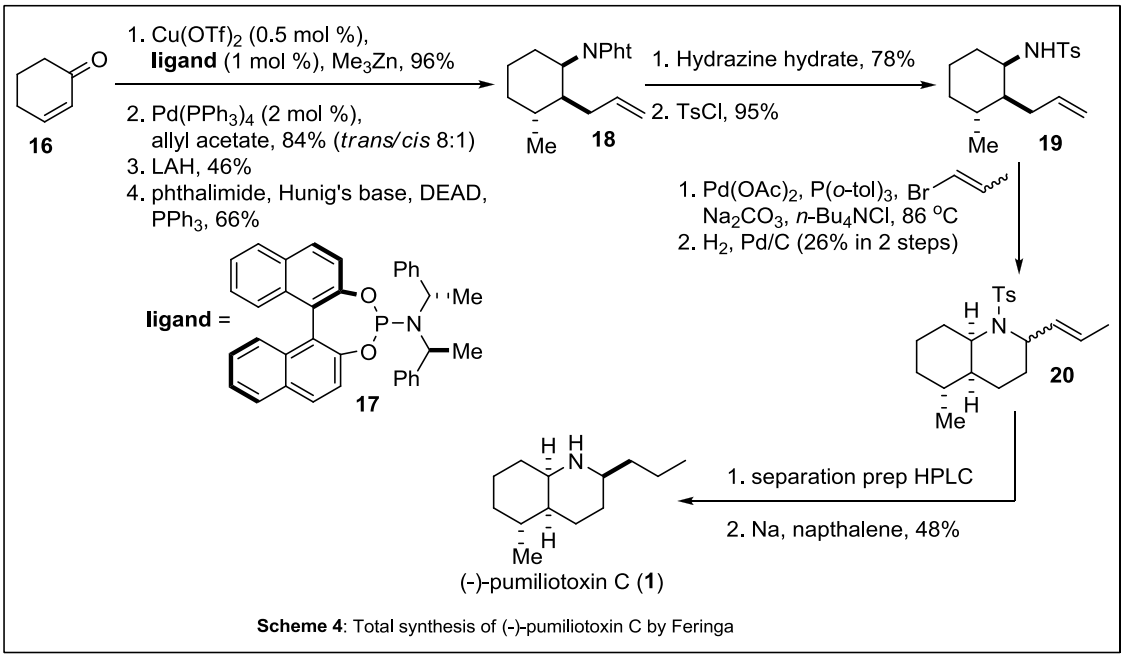
Scheme 2: Total synthesis of (-)-pumiliotoxin C by Comins

Synthesis of **1** started with nucleophilic addition of 1-acylpyridinium salt **8** with 5-(l-penteny1)magnesium bromide to furnish *N*-acyldihydropyridone **9** which was exposed under the reaction conditions to afford enone **10**. The desired stereochemistry was achieved *via* conjugate addition of lithium dimethylcuprate followed by protonation of the intermediate enolate to give ketone **11**. Ketone **11** was then converted to vinyl triflate followed by hydrogenation to give (-)-pumiliotoxin C.

Feringa and coworkers[7] reported a first catalytic asymmetric synthesis of (-)-pumiliotoxin C in 8 steps starting from 2-cyclohexenone **16**. The key reactions in their synthetic approach are a tandem asymmetric conjugate addition–allylic substitution reaction and a tandem Heck-allylic substitution reaction (**Scheme 4**). The synthesis started with the copper-phosphoramidite catalyzed addition of dimethylzinc to **16**, with the help of phosphoramidite

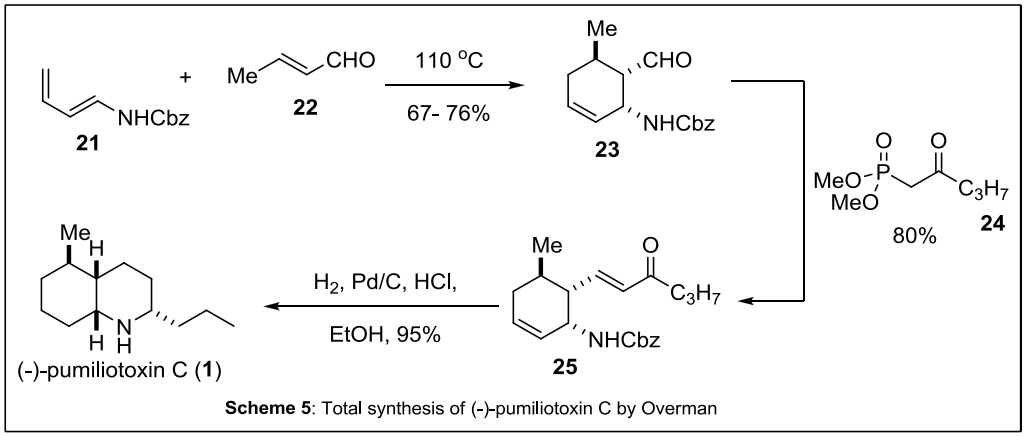
[6] a) Comins, D. L.; Dehghani, A. *J. Chem. Soc., Chem. Commun.* **1993**, 1838. b) Comins, D. L.; Joseph, S. P.; Goehring, R. R. *J. Am. Chem. Soc.* **1994**, *116*, 4719.
[7] Dijk, E. W.; Panella, L.; Pinho, P.; Naasz, R.; Meetsma, A.; Minnaard, A. J.; Feringa, B. L. *Tetrahedron* **2004**, *60*, 9687.

ligand **17**, resulted to an excellent enantioselectivity. The generated zinc enolate was exposed to catalytic $Pd(PPh_3)_4$ and allyl acetate to give a ketone product which was converted to alcohol in the presence LAH.



Scheme 4: Total synthesis of (-)-pumiliotoxin C by Feringa

The alcohol was subjected to Mitsunobu reaction using phthalimide as the nucleophile, to afford **18** in good yield. This was followed by hydrazinolysis and tosylation to furnish *N*-tosylamide **19**. With the key intermediate in hand, the tandem Heck-allylic substitution reaction led to the formation of the desired perhydroquinoline skeleton followed by hydrogenation to give product **20**. Stereoisomers of **20** were separated by preparative HPLC to give the pure isomer of the desired compound with the correct stereochemistry which was followed by removal of the tosyl group to give **1**.

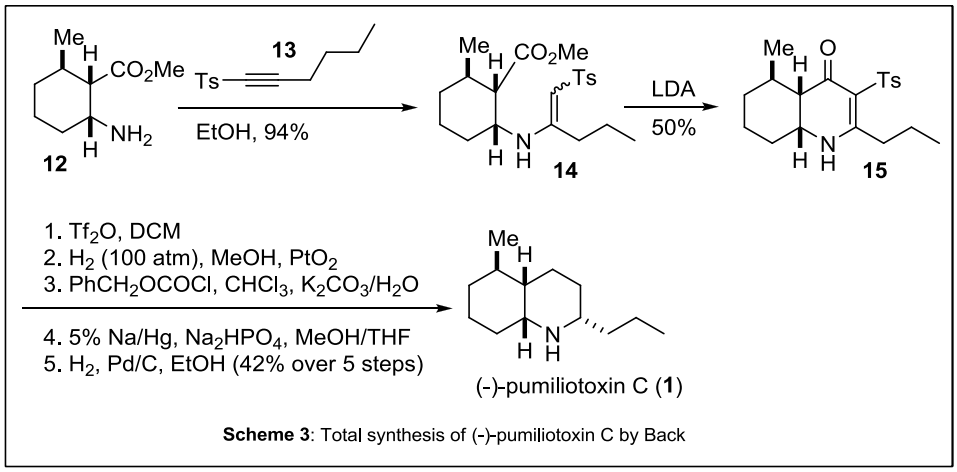


Scheme 5: Total synthesis of (-)-pumiliotoxin C by Overman

Overman's[8] approach toward the racemic synthesis of pumiliotoxin C highlights a Diels-Alder reaction between benzyloxycarbonyl-protected aminobutadiene **21** and commercially available *trans*-crotonaldehyde **22** to give cycloadduct **23** (**Scheme 5**). Phosphonate anion olefination of **23** afforded enone **25,** in good yield, which was followed by hydrogenation in the presence of HCl, to afford racemic pumiliotoxin C in three steps from diene **21.**

Back[9] also reported a concise enantioselective synthesis of (-)-pumiliotoxin C through the conjugate addition reaction of the two key intermediate, enantiopure amino ester **12** and acetylenic sulfone **13** to furnish substrate **14** (**Scheme 3**), followed a by cyclization reaction when exposed to LDA to afford to enaminone **15**. Hydrogenation of the resulting enol triflate followed by reductive desulfonylation of the Cbz protected intermediate followed by deprotection, led to (-)-pumiliotoxin C in 42% over five steps. This is the shortest reported synthesis of **1** to date.

[8] Overman, L. E.;. Jessup, P. J. *J. Am. Chem. Soc*. **1978**, *100*, 5179.
[9] Back, T. G.; Nakajima, K. *J. Org. Chem.* **1998**, *63*, 6566.



Scheme 3: Total synthesis of (-)-pumiliotoxin C by Back

Molybdenum π-Complex Scaffolds: Basic Concept

The development of mild, efficient, stereo and regio-selective synthetic strategies is still an ongoing challenge in modern organic synthesis. The fascinating structural and functional group diversity of naturally occurring products continues to challenge the synthetic chemist to innovate more concise and economical approaches to access these complex molecules, especially those which have revealed pharmacological importance.[10]

In recent years, several strategies have been employed in the synthesis of complex natural products. Achieving high enantioselectivity in chemical bond formation in reactions still remains a challenging task. Several methodologies have been utilized to address the necessity and efficient ways for controlling absolute stereochemistry: employing "chirons"[11] or auxiliaries[12] derived from "chiral pool", classical or enzymatic resolutions,[13] and metallo-[14] or

[10] a) Faulkner, D. J. *Nat. Prod. Rep*. **2000**, *17*, 7-55. b) Faulkner, D. J. *Nat. Prod. Rep*. **1998**, *15*, 113-158. c) Class, Y. J.; DeShong, P. *Chem. Rev.* **1995**, *95*, 1843-1857. d) Norcross, R. D.; Patterson, I. *Chem. Rev*. **1995**, *95*, 2041-2114.

[11] a) Hanessian, S. *Pure Appl. Chem.* **1993**, *65*, 1189-1204. b) Hanessian, S. Total Synthesis of Natural Products: the 'Chiron' Approach; Pergamon Press: Oxford, UK, 1983.

[12] Blaser, H. U. *Chem. Rev.* **1992**, *92*, 935-952.

[13] Mulzer, J. Enzymes in Organic Synthesis. 2. In *Organic Synthesis Highlights*; Mulzer, J., Altenbach, H. J., Braun, M., Krohn, K., Reissig, H. U., Eds.; VCH Verlagsgesellschaft: Weinheim, Germany, 1991; pp 216-223. Mulzer, J. Enzymes in Organic Synthesis. 1. In *Organic Synthesis Highlights*; Mulzer, J., Altenbach, H. J., Braun, M., Krohn, K., Reissig, H. U., Eds.; VCH Verlagsgesellschaft: Weinheim, Germany, 1991; pp 207-215.

[14] Ojima, I. *Catalytic Asymmetric Synthesis*, 2nd ed.; Wiley: New Yort, 2000; p864.

organo-[15] catalytic asymmetric transformations.

Another tactical approach towards enantiocontrolled synthesis is the method that employs enantiomeric scaffolding. In enantiomeric scaffolding, commercial or non-commercial simple starting materials with high enantiopurity act as a pivotal point for the assembly of several members of important natural products. Scaffolds of this type possess a useful functionality that permits stereocontrolled reaction for the formation of the chemical bonds. Examples of enantiomeric scaffolds used in natural synthesis are the Wieland-Miescher ketone[16] and the Roche ester,[17] both of which are commercially available. Other scaffold examples include the works of Comins,[18] Husson and Royer,[19] and Bosch.[20]

Over the past decade the Liebeskind laboratory has employed a strategic approach to enantiocontrolled bond construction in complex organic systems through the use of high enantiopurity organometallic complexes of "enantiomeric scaffolds".

[15] Seayad, J.; List, B. *Org. Biomol. Chem.* **2005**, *3*, 719-724.
[16] Wieland, P.; Miescher, K. *Helv. Chim. Acta* **1950**, *33*, 2215-2228. Selected examples in synthesis: Danishefsky, S. J.; Masters, J. J.; Young, W. B.; Link, J. T.; Snyder, L. B.; Magee, T. V.; Jung, D. K.; Isaacs, R. C. A.; Bornmann, W. G.; Alaimo, C. A.; Coburn, C. A.; Di Grandi, M. J. *J. Am. Chem. Soc.* **1996**, *118*, 2843–2859.
[17] Selected examples in synthesis see: Smith, A. B., III; Adams, C. M.; Lodise Barbosa, S. A.; Degnan, A. P. *Proc. Natl. Acad. Sci. USA*, **2004**, *101*, 12042-12047.
[18] Selected examples: a) Comins, D. L.; King, L. S.; Smith E. D.; Fevrier, F. C. *Org. Lett.* **2005**, *7*, 5059-5062. b) Comins, D. L.; Kuethe, J. T.; Miller, T. M.; Fevrier, F. C.; Brooks, C. A. *J. Org. Chem.* **2005**, *70*, 5221-5234. c) Joseph, S.; Comins, D. L. *Curr. Opin. Drug Discovery Dev.* **2002**, *5*, 870-880.
[19] Husson, H.-P.; Royer, J. *Chem. Soc. Rev.* **1999**, *28*, 383-394.
[20] Selected examples: Escolano, C.; Amat, M.; Bosch, J. *Chem. Eur. J.* **2006**, *12*, 8198-8207. (b) Amat, M.; Perez, M.; Minaglia, A. T.; Casamitjana, N.; Bosch, J. *Org. Lett.* **2005**, *7*, 3653-3656.

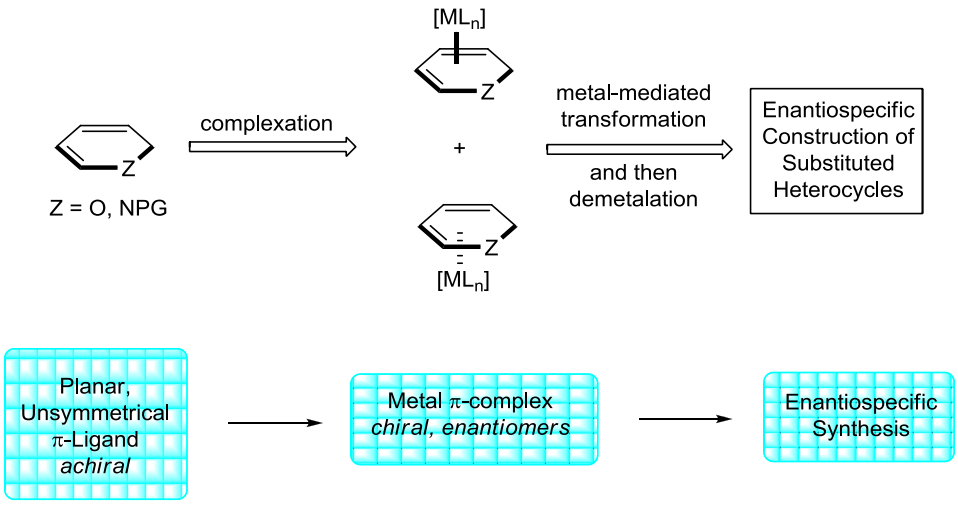


Figure 2: Metal π-complexes in enantiospecific heterocyclic synthesis

In this approach (**Figure 2**), the first step is complexation of a transition metal to a planar, unsymmetrical π-ligand, which results in the formation of two enantiomers of an inexpensive and air-stable metal π-complex. The two enantiomers can easily be separated using chiral reagents.[21] Successive metal-mediated transformations of the scaffold, which are often regio- and stereo-controlled (**Figure 3**), followed by demetalation, will generate heterocycles with multiple stereocenters.

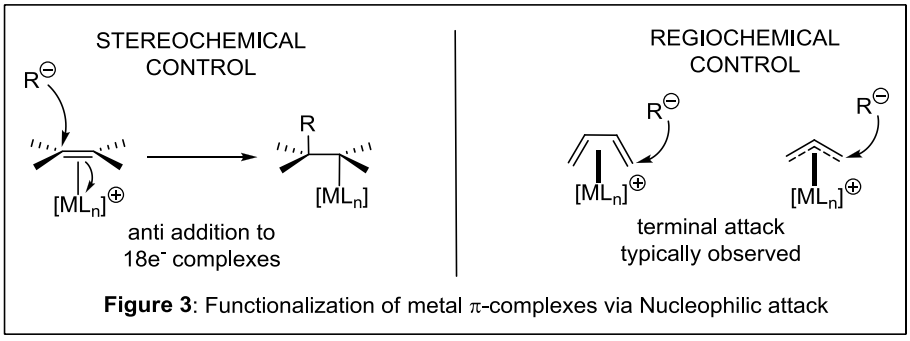


Figure 3: Functionalization of metal π-complexes via Nucleophilic attack

The transition metal complex chemistry developed in the Liebeskind laboratory utilizes four crucial molybdenum-based organometallic enantiomeric scaffolds based on oxygen and nitrogen-containing heterocycles (**Figure 4**).

[21] Coombs, T. C.; Lee, M. D., IV; Wong, H.; Armstrong, M. A.; Cheng, B.; Chen, W.; Moretto, A. F.; Liebeskind, L. S. *J. Org. Chem.* **2008**, *73*, 882-888.

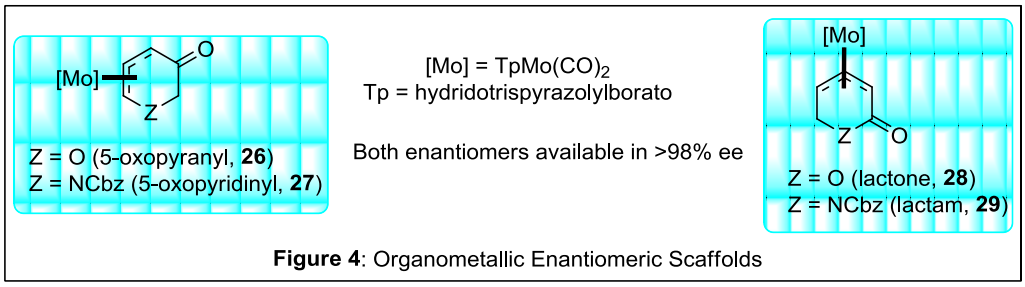


Figure 4: Organometallic Enantiomeric Scaffolds

Synthesis of Substituted Heterocycles of High Enantiopurity using Heterocycle Metal π-Complexes as Chiral Scaffolds

Over the past decade, the simple chiral, air stable starting materials, $TpMo(CO)_2(\eta^3$-5-oxo-pyranyl) and $TpMo(CO)_2(\eta^3$-5-oxo-pyridinyl), complexes **26** and **27**, respectively have been used in the total synthesis of various families of heterocyclic natural products with potential medicinal interest. Starting with **26** and **27** of high enantiopurity diverse methodogies have been developed, such as sequential functionalization, [5+2] cycloaddition, [5+3] cycloaddition and [4+2] cycloaddition (**Figure 5**).

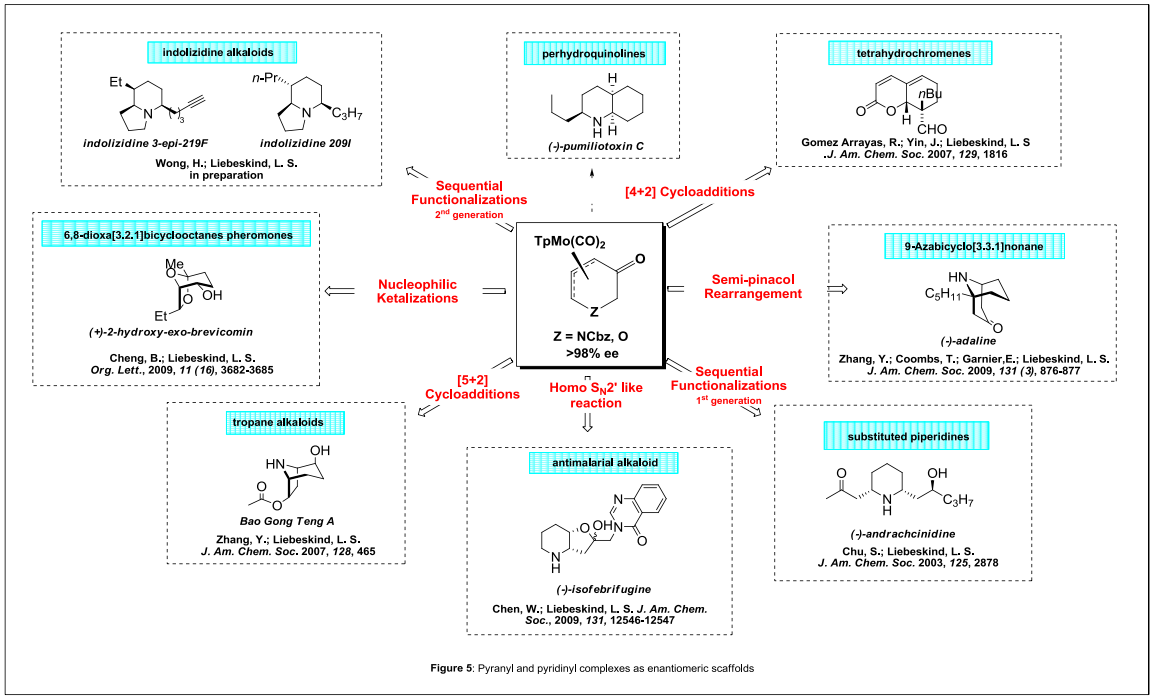
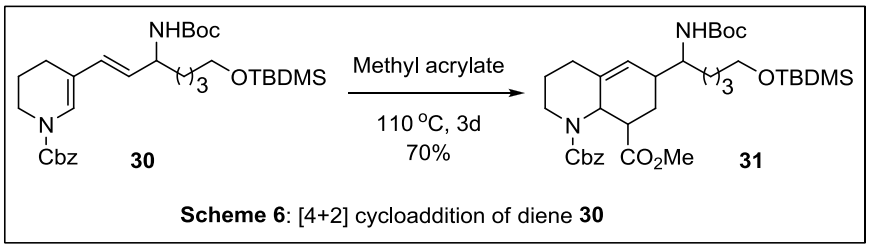


Figure 5: Pyranyl and pyridinyl complexes as enantiomeric scaffolds

Regio- and Enantiocontrolled [4+2] Cycloaddition of Molybdenum-based Scaffolds

In contrast to transition metal-mediated [3+2] cycloaddition reactions,[22] metal-assisted [4+2] cycloadditions are still an unexplored field in synthetic organic chemistry. Overman and coworkers[23] have reported unsuccessful attempts of [4+2] cycloaddition reactions of racemic oxazolidinone **30** with various dienophiles. Only methyl acrylate (**Scheme 6**) was able to undergo the Diels-Alder reaction to furnish mixture of two major cycloadducts (1.4:1) and one minor which couldn't be separated easily by chromatographic purification.[22] Moreover, cycloaddition proceeded under high temperature and longer reaction time. Attempts using Lewis acid-mediated conditions at low temperature were unsuccessful.



Scheme 6: [4+2] cycloaddition of diene **30**

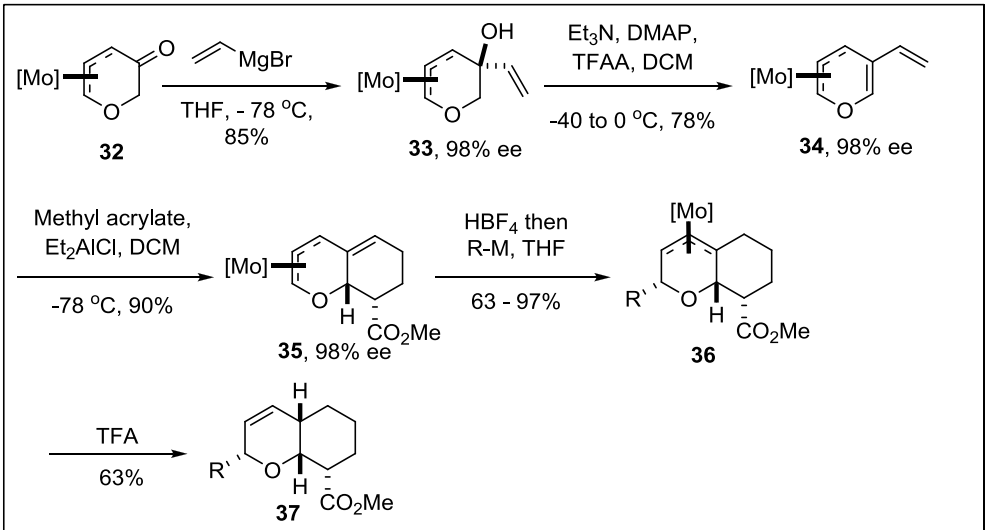
Recently, the Liebeskind laboratory[24] has developed a novel regio- and enantiocontrolled methodology taking advantage of a Lewis acid-mediated [4+2] cycloaddition of $TpMo(CO)_2$(3-alkenyl-η^3-4,5,6-pyranyl) complexes to provide functionalized pyrans (**Scheme 7**). In this strategic approach, the Lewis acid-catalyzed cycloaddition proceeded smoothly with excellent *endo*-selectivity to provide cycloadduct **35,** the excellent regio- and stereoselectivity attributed to attack of the dienophile at the face of the diene away from the molybdenum. From

[22] a) Frühauf, H.-W. *Chem. Rev*. **1997**, *97*, 523. b) Welker, M. E. *Chem. Rev*. **1992**, *92*, 97. c) Wojcicki, A. *Coord. Chem. Rev*. **1990**, *105*, 35. d) Rosenblum, M. *J. Organomet. Chem.* **1986**, *300*, 191. e) Wojcicki, A. Fudam. Res. Organomet. Chem., Proc. China-Jpn.-U. S. Trilateral Semin. Organomet. Chem., 1st, Tsutsui, M.; Ishii, Y.; Yaozeng, H., Ed.; Van Nostrand Rheingold Co.: New York, 1982, pp 569. f) Chen, T.; Jiang, S.; Turos, E. *Tetrahedron Lett*. **1994**, *35*, 8325. g) Jiang, S. C.; Turos, E. *Organometallics* **1993**, *12*, 4280. h) Jiang, S. C.; Turos, E. *Tetrahedron Lett*. **1991**, *32*, 4639.

[23] Brosius, A. D.; Overman, L. E.; Schwink, L. *J. Am. Chem. Soc*. **1999**, *121*, 700.

[24] Arrayás, R. G.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2001**, *123*, 6185-6186.

$TpMo(CO)_2(\eta^3$-5-oxo-pyranyl) starting material, diene **34** was easily prepared in two steps *via* Grignard addition and dehydration reaction. A novel protonation-nucleophilic addition transformation of **35** lead to **36** in excellent yield followed by TFA demetalation gave oxadecalines product **37** in good yield.



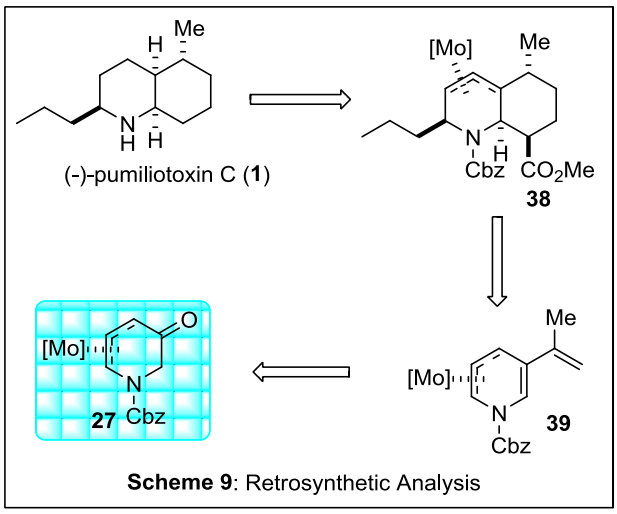
Scheme 7: [4+2] cycloaddition/demetalation sequence provides 2,6-*cis* tetrahydrochromenes

Proposed Synthesis of (-)-Pumiliotoxin C using Molybdenum Scaffold

The first generation total synthesis of (-)-pumiliotoxin C using stoichiometric organomolybdenum complexes was a project initiated by Dr. Chutian Shu,[25] subsequently undertaken and modified by Shuangpei Liu.[26] Liu's retrosynthetic approach for the construction of decahydroquinolines is shown below (**Scheme 9**). The bicyclic skeleton **38** could be rapidly assembled in one step using a novel regio- and enantiocontrolled asymmetric [4+2] cycloaddition of $TpMo(CO)_2$(3-alkenyl-η^3-4,5,6-pyridinyl) diene **39**. Diene **39** could be easily formed with high enantioselectivity from the $TpMo(CO)_2(\eta^3$-5-oxo-pyridinyl) **27** *via* a Grignard reaction and dehydration reaction. As demonstrated from Dr. Arrayas work,[27] A Diels-Alder reaction would

[25] Shu, C.T. Ph.D. Dissertation, 2002, Emory University.
[26] Liu, S. Master Thesis, 2006, Emory University.
[27] Arrayás, R. G.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2001**, *123*, 6185-6186.

generate two new stereocenters by the controlled approach of the dienophile away from the bulky molybdenum complex. Moreover, sequential functionalization-demetallation steps will lead to the target molecule.



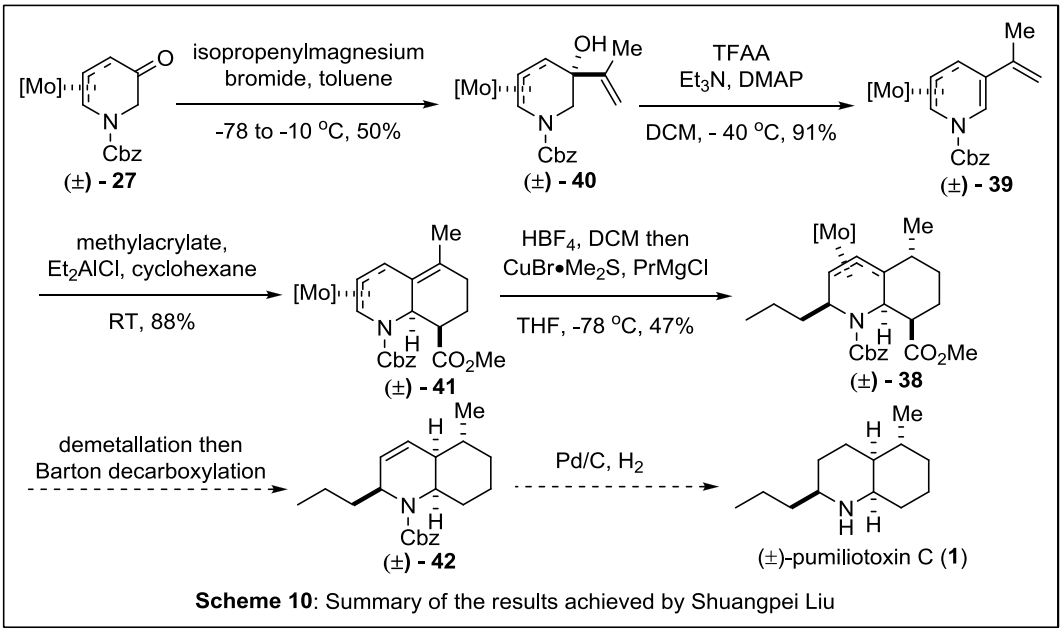
Scheme 9: Retrosynthetic Analysis

Previous studies directed towards the total synthesis of (±)-**1** are summarized below (**Scheme 10**). This approach employs racemic starting material **27** as a model study for the synthesis. In the first step, scaffold **27** was subjected to Grignard reaction with isopropenylmagnesiun bromide to give alcohol **40**. The resulting alcohol was treated with TFAA in the presence of triethylamine to afford the desired diene **39**, which was reacted with methyl acrylate and a full equivalent of Et_2AlCl for the key [4+2] cycloaddition step to furnish of cycloadduct **41**. This was followed by a sequential protonation-nucleophilic addition to attach the alkyl side chain to form product **38**. Demetallation, and a Barton decarboxylation and hydrogenation were the proposed final steps to reach the targeted racemic natural product **1**.

In this synthetic route, the key sequential protonation-nucleophilic addition step was found to be challenging owing to not only low reaction yield but irreproducibility.[28] It was hypothesized that the presence of the additional functional group (-CO_2Me) in the cycloaddition

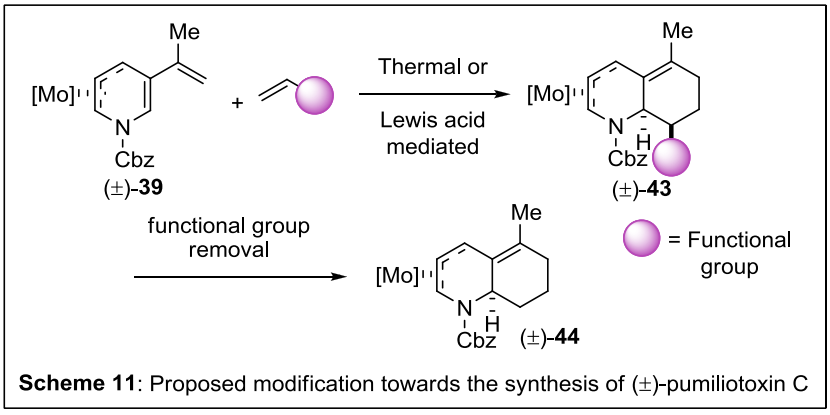
[28] Shu, C.T. Ph.D. Dissertation, 2002, Emory University

product, competes with the double bond adjacent to η^3-allylmolybdenum moiety during the protonation step, hence resulting to poor yields and side reactions.



Scheme 10: Summary of the results achieved by Shuangpei Liu

In this project a third generation of the synthesis was proposed with modifications to addresses the challenges in the sequential protonation-nucleophilic addition step.



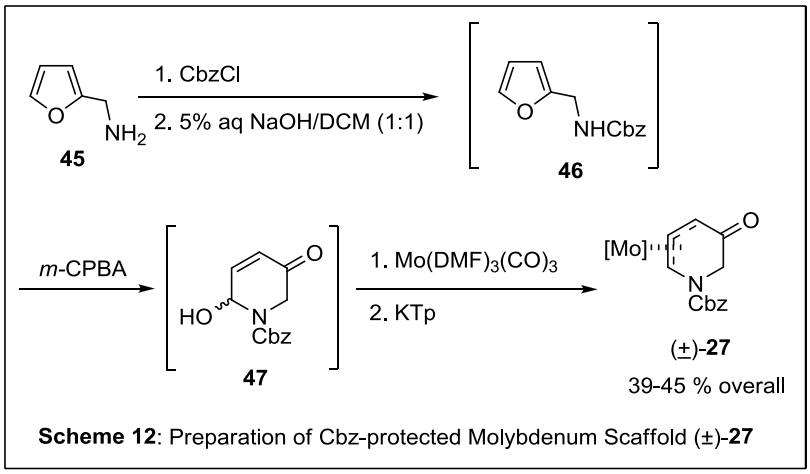
Scheme 11: Proposed modification towards the synthesis of (±)-pumiliotoxin C

As shown in **Scheme 11**, a new dienophile has to be employed such that upon formation of the cycloadduct **43**, the dienophile functional group can be easily removed to form **44**, adding no extra functionality/Lewis basic sites that would interfere with the sequential protonation-nucleophilic addition step.

2. Results and Discussion:

Synthesis of $TpMo(CO)_2(\eta^3$-5-oxo-pyridinyl) Scaffold

The synthesis of racemic $TpMo(CO)_2(\eta^3$-5-oxo-pyridinyl) complex **27** was significantly improved[29] using the Achmatowicz reaction as follows.[30] In the first step (**Scheme 12**), a mixture of 5 % NaOH/DCM [1:1] was used to protect furfuryl amine **45** with CbzCl, providing compound **46**, without column chromatographic purification. This was followed by the oxidative rearrangement of Cbz-protected furfuryl amine **46** in the presence of *m*-CPBA to provide the aza-Achmatowicz rearrangement product **47**. Without further purification, oxidative addition to **47** with $Mo(CO)_3(DMF)_3$,[31] followed by ligand exchange with potassium hydridotris(1-pyrazolyl)borate (KTp)[32] provided the racemic scaffold **27** in 39-45 % yield from **45**. This reaction sequence can be carried out on large scale to generate the starting materials on multi-gram scale.

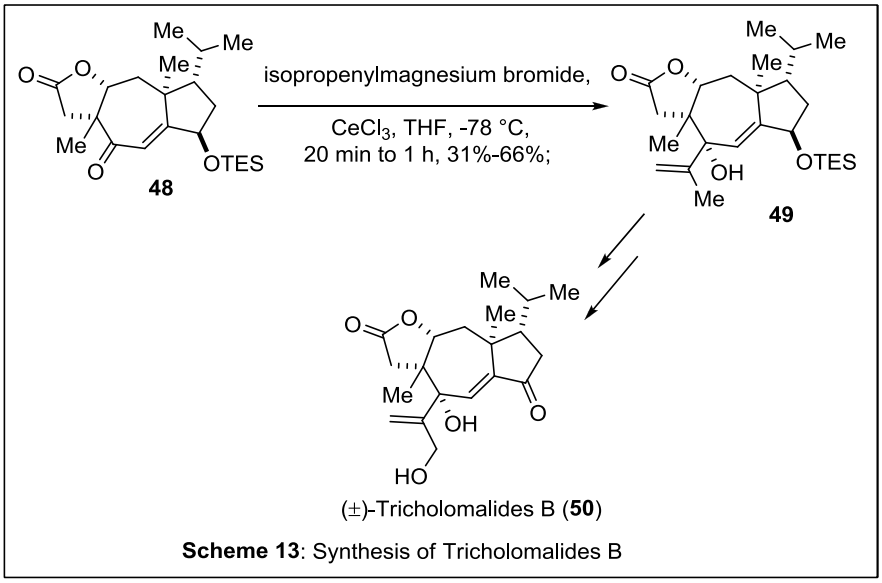


Scheme 12: Preparation of Cbz-protected Molybdenum Scaffold (±)-**27**

[29] Coombs, T. C.; Lee, M. D., IV; Wong, H.; Armstrong, M. A.; Cheng, B.; Chen, W.; Moretto, A. F.; Liebeskind, L. S. *J. Org. Chem.* **2008**, *73*, 882-888.
[30] Achmatowicz, O., Jr.; Bukowski, P.; Szechner, B.; Zwierzchowska, Z.; Zamojski, A. *Tetrahedron* **1971**, *27*, 1973-1996.
[31] Pasquali, M.; Leoni, P.; Sabatino, P.; Braga, D. *Gazz. Chim. Ital.* **1992**, *122*, 275-277.
[32] a) Trofimenko, S. *Chem. Rev.* **1993**, *93*, 943-980. b) Trofimenko, S. *J. Am. Chem. Soc.* **1967**, *89*, 3170-3177.

Grignard Addition to $TpMo(CO)_2(\eta^3$-5-oxo-pyridinyl) Scaffold: Optimization[33]

In an effort to afford alcohol **40**, $TpMo(CO)_2(\eta^3$-5-oxo-pyridinyl) complex **27** was reacted with an excess of isopropenylmagnesiun bromide (3.0 – 8.0 equiv.) in THF at -78 ^oC and the reaction mixture was slowly brought to room temperature. Nevertheless, poor conversion of the starting material was always observed. This is due to the facile enolization of the starting material. To optimize the reaction yield, a modification of Danishefsky's[34] conditions were used to minimize the enolization. In their studies towards the total synthesis and structural revision of (±)-tricholomalides A and B, as outlined in **Scheme 13**, enone **17** was subjected to Grignard-type conditions[35] to provide alcohol **18** (31−66%) yield.



Scheme 13: Synthesis of Tricholomalides B

Utilizing the cerium-modified reagent, which is more nucleophilic and less basic, led to surpression of enolization, complete conversion of the starting material, and higher isolated

[33] For further optimization studies see: Liu, S. Master Thesis, 2006, Emory University

[34] Wang, Z.; Min, S-J.; Danishefsky.; *J. Am. Chem. Soc*. **2009**, *131*, 10848–10849. Yields were significantly dependant on the quality of cerium reagent preparation such as dryness and $CeCl_3$/THF slurry. See experimental section for details.

[35] Imamoto, T.; Kusmoto, T.; Tawarayama, Y.; Sugiura, Y.; Mita, T.; Hatanaka, Y.; Yokoyama, M. *J. Org. Chem.* **1984**, *49*, 3904-3912. (b) Imamoto, T.; Takiyama, N.; Nakamura, K.; Hatajima, T.; Kamiya, Y.; *J. Am. Chem. Soc*. **1989**, *111*, 4392-4398.

yields of alcohols as shown in **Table 1**.

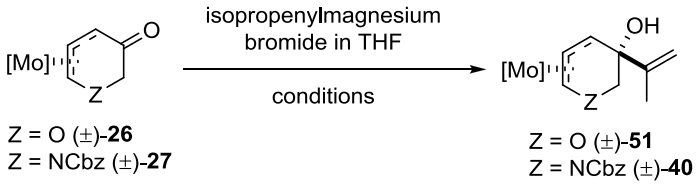


Table 1: Optimization of grignard reaction

Z	Grignard equiv	Additive	Solvent	Temp (^{o}C)	Yield (%)
O	3.0 – 8.0	-	Toluene	-78→RT	65
	5.0	-	THF	-40→-10	79
	1.5	$CeCl_3.7H_2O$ (1.5 equiv)	THF	-78	97[a]
NCbz	3.0 – 8.0	-	Toluene	-78→RT	30→65[b]
	3.0 – 8.0	-	THF	-78→RT	30→40[c]
	1.5	$CeCl_3.7H_2O$ (1.5 equiv)	THF	-78	85→90[a,d]

[a] Reaction time, 10 min [b] SM = (40→50%). [c] SM = (20→30%). [d] No starting material recovered

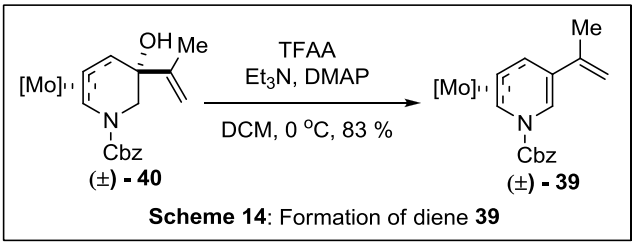
From **Table 1** it can be observed that the excess amount of cerium-modified Grignard required for the reaction to complete is very small and starting material is recovered. Moreover the reaction time is significantly shorter and the conditions work well for both the pyranyl- and pyridinylmolybdenum systems.

Dehydration Reaction: Diene Formation

The dehydration of **40** proved to be somewhat more difficult than originally anticipated.[36] Typical reaction conditions[37] led to low yield of the desired diene **39** and the production of side products, which likely result from a Friedel−Crafts-like reaction of the diene molybdenum complex with TFAA. Fortunately, utilizing the improved procedure by Dr. Wong,[38] the dehydration of **40** with TFAA/Et_3N in the presence of two equivalent of DMAP

[36] Liu, S. Master Thesis, 2006, Emory University.
[37] Conditions includes TFAA, Et_3N, CH_2Cl_2, room temperature, 40 h. Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1999**, *121*, 5811−5812.
[38] Wong, H.; Garnier-Amblard, E.C.; Liebeskind, L.S.; *J. Am. Chem. Soc.*, **2011**, *133*, 7517–7527.

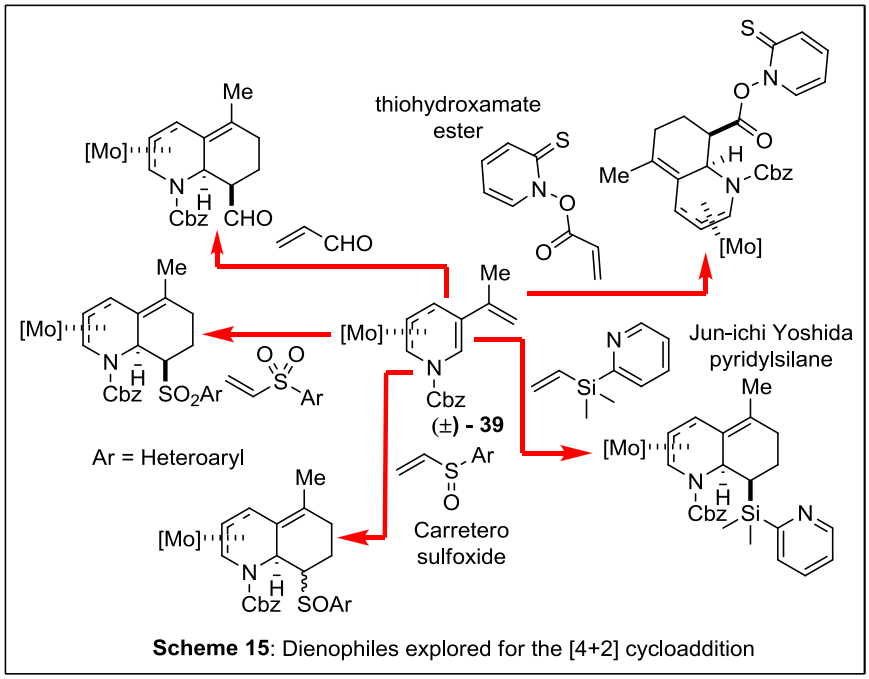
proceded cleanly and rapidly under mild conditions (DCM, 10 min, 0 °C) to give diene **39** in 83% yield.



Scheme 14: Formation of diene **39**

Approach to Bicyclic Skeleton: [4+2] Cycloaddition of the Pyridinyl Mo Complex

As depicted in **Scheme 15**, a variety of dienophiles, including a non-traditional dienophile such as Jun-ichi Yoshida's pyridylsilane,[39] were employed as potential candidates for this study. After several attempts, only vinyl sulfone and acrolein were successful dienophiles to undergo [4+2] cycloaddition in both thermal and Lewis acid mediated conditions.

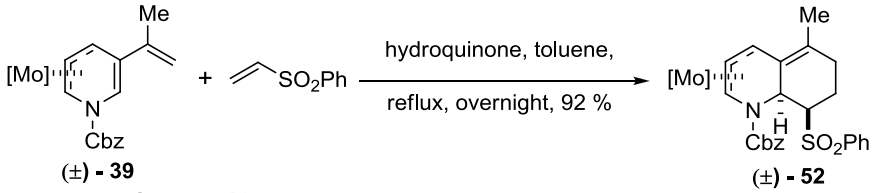


Scheme 15: Dienophiles explored for the [4+2] cycloaddition

[39] a) K. Itami, K. Mitsudo, K. Fujita, Y. Ohashi, and J. Yoshida, *J. Am. Chem. Soc*. **2004**, *126*, 11058-11066. b) K. Itami, Y. Ushiogi, T. Nokami, Y. Ohashi, and J. Yoshida, *Org. Lett.* **2004**, *6*, 3695-3698. c) Nokami, T.; Tomida, Y.; Kamei, T.; Itami, K.; Yoshida, J. *Org. Lett.* **2006**, *8*, 729-731.

Thermal [4+2] Cycloaddition: Using Vinyl Sulfone

Thermal [4+2] cycloadditions were performed with molybdenum diene **39** using dienophiles bearing strong electron withdrawing groups. After several attempts toluene was found to be the best solvent for this transformation (**Scheme 16**).[40] Simply refluxing diene **39** and hydroquinone in toluene overnight with a highly reactive phenyl vinyl sulfone led to the formation of a single diastereomeric cycloadduct **52** in an excellent yield, 92 %.



Scheme 16: [4+2] cycloaddition of with phenyl vinyl sulphone

The excellent *endo*-selectivity is due to the bulky $TpMo(CO)_2$ moiety which induces complete facial diastereoselectivity derived from attack of the dienophile at the face of the diene away from the molybdenum. The regiochemistry and the *endo* stereochemistry of the cycloadducts **52** were unambiguously established by X-Ray crystallographic analysis.

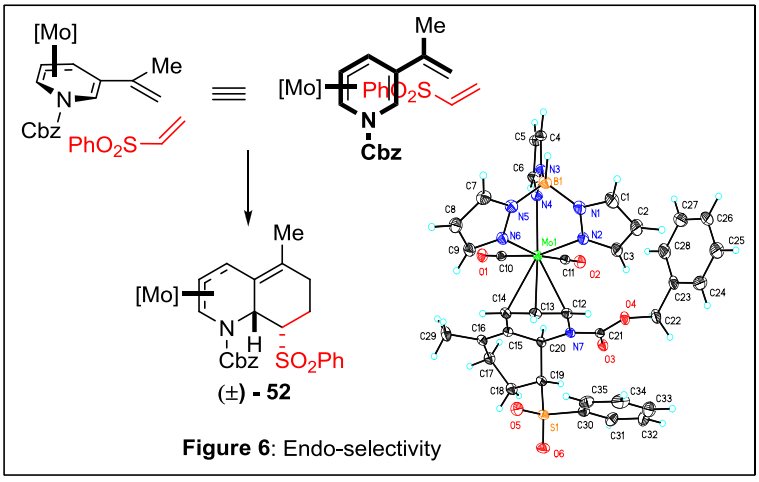
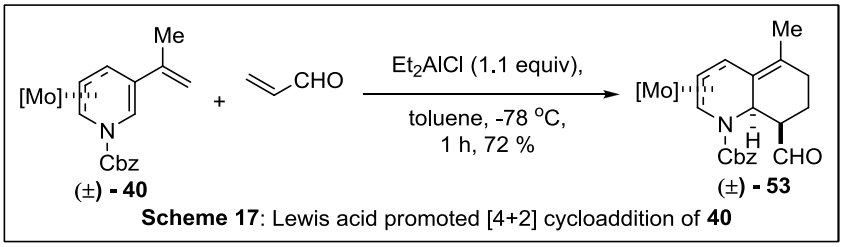


Figure 6: Endo-selectivity

[40] Other solvents such as benzene, DMF, DCM, THF, dioxane were tested. Moreover using full equivalent ofLlewis acid, Et_2AlCl in DCM, toluene, cyclohexane did not give desired product.

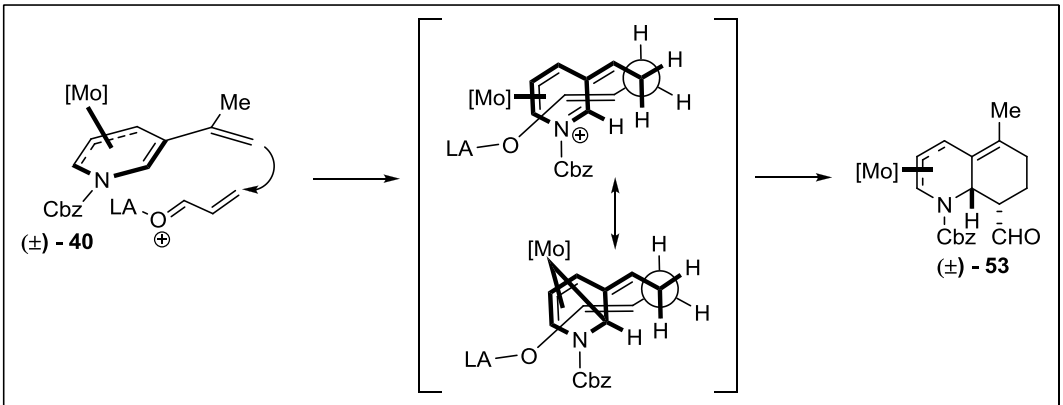
Lewis Acid Mediated [4+2] Cycloaddition: Using Acrolein

The novel methodology directed towards highly functionalized of 1-oxadecalines, the regio- and enantiocontrolled [4+2] cycloadditions of the $TpMo(CO)_2$(3-alkenyl-η^3-4,5,6-pyranyl) complexes[41] demonstrated the need for a full equivalent of Et_2AlCl to drive the reaction to completion. Similarly, using the same reaction conditions, when **40** was treated with acrolein in the presence of Et_2AlCl cycloadduct **53**, a single diastereomer was obtained in good yield (72 %) after only 1 h at -78 °C.



Scheme 17: Lewis acid promoted [4+2] cycloaddition of **40**

The observed regio- and stereoselectivities of this cycloaddition reaction with acrolein can also be explained as a result of the bulky $TpMo(CO)_2$ group, which blocks the approach of diene system which invokes a stepwise, *endo*-selective mechanism shown in **Scheme 18**.[39]



Scheme 18: Proposed mechanism for cycloaddition of **40**

[41] Arrayás, R. G.; Jingjun, Y.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2007**, *129*, 1816-1825.

Functional Group Removal

Desulfonylation

Since the success of a thermal [4 + 2] cycloaddition step for the synthesis of the bicyclic structure using phenyl vinyl sulfones would depend crucially on the desulfonylation of **52**, a variety of desulfonylating agents available in the literature[42] were investigated (**Table 2**). Na-Hg-mediated reduction[43] is the most widely used radical-based method for the desulfonylation of organic molecules and has been used extensively for the desulfonylation. Another electron-transfer method that uses Mg metal in methanol has also been reported.[44] However, none of these reagents were able to efficiently desulfonylate **52** (**Table 2**, entry 1 and 2), with starting material being recovered even at room temperature. Moreover, a mixture of *n*Bu_3SnH and AIBN is known for it's ability to induce desulfonylation but in this case it was not suitable for the removal of the sulfonyl group (**Table 2**, entry 3). In all cases studied, sodium and lithium napthalenides, were found to be too harsh and led to decomposition. Reaction systems making direct use of Raney-Ni for the reduction of sulfones to the corresponding carbon-hydrogen bonds have been reported.[45] However, exposing **52** to Raney-Ni was shown to be unsuccessful as it resulted to the deprotection of Cbz group in 55% yield (**Table 2**, entry 7). At this point, attention was directed towards the decarbonylation of the Lewis acid promoted cycloaddition product using acrolein.

---

[42] For a review on desulfonylation, see: Najera, C.; Yus, M. *Tetrahedron.* **1999**, *40*, 10547

[43] Francüois, D.; Lallemand, M. C.; Selkti, M.; Tomas, A.; Kunesch, N.; Husson, H. P. *Angew. Chem., Int. Ed.* **1998**, *37*, 104.

[44] For a review on Mg in MeOH, see: Lee, G. H.; Youn, I. K.; Choi, E. B.; Lee, H. K.; Yon, G. H.; Yang, H. C.; Pak, C. S. *Curr. Org. Chem.* **2004**, *8*, 1263.

[45] For a review on Mg in MeOH, see: Lee, G. H.; Youn, I. K.; Choi, E. B.; Lee, H. K.; Yon, G. H.; Yang, H. C.; Pak, C. S. *Curr. Org. Chem.* **2004**, *8*, 1263.

[45] a) Oikawa, M.; Oikawa, H.; Ichthara, A. *Tetrahedron Lett*. **1993**, *34*, 4797. b) Oikawa, M.; Oikawa, H.; lchihara, A. *Tetrahedron* **1995**, *51*, 6237. c) Gamble, M. P.; Giblin, G. M. P.; Taylor. R. J. K. *Synlett* **1995**, 779. d) Sheehan, S. M.; Padwa, A. *J. Org. Chem.* **1997**, *63*, 4438.

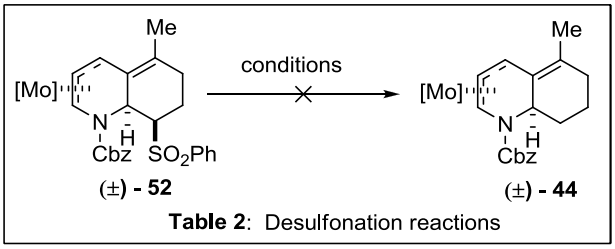


Table 2: Desulfonation reactions

Entry	Reagents	Solvent	Temp (^{o}C)	Results
1	10 % Na/Hg amalgam, Na_2HPO_4	THF:MeOH (1:2)	-30→RT	SM
2	Mg, 20 mol % $NiBr_2$	MeOH	-60	SM
3	*n*Bu_3SnH, AIBN	toluene	reflux	SM
4	Na naphthalenide	DME	-60	decomposition
5	Li naphthalenide	DME	-60	decomposition
6	Li naphthalenide	THF	-78	decomposition
7	Raney-Ni (excess)	isopropanol	reflux	55 % side product[a]

[a] Cbz deprotection of **52**

Decarbonylation

The efficient decarbonylation of aldehydes used in complex synthesis, is still one of the challenges in synthetic organic chemistry.[46] The first decarbonylation reaction of aldehydes was reported by Tsuji and Ohno employing a stoichiometric amount of Wilkinson's complex, $RhCl(PPh_3)_3$.[47] Meanwhile, the first catalytic decarbonylation reaction was reported by Doughty and Pignolet.[48] They found that using chelating diphosphines ligand with rhodium complexes, their reactivity as catalysts was significantly improved.

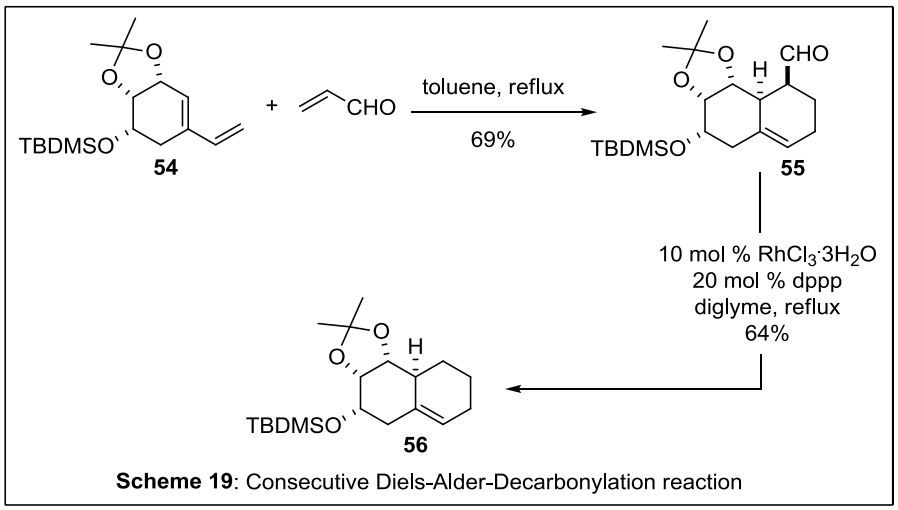
Recently, Madsen and co-workers reported a more practical catalytic approach for the decarbonylation of a wide range of aldehydes using commercially available $RhCl_3 \cdot 3H_2O$ and

[46] *a*) Padwa, A.; Zhang, H. *J. Org. Chem.* **2007**, *72*, 2570–2582; *b*) Zhang, H.; Padwa, A. *Tetrahedron Lett.* **2006**, *47*, 3905–3908; *c*) Ikeda, S.; Shibuya, M.; Iwabuchi, Y. *Chem. Commun.* **2007**, 504–506; *d*) Malerich, J. P.; Maimone, T. J.; Elliott, G. I.; Trauner, D. *J. Am. Chem. Soc.* **2005**, *127*, 6276–6283; *e*) Harmata, M.; Wacharasindhu, S. *Org. Lett.* **2005**, *7*, 2563–2565; *f*) Kato, T.; Hoshikawa, M.; Yaguchi, Y.; Izumi, K.; Uotsu, Y.; Sakai, K. *Tetrahedron* **2002**, *58*, 9213–9222; *g*) Zeng, C. M.; Han, M.; Covey, D. F.: *J. Org. Chem.* **2000**, *65*, 2264–2266; *h*) Sobrio, F.; Amokhtari, M.; Gourand, F.; Dhilly, M.; Dauphin, F.; Barré, L. *Bioorg. Med. Chem.* **2000**, *8*, 2511–2518; *i*) Weatherhead, G. S.; Cortez, G. A.; Schrock, R. R.; Hoveyda, H. A. *Proc. Natl. Acad. Sci. U. S. A.* **2004**, *101*, 5805–5809; *j*) Boeckman, Jr,, R. K.; Zhang, J.; Reeder, M. R. *Org. Lett.* **2002**, *4*, 3891–3894.

[47] *a*) Tsuji, J.; Ohno, K. *Tetrahedron Lett.* **1965**, *6*, 3969–3971; *b*) Ohno, K.; Tsuji, J. *J. Am. Chem. Soc.* **1968**, *90*, 99–107.

[48] Doughty, D. H.; Pignolet, L. H., *J. Am. Chem. Soc.* **1978**, *100*, 7083–7085.

dppp [1,3-bis(diphenylphosphino)propane] in diglyme solution.[49] To demonstrate the synthetic usefulness of the methodology, they investigated the decarbonylation of aldehyde **55** (**Scheme 19**).



Scheme 19: Consecutive Diels-Alder-Decarbonylation reaction

Aldehyde **55** was prepared from the Diels-Alder reaction of diene **54** and acrolein. Exposing **55** to decarbonylation conditions led to smoothly formation of bicyclic cycloadduct **56** in good yield without cleaving the protecting group. Owing to the core skeleton similarity between **55** and **53**, these reaction conditions seemed to be a great starting point for the investigation of decarbonylation of the molybdenum complex **53**.

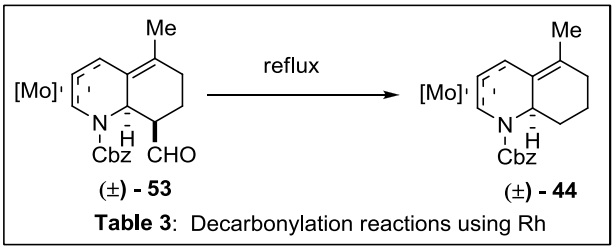


Table 3: Decarbonylation reactions using Rh

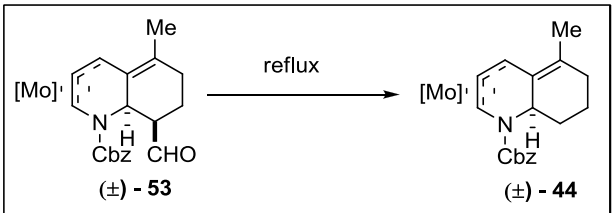
Entry	Reagents	Solvent	Time (h)	Results (%)
1	$Rh(PPh_3)_3Cl$ (1.5 eq)	toluene	24	86
2	$RhCl_3{\cdot}3H_2O$ (5 mol %), dppp (10 mol %)	diglyme	48	trace
3	$RhCl_3{\cdot}3H_2O$ (5 mol %), dppp (10 mol %)	toluene	48	trace
4	$RhCl_3{\cdot}3H_2O$ (5 mol %), dppp (10 mol %)	dioxane	48	trace
5	$RhCl_3{\cdot}3H_2O$ (5 mol %), dppp (10 mol %)	DMSO	48	trace
6	$RhCl_3{\cdot}3H_2O$ (5 mol %), dppp (10 mol %)	DME	48	trace

[49] Fristrup, P.; Kreis, M.; Palmelund, A.; Norrby, P.; Madsen, R. *J. Am. Chem. Soc.* 2008, **130**, 5206–5215.

7	$RhCl_3{\cdot}3H_2O$ (10 mol %), dppp (20 mol %)	diglyme	48	trace

Other ligands tried BINAP, PPh_3

When the decarbonylation of **53** was carried out in the presence of 1.5 equivalent of Wilkinson's catalyst in refluxing toluene, the decarbonylation product **44** was obtained in 86 % yield (**Table 3**, entry 1). This result marks the first reported molybdenum bicyclic complex with no extra functionality. However, using the catalytic system (**Table 3**, entries 2–7) with different solvent led to only trace amount of the decarbonylated product. The higher boiling solvent, DMSO, still gave only a trace amount of product. Also using a monodentate ligand (PPh_3) and a bidentate ligand (BINAP) showed no effect. Moreover, increasing catalyst loading (**Table 3**, entry 7) did not increase the yield of **44**.



(±) - 53 (±) - 44

Table 4: Decarbonylation reactions using Ir

Entry	Reagents	Solvent	Results
1	$[IrCl(cod)]_2$ (2.5 mol %), PPh_3 (5 mol %)	dioxane	NR
2	$[IrCl(cod)]_2$ (2.5 mol %), PPh_3 (5 mol %)	diglyme	NR
3	$[IrCl(cod)]_2$ (2.5 mol %), PPh_3 (5 mol %)	toluene	NR
4	$[IrCl(cod)]_2$ (2.5 mol %), PPh_3 (5 mol %)	THF	NR
5	$[IrCl(cod)]_2$ (2.5 mol %), PPh_3 (5 mol %)	DME	NR
6	$[IrCl(cod)]_2$ (5 mol %), PPh_3 (10 mol %)	dioxane	NR

All reactions were carried out for 48 h. NR = No reaction, complete recovery of starting material

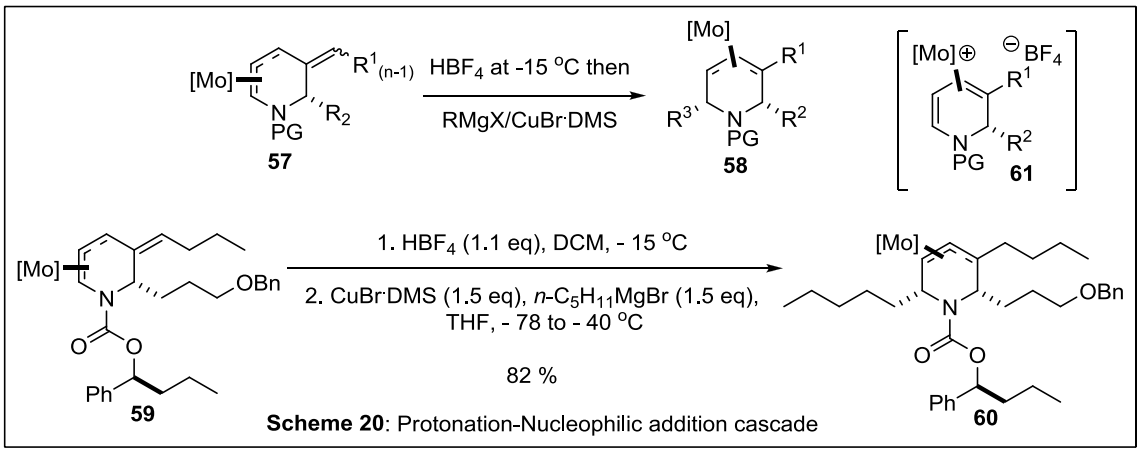
One disadvantage of using a rhodium catalyst for the efficient decarbonylation of aldehydes is that very high reaction temperatures are required even in stoichiometric cases. Recently Yasushi Tsuji and co-workers[50] reported a practical method involving iridium-catalyzed decarbonylation of aldehydes utilizing a monodentate phosphine (PPh_3) ligand in the presence of catalytic amount of commercially available $[IrCl(cod)]_2$ in refluxing dioxane. The reaction works well with low boiling solvent (THF) and a wide range of substrates containing diverse functional groups. As

[50] Iwai, T.; Fujihara, T.; Tsuji, Y. *Chem. Commun.* **2008**, 6215-6217.

depicted in **Table 4**, when the reaction conditions were used on the aldehyde **53**, no reaction was observed.

Protonation-Nucleophilic Addition of the Pyridinyl Cycloadducts

With **44** in hand from the stoichiometric decarbonylation using $RhCl(PPh_3)_3$, attention was directed towards the protonation-nucleophilic addition sequence. Installation of the alkyl side chain onto complex **44** can be achieved *via* a sequential protonation-nucleophilic addition.[51] In 2007, the Liebeskind laboratory reported an approach to functionalized pyrans which took advantage of the unsual reactivity of the double bond adjacent to η^3-allylmolybdenum moiety.[52] This methodology was further modified and extended towards the general synthesis of 2,3,6-trisubstituted tetrahydropyridinyl molybdenum complexes.[53]



Scheme 20: Protonation-Nucleophilic addition cascade

As shown in **Scheme 20**, protonation of double bond of **57** results in the formation of cation diene complex **61**, which is followed by the nucleophilic attack on diene complex **18** by the organocuprate generated *in situ* from RMgX and CuBr·DMS to furnish **58**. To demonstrate the synthetic utility of this protocol, 2,3,6-trisubstituted tetrahydropyridinyl molybdenum complex

[51] Liu, S. Master Thesis, 2006, Emory University.
[52] Arrayás, R. G.; Jingjun, Y.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2007**, *129*, 1816-1825.
[53] Wong, H.; Garnier-Amblard, E.C.; Liebeskind, L.S.; *J. Am. Chem. Soc.* **2011**, *133*, 7517–7527.

60, which is a key precursor in the synthesis of quinolizidine (-)-251AA, was generated in good yield from **59** under the protonation-nucleophilic addition reaction conditions.[54] As was noted earlier,[55] installation of propyl side chain on complex **41** was found to be challenging and it was assumed that the presence of the ester functional group might be competing during the protonation step. With **44** in hand, initial studies were carried out to test the temperature dependence of the reaction (**Table 5**). Unfortunately, at 0 ^{o}C the reaction led to the decomposition of the starting material (entry 1). Interestingly, addition of HBF_4 at -15 ^{o}C similar to Dr. Heilam Wong's condition[56] (entry 2) proved to be better alternative as it resulted to 43 % yield of the product and 24 % recovered starting material. At much lower temperatures no product was observed, suggesting that lower temperature suppresses the formation of the cation diene complex.

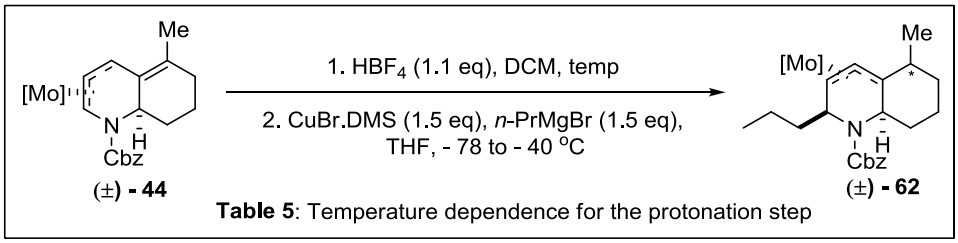


Table 5: Temperature dependence for the protonation step

Entry	Temperature (^{o}C)	Yields (%)
1	0	decomposition
2	-15	43 (Prod.), 24 (SM)
3	-40	58 (SM)
4	-78	62 (SM)

To examine the dependence of HBF_4 on the formation of the cation diene from starting material **44**, individual experiments were carried out (**Table 6**). When using large amounts of acid, no significantly increase the yield of **62** was observed. Interesting, doubling the amount of HBF_4 (entry 2 and 3) showed no change in yield.

[54] Wong, H.; Garnier-Amblard, E.C.; Liebeskind, L.S.; *J. Am. Chem. Soc.* **2011**, *133*, 7517–7527.
[55] For extensive studies on this step, see: Liu, S. Master Thesis, 2006, Emory University.
[56] Wong, H.; Garnier-Amblard, E.C.; Liebeskind, L.S.; *J. Am. Chem. Soc.* **2011**, *133*, 7517–7527.

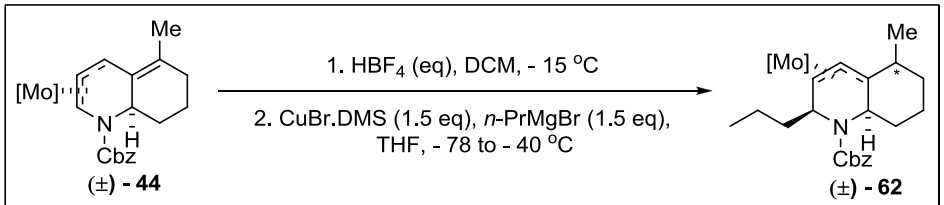


Table 6: HBF_4 equivalent dependence for the protonation step

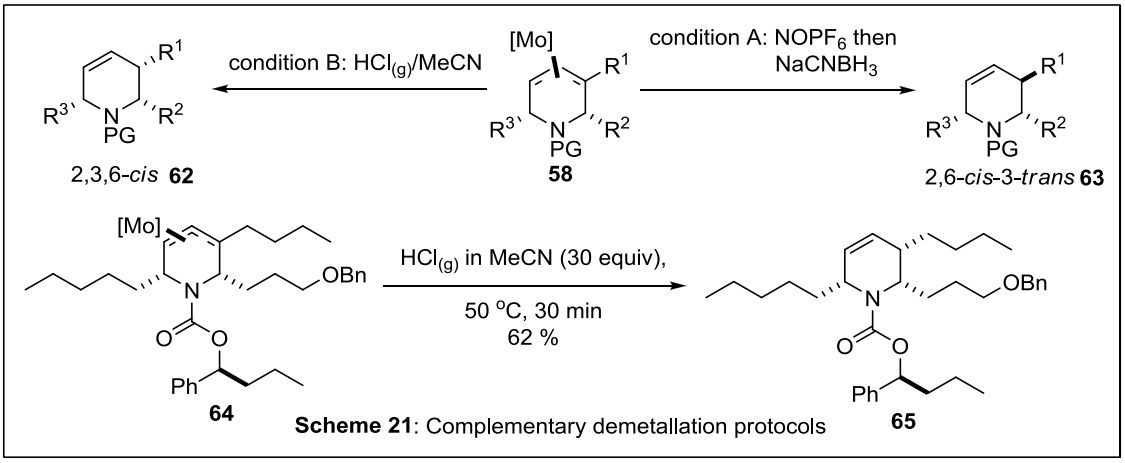
Entry	HBF_4 (equiv.)	Yields (%)
1	1.1	43 (Prod.), 24 (SM)
2	2.0	35 (Prod.), 12 (SM)
3	4.0	36 (Prod.), 2 (SM)

Other conditions such as solvent (toluene, DME) used for protonation step, increasing amount of organocuprate mixture [*n*PrMgCl (4.0 equiv.) and CuBr·DMS (2.0 equiv.)], were unsuccessful.

The Demetallation Protocols

In order to commence the synthesis of (±)-pumiliotoxin, attention was directed towards the demetallation protocol. **Scheme 21**, illustrates the two demetallation methods that have been widely employed in the Liebeskind laboratory. Depending on the reaction conditions[57] both 2,6-*cis*-3-*trans* and 2,3,6-*cis* tetrahydropyridines can easily be approached. The formation 2,3,6-*cis* tetrahydropyridines is of special interest since that will led to the construction of the structural motif of pumiliotoxin C. Treating **64** under the reaction conditions generated 2,3,6-*cis* tetrahydropyridines in good yield.

[57] Wong, H.; Garnier-Amblard, E.C.; Liebeskind, L.S.; *J. Am. Chem. Soc.*, **2011**, *133,* 7517–7527.



Scheme 21: Complementary demetallation protocols

The demetallation of **62** was carried out in the same manner as that of **64** (**Table 7**, entry 1) and led to recovery of starting material (50 %). Furthermore, increasing the temperature led to decomposition (entry 2). Using acidic conditions in the presence of TFA, no reaction was observed (entry 3 and 4)

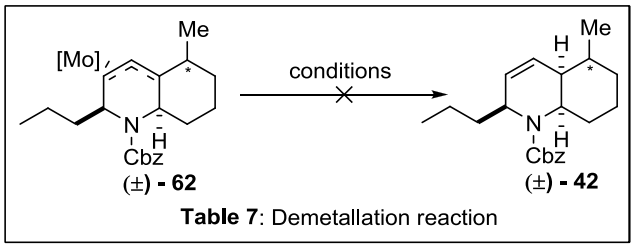


Table 7: Demetallation reaction

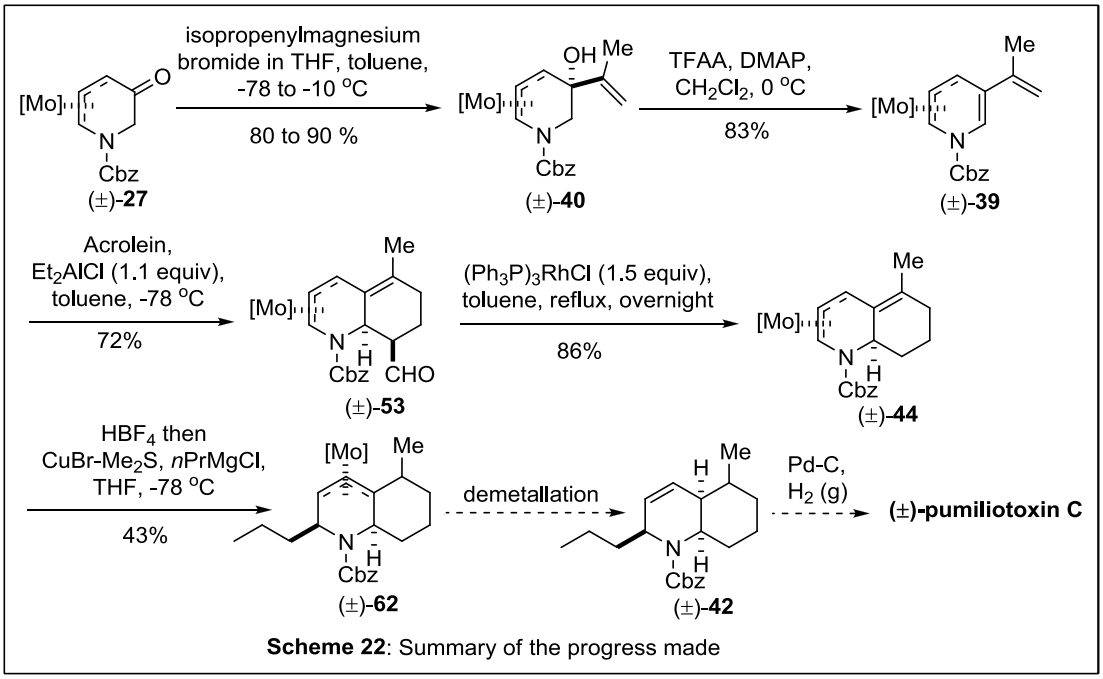
Entry	Conditions	Temperature (°C)	Yield (%)
1	HCl(g) in MeCN (2.1M, 30 equiv)	50	50 (SM)
2		80	decomposition
3	TFA (30 equiv), DCM	RT	NR
4		reflux	NR

NR = No reaction, complete recovery of starting material

3. Conclusions

An approach towards the synthesis of (±)-pumiliotoxin C has been modified and investigated as summarized in **Scheme 22**. The first synthesis of bicylic structure **44** with no extra functionalities was achieved. The [4+2] cycloaddition of $TpMo(CO)_2(\eta^3$-5-oxo-pyridinyl)

complex has proved to be a key step in generating the cycloadduct complex. More conditions needs to be investigated for the completion of the synthesis of the natural product.



Scheme 22: Summary of the progress made

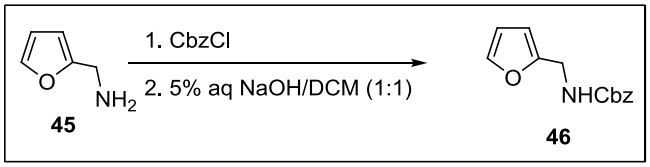
4. Experimental Section

General Methods

Reagents were obtained from Aldrich Chemical and used without further purification. Optima grade solvents were obtained from Fisher Scientific, degassed with argon, and purified on a solvent drying system as described[58] unless otherwise specified. Dry diethyl ether was purchased from Mallinckrodt and used as received, unless otherwise specified. Sparging with argon or using freeze-thaw-pump method degassed solvents. Unless otherwise specified, all reactions were performed in flame-dried glassware under positive Argon pressure with magnetic stirring. Cold baths were generated as follows: 0 °C, wet ice/water; -40 °C, dry ice/CH_3CN; -78 °C, dry ice/acetone. Analytical thin-layer chromatography (TLC) was carried out on commercial Merck Silica gel 60 plates, 0.25 thickness, with fluorescent indicator (F-254). Visualization was accomplished by UV light or stained with 5% phosphomolybdic acid (PMA) in ethanol or 0.75% potassium permanganate ($KMnO_4$) in H_2O. Column chromatography was performed by the method of Still[59] with 32-63 μm silica gel (Woelm). Unless otherwise indicated, all ^1H and ^{13}C NMR spectra were recorded on a Varian Inova 400 MHz (400 MHz ^1H NMR, 100 MHz ^{13}C NMR) at room temperature in $CDCl_3$ with internal $CHCl_3$ as the reference (7.27 ppm for ^1H NMR and 77.23 ppm for ^{13}C NMR). Chemical shifts are expressed in ppm, coupling constants are expressed in Hertz. The letters m, s, d, t, and q stand for multiplet, singlet, doublet, triplet, and quartet, respectively. The letters br indicate that the signal is broad. IR spectra were recorded on a Nicolet™ 380 FT-IR spectrometer, equipped with a diamond plate. Peaks are reported (cm^-

[58] Pangborn, A. B.; Giardello, M. A.; Grubbs, R. H.; Rosen, R. K.; Timmers, F. J. *Organometallics* **1996**, *15*, 1518-1520.
[59] Still, W.C.; Khan, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923-2925.

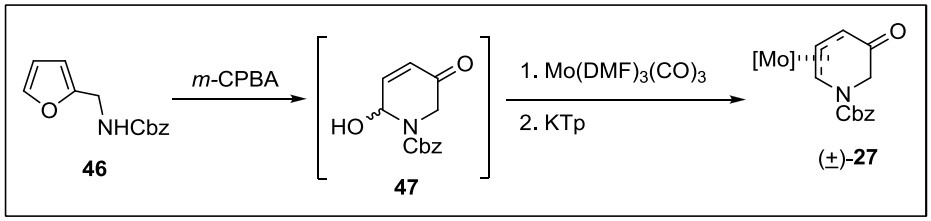
[1]) with the following relative intensities: s (strong, 67-100%), m (medium, 40-67%), w (weak, 20-40%) and br (broad). *Since almost all of the Tp molybdenum complexes decompose at about 180-200 ºC melting points are not significant and are not shown in the experimental section*. Optical rotations were measured with a Perkin-Elmer 241MC polarimeter. HPLC analyses were carried out at room temperature using an Agilent 1100 system with a quaternary pump. Separations were achieved on DAICEL chiral CHIRALPAK AS reversed phase columns using a Waters™ 486 UV detector (HPLC grade acetonitrile and water were used).



Compound 46[60] To a round bottom flask charged with furfuryl amine **45** (19.05 mL, 0.206 mol, 1.00 equiv.) in CH_2Cl_2 (1030 mL) was added NaOH (9.06 g, 0.227 mol, 1.10 equiv.) in H_20 (180 mL) and benzyl chloroformate (31.88 mL, 0.227 mol, 1.10 equiv.) at ambient temperature. The red-orange suspension was stirred at room temperature for 23 hours. The reaction mixture was quenched with $NaHCO_3$ (100 mL), then diluted with EtOAc (300 mL). The organic and aqueous layers were separated, and the organic layer was washed with brine (3 x 300 mL), dried over $MgSO_4$, and the solvent was removed under reduced pressure to provide the crude product. The crude product was purified by flash chromatography (SiO_2, 6.5 cm x 23.0 cm, hexanes: EtOAc = 3:1) to afford the product **46** (4 g, 93 %) as a pale yellow oil, which solidified at low temperature. TLC: R_f = 0.59 (hexanes: EtOAc = 1:1). IR (cm^{-1}): 3327 (w), 1703 (s), 1519 (m), 1241 (s), 729 (s). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34-7.32 (m, 6 H), 6.30 (dd, *J* = 3.1, 1.9 Hz, 1 H), 6.22 (d, *J* = 2.6 Hz, 1 H), 5.60 (br s, 1 H), 5.11 (s, 2 H), 4.34 (d, *J* = 5.4 Hz, 2 H). ^{13}C NMR

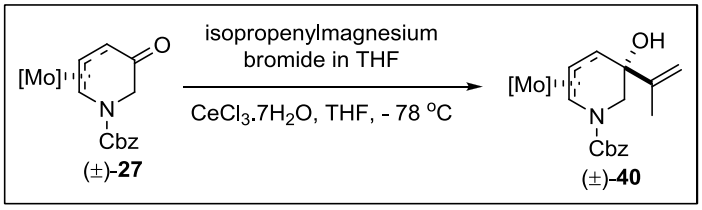
[60] Coombs, T. C.; Lee; Wong, H.; Armstrong, M.; Cheng, B.; Chen, W.; Moretto, A. F.; Liebeskind, L. S. *J. Org. Chem*. **2008,** *73*, 882-888.

(100 MHz, $CDCl_3$): δ 156.3, 151.7, 142.4, 136.6, 128.7, 128.4, 110.6, 107.5, 67.2, 38.3. HRMS (ESI) calcd for $C_{13}H_{14}NO_3$ ($[M + H]^+$): 232.0974 Found: 232.0965.



Compound (±)-27.[60] The residue **46** (10.0 g, 43.2 mmol, 1.0 equiv.) was dissolved in CH_2Cl_2 (63 mL) and cooled to 0 °C. To the solution was added *m*CPBA (~77 % purity, 11.19 g, 65.0 mmol, 1.50 equiv.) portionwise. After holding the temperature at 0 °C for 1.5 hours, the white solids were removed by vacuum filtration. The filtrate was degassed with argon for 30 minutes. To the degassed solution at 0 °C was added solid $Mo(DMF)_3(CO)_3$ (17.17 g, 42.8 mmol, 0.99 equiv.). After stirring for 5 minutes at 0 °C, the reaction was warmed to room temperature and stirred for 1.0 hour. To the reaction mixture was added KTp (12.1 g, 48.0 mmol, 1.11 equiv.). The reaction mixture was stirred at room temperature for 1 hour, filtered over a pad of Celite®, and concentrated under reduced pressure. The crude product was subjected to short filter chromatography (SiO_2, 5.0 cm x 20.0 cm, hexanes: EtOAc = 9:1 ramping gradually to hexanes: EtOAc = 2:1). Fractions overlapping with impurities were collected and subjected to a second chromatography (SiO_2, 5.0 cm x 20.0 cm, hexanes: EtOAc = 4:1) to afford the product **(±)-27** (10.23 g, 39.6 %) as an orange solid. TLC: R_f = 0.62 (hexanes: EtOAc = 1:1). IR (cm^{-1}) 1968 (s), 1875 (s), 1696 (s), 1654 (s). ^1H NMR (mixture of two rotamers- 400 MHz, $CDCl_3$): δ 8.45 (d, *J* = 1.9 Hz, 0.4 H), 8.42 (d, *J* = 1.9 Hz, 0.6 H), 8.31 (d, *J* = 1.9 Hz, 0.6 H), 7.76 (d, *J* = 1.9 Hz, 0.4 H), 7.74 (d, *J* = 1.9 Hz, 0.6 H), 7.70 (d, *J* = 1.9 Hz, 0.4 H), 7.65 (d, *J* = 1.9 Hz, 0.6 H), 7.62 (d, *J* = 1.9 Hz, 0.6 H), 7.60 (d, *J* = 1.9 Hz, 0.4 H), 7.58 (d, *J* = 1.9 Hz, 0.4 H), 7.47-7.52 (m, 1.6 H), 7.40-7.44 (m, 2 H), 7.27-7.38 (m, 3 H), 7.22 (dd, *J* = 6.4, 1.9 Hz, 0.4 H), 6.28-6.30 (m, 1.6 H),

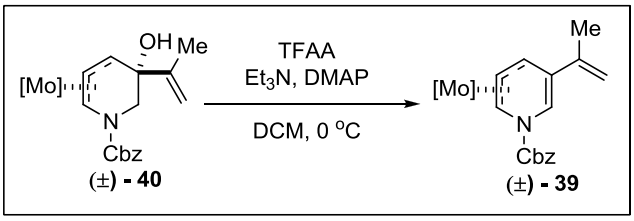
6.22-6.24 (m, 1 H), 5.97 (t, *J* = 2.2 Hz, 0.4 H), 5.27 (AB quartet, *J* = 11.4 Hz, 0.4 Hz, 2 H), 5.24 (s, 0.6 H), 4.74-4.77 (m, 1 H), 4.09 (t, *J* = 6.4 Hz, 0.6 H), 3.98 (t, *J* = 6.4 Hz, 0.4 H), 3.41 (AB quartet, *J* = 20.0 Hz, 0.4 H), 3.39 (AB quartet, *J* = 19.7 Hz, 0.6 H). 13C NMR (100 MHz, $CDCl_3$): δ 224.9, 224.5, 222.6, 221.9, 193.3, 192.6, 154.4, 153.6, 147.1, 147.0, 144.2, 143.3, 141.3, 141.2, 136.33, 136.31, 136.2, 136.1, 135.4, 135.1, 134.6, 128.7, 128.5, 128.4, 128.3, 128.0, 127.6, 106.0, 105.8,105.6, 93.7, 92.2, 68.7, 67.9, 64.4, 64.0, 63.7, 63.3, 47.7, 47.6. HRMS (ESI) calcd. For $C_{24}H_{23}BMoN_7O_5$ ($[M+H]^+$): 598.0908 Found: 598.0905. HPLC: Daicel® Chiralcel AS-RH, CH_3CN: H_2O = 50: 50, 1.0 mL/min., λ = 254 nm, **(+)-27** t_R = 15.74 min., **(-)-27** t_R = 22.87 min.



Compound (±)-40.[61] $CeCl_3.7H_2O$ (0.18 g, 0.495 mmol, 99.999% purity, from Sigma - Aldrich) was dried under high vacuum at 140 °C overnight, and cooled to 0 °C, 3 mL THF was added, the slurry was sonicated for 10 min and stirred for 8 h at room temperature before cooled to -78 °C. 1.0 mL isopropenylmagnesium bromide (0.5 M in THF) was added dropwise, and the whole slurry was stirred for 1.5 h at the same temperature. **(±)-27** (0.5 g, 0.33 mmol, dissolved in 2 mL THF) was added dropwise, and stirred for 1 h. The mixture was quenched with 1.0 mL $NaHCO_3$ (sat.) and then slowly warmed to room temperature and Et_2O was added, and the aqueous layer was separated and re-extracted with Et_2O. The combined Et_2O solution was washed with brine and dried over $MgSO_4$. Vacuum concentration and silica gel column chromatography (Hexane: EA = 5:1) gave **(±)-40** as an orange solid (0.18 g, 86%). IR (CH_2Cl_2, cm^{-1}): 3451 (br), 3127 (w),

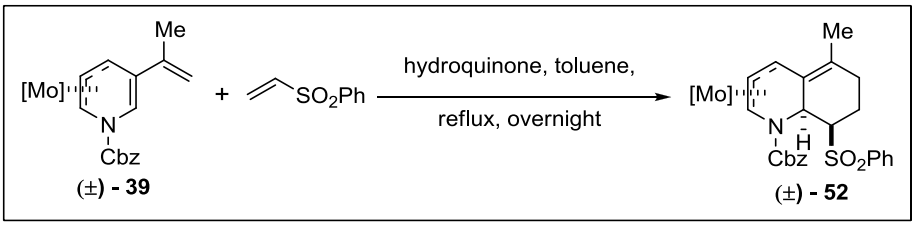
[61] Liu, S. Master Thesis, 2006, Emory University.

2957 (w), 1945 (s), 1849 (s), 1698 (s), 1505 (m), 1455 (m), 1393 (s), 105 (s), 1220 (s), 1123 (s), 1050 (s), 988.2 (m), 907.1 (w), 760.4 (s), 721.8 (s). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.46 (dd, *J* = 1.9, 7.0 Hz, 1H), 8.21 (d, *J* = 1.9 Hz, 0.6H), 7.78 (dd, *J* = 1.9, 6.4 Hz, 1H), 7.62 (d, *J* = 1.9 Hz, 0.4H), 7.60 (dd, *J* = 2.2, 4.3 Hz, 1H), 7.57 (d, *J* = 2.2 Hz, 0.5H), 7.55 (d, *J* = 2.2 Hz, 0.5H), 7.46-7.51 (m, 2H), 7.30-7.42 (m, 4H), 7.14 (dd, *J* = 1.9, 6.0 Hz, 0.6H), 6.91 (dd, *J* = 1.9, 6.0 Hz, 0.4H), 6.28 (q, *J* = 1.9 Hz, 1H), 6.24 (t, *J* = 2.2 Hz, 0.6H), 6.18-6.21 (m, 1H), 5.96 (t, *J* = 2.2 Hz, 0.4H), 5.17-5.34 (m, 3H), 4.91 (d, *J* = 8.0 Hz, 1H), 4.52 (t, *J* = 9.0 Hz, 1H), 3.76 (t, *J* = 13.0 Hz, 0.4H), 3.69 (d, *J* = 13.0 Hz, 0.6H), 3,57 (dd, *J* = 6.4, 7.6 Hz, 0.6H), 3,46 (dd, *J* = 6.4, 7.6 Hz, 0.4H), 2.82 (s, 0.6H), 2.75 (s, 0.4H), 2.09 (d, *J* = 4.1 Hz, 0.4H), 2.06 (d, *J* = 4.1 Hz, 0.6H), 1.99 (s, 1.2H), 1.97 (s, 1.8H); ^{13}C NMR ($CDCl_3$, 400 MHz): δ 233.7, 232.8, 224.2, 223.8, 155.6, 155.1, 151.0, 147.1, 144.1, 143.1, 141.4, 141.2, 136.3, 136.2, 136.0, 134.7, 129.0, 128.8, 128.7, 128.2, 128.0, 111.0, 110.8, 106.2, 106.0, 105.7, 105.6, 91.2, 89.8, 74.8, 74.7, 72.4, 71,7, 68.8, 68.1, 59.3. HRMS (ESI) Calcd. for $C_{27}H_{28}BMoN_7O_5^+$ ($M+H^+$): 639.1299. Found: 639.1307.



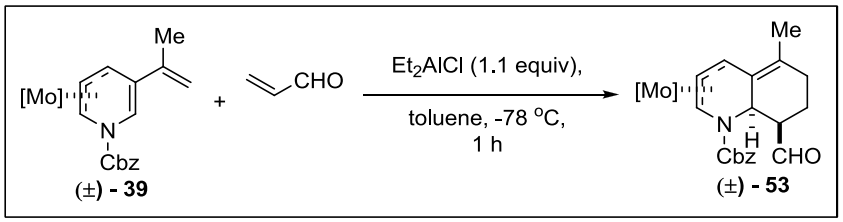
Compound (±)-39.[61] To a solution of alcohol **(±)-40** (3.11 g, 4.86 mmol) in DCM (20 mL) was added DMAP (0.15 g, 1.22 mmol) and Et_3N (2.70 mL, 19.44 mmol). The solution was cooled to 0 °C and TFAA (1.33 mL, 9.72 mmol) was added dropwise. After 10 min, the mixture was quenched with water (10 mL) and ethyl acetate (10 mL). The organic phase was separated and the water phase was extracted with ethyl acetate (25 mL x 3). The combined organic phases were washed with brine (25 mL x 3) and dried ($MgSO_4$). Volatiles were removed under reduced pressure. The concentrated crude material was purified by column chromatography on silica gel

(hexanes: EtOAc = 5:1) to afford **(±)-39** as an orange solid (2.50 g, 83 %). IR (CH_2Cl_2, cm^{-1}): 3123 (w), 2976 (w), 1934 (s), 1849 (s), 1710 (s), 1621 (s), 1502 (s); ^1H NMR ($CDCl_3$, 600 MHz): δ 8.43 (d, *J* = 1.9 Hz, 0.4H), 8.22 (dd, *J* = 1.9, 6.0 Hz, 1H), 7.83 (dd, *J* = 1.9, 5.1 Hz, 1H), 7.76 (d, *J* = 1.9 Hz, 0.6H), 7.63 (s, 1H), 7.60 (d, *J* = 1.9 Hz, 0.4H), 7.55 (d, *J* = 2.5 Hz, 1H), 7.53 (d, *J* = 1.6 Hz, 0.6H), 7.34-7.49 (m, 5.4H), 7.12 (d, *J* = 5.7 Hz, 0.6H), 6.60 (s, 0.6H), 6.45 (s, 0.4H), 6.28 (t, *J* = 2.2 Hz, 0.4H), 6.23-6.25 (m, 1H), 6.19 (q, *J* = 2.2 Hz, 1H), 5.95 (t, *J* = 2.2 Hz, 0.6H), 5.50 (d, *J* = 2.5 Hz, 1H), 5.32-5.41 (m, 2H), 5.22 (d, *J* = 6.4 Hz, 1H), 5.15 (s, 1H), 2.83 (t, *J* = 6.4 Hz, 0.4H), 2.73 (t, *J* = 6.4 Hz, 0.6H), 2.00 (s, 1.6H), 1.94 (s, 1.4H); ^{13}C NMR ($CDCl_3$, 400 MHz): δ 229.4, 228.7, 224.1, 223.4, 153.2, 146.3, 144.5, 143.4, 140.7, 140.6, 140.4, 140.2, 136.3, 136.2, 136.1, 135.9, 135.4, 134.6, 129.3, 128.9, 128.8, 128.5, 128.1, 126.0, 125.5, 87.5, 86.4, 69.6, 68.7, 61.0, 60.5, 51.7, 51.3. HRMS (ESI) Calcd. for $C_{27}H_{28}BMoN_7O_5^+$ $[(M+H)^+]$: 621.1193. Found: 621.1215.



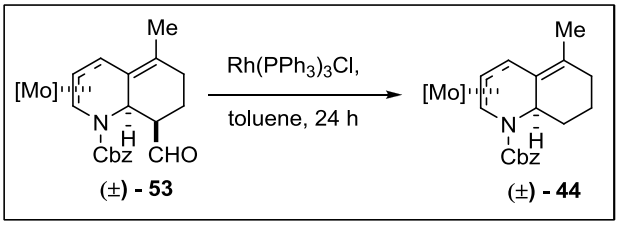
Compound (±)-52. To a solution of **(±)-39** (0.21 g, 0.34 mmol) in toluene (8 mL) were successively added hydroquinone and phenyl vinyl sulfone (, 1.02 mmol) at room temperature The solution was reflux for 16 h and the mixture was quenched with water (3 mL) and ethyl acetate (3 mL). The organic phase was separated and the water phase was extracted with ethyl acetate (10 mL x 3). The combined organic phases were washed with brine (10 mL x 3) and dried ($MgSO_4$). Volatiles were removed under reduced pressure. The concentrated crude material was purified by column chromatography on silica gel (hexanes: EtOAc = 5:1) to afford **(±)-52** as a yellow solid (0.584 g, 88%). IR (CH_2Cl_2, cm^{-1}): 3115 (w), 2903 (w), 2509 (w), 1939 (s), 1859

(s), 1698 (s), 1504 (s), 1407 (s); ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.30 - 8.12 (m, 3 H), 7.84 - 7.67 (m, 5 H), 7.63 - 7.04 (m, 41 H), 6.63 - 6.47 (m, 1 H), 6.33 - 6.20 (m, 2 H), 6.03 (d, *J* = 4.7 Hz, 7 H), 5.62 - 5.46 (m, 2 H), 5.24 (br. s., 3 H), 5.10 - 4.94 (m, 1 H), 4.82 - 4.67 (m, 3 H), 4.55 (br. s., 2 H), 4.50 - 4.38 (m, 2 H), 4.10 (br. s., 1 H), 3.62 (br. s., 1 H), 3.56 - 3.45 (m, 2 H), 3.38 (br. s., 3 H), 3.29 (dddd, *J* = 1.6, 3.5, 5.2, 6.9 Hz, 1 H), 2.18 - 2.01 (m, 8 H), 1.97 (d, *J* = 7.0 Hz, 2 H), 1.95 - 1.83 (m, 9 H). ^{13}C NMR ($CDCl_3$, 400 MHz): δ 227.72, 224.51, 154.82, 147.39, 143.39, 141.18, 135.76, 132.88, 130.88, 129.28, 128.67, 128.56, 127.87, 124.29, 116.09, 105.83, 105.43, 105.34, 91.67, 68.59, 60.80, 60.40, 58.93, 50.58, 28.09, 20.72, 18.94



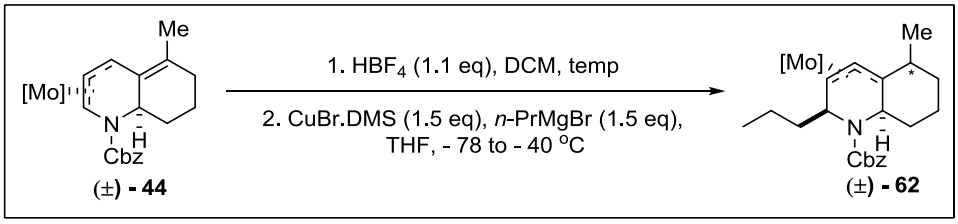
Compound (±)-53. To a solution of **(±)-39** (0.08 g, 0.13 mmol) in toluene (2 mL) were cooled at –78 °C and successively added acrolein (0.03 mL, 0.39 mmol) and a 1M solution of Et_2AlCl (0.14 mL, 0.143 mmol). The solution was stirred at room temperature for 1 h and it was passed through a short pad of silica gel (5 % Et_3N neutralized). After evaporation of the solvent, the remaining crude product was purified by silica gel (5 % Et_3N neutralized) column chromatography to afford **(±)-53** as an orange solid (0.063 g, 72 %). IR (CH_2Cl_2, cm^{-1}): 3134 (w), 2927 (m), 1927 (s), 1830 (s), 1701 (s), 1500 (s), 1406 (m), 1381 (s); ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 9.70 - 9.64 (m, 1 H), 8.59 (s, 1 H), 8.46 - 8.38 (m, 1 H), 7.75 - 7.30 (m, 15 H), 7.10 (dd, *J* = 1.6, 6.3 Hz, 1 H), 6.29 - 6.19 (m, 3 H), 5.80 (t, *J* = 2.0 Hz, 1 H), 5.39 - 5.28 (m, 2 H), 5.28 - 5.17 (m, 3 H), 4.13 (q, *J* = 7.2 Hz, 1 H), 3.65 (t, *J* = 6.7 Hz, 1 H), 3.56 - 3.46 (m, 3 H), 3.17 (br. s., 1 H), 2.35 - 2.03 (m, 5 H), 2.01 (s, 4 H), 1.94 - 1.83 (m, 1 H), 1.70 - 1.54 (m, 2 H), 1.30 - 1.24 (m, 1 H). ^{13}C NMR ($CDCl_3$, 400 MHz): δ 226.90, 203.35, 155.52, 147.48, 143.87,

140.05, 135.85, 134.41, 131.54, 129.49, 128.75, 128.58, 128.29, 127.92, 126.55, 105.91, 105.47, 93.11, 68.93, 68.44, 61.11,59.01, 51.16, 49.05, 28.10, 21.06, 20.11, 18.86, 14.19.



(±) - 53 (±) - 44

Compound (±)-44. To a solution of **(±)-53** (0.1390 g, 0.21 mmol) in toluene (5 mL) were successively added at room temperature $Rh(PPh_3)_3Cl$ (0.30 g, 0.315 mmol). The solution was reflux for 24 h. The mixture was then cooled down to room temperature and quenched with water (6 mL) and ethyl acetate (6 mL). The organic phase was separated and the water phase was extracted with ethyl acetate (15 mL x 3). The combined organic phases were washed with brine (10 mL x 3) and dried ($MgSO_4$). The organic solvent was removed under reduced pressure. The concentrated crude material was purified by column chromatography on silica gel (hexanes: EtOAc = 4:1) to afford **(±)-44** as an orange solid (0.1228 g, 86 %). IR (CH_2Cl_2, cm^{-1}): 3116 (w), 2938 (m), 2467 (m), 1921 (s), 1825 (s), 1691 (s), 1502 (m), 1407 (s); ^1H NMR ($CDCl_3$, 400 MHz): δ = 8.62 - 8.38 (m, 2 H), 7.86 - 7.64 (m, 4 H), 7.64 - 7.45 (m, 7 H), 7.40 (d, *J* = 6.3 Hz, 6 H), 7.09 (br. s., 1 H), 6.30 - 6.16 (m, 3 H), 5.81 (br. s., 1 H), 5.39 - 5.14 (m, 5 H), 3.61 - 3.36 (m, 2 H), 3.23 - 3.13 (m, 1 H), 2.81 - 2.56 (m, 2 H), 2.28 (br. s., 2 H), 2.20 - 2.07 (m, 2 H), 2.07 - 1.91 (m, 5 H), 1.75 (br. s., 1 H), 1.60 (br. s., 3 H), 1.33 - 1.08 (m, 4 H). ^{13}C NMR ($CDCl_3$, 400 MHz): δ 171.11, 147.42, 143.83, 139.99, 135.79, 134.31, 132.03, 128.53, 128.41, 128.10, 127.94, 124.86, 105.78, 105.35, 94.17, 68.46, 60.76, 60.37, 58.96, 53.40, 51.54, 31.57, 22.63, 21.03, 19.41, 18.99, 14.18, 14.11.



Compound (±)-62. To a solution of **(±)-44** (0.1 g, 0.15 mmol) in DCM (3 mL) at –15 ^{o}C was added dropwise a solution of tetrafluoroboric acid HBF_4 (54 wt % in Et_2O, 0.03 mL, 0.165 mmol). The yellow solution turned deep orange immediately. DCM was removed under vacuum and the obtained red solid was dissolved in THF (3 mL) and cooled to –78 ^{o}C. To a Schlenk flask charged with copper bromide dimethylsulfide complex CuBr·DMS (0.05 g, 0.225 mmol) was added THF (3 mL) at –78 ^{o}C and *n*PrMgBr (0.11 mL, 0.225 mmol) was then added dropwise. The light yellow suspension was warmed to –50 ^{o}C and stirred for 30 min to form a brownish yellow suspension. The THF solution of the cationic diene was cannulated into the cuprate suspension at –78 ^{o}C (the cationic diene complex was rinsed with THF to accomplish full transfer). The reaction was slowly warmed to –40 ^{o}C over 20 min. MeOH (1 mL) and Et_3N (1 mL) were added to quench the reaction. The crude mixture was filtered through a short plug of silica gel (flushed with Et_2O) and washed with water quickly (to remove trace of Cu(II)). After drying ($MgSO_4$) the organic layer was concentrated and purified by column chromatography on silica gel (hexane: EtOAc = 4:1) to afford **(±)-62** as a yellow solid (0.042 g, 43 %). IR (CH_2Cl_2, cm^{-1}): 2951 (w), 2466 (m), 1937 (s), 1845 (s), 1686 (s), 1421 (s), 1407 (s); ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.81 - 7.46 (m, 6 H), 7.45 - 7.25 (m, 6 H), 6.22 (br. s., 3 H), 5.23 - 5.09 (m, 2 H), 5.09 - 4.99 (m, 1 H), 4.53 - 4.30 (m, 3 H), 4.24 (dd, *J* = 2.5, 7.2 Hz, 1 H), 4.07 (dd, *J* = 4.7, 7.0 Hz, 1 H), 2.95 - 2.82 (m, 1 H), 2.32 (d, *J* = 12.9 Hz, 1 H), 2.20 (d, *J* = 10.2 Hz, 1 H), 2.09 - 1.91 (m, 4 H), 1.91 - 1.74 (m, 3 H), 1.73 - 1.45 (m, 9 H), 1.45 - 1.19 (m, 4 H), 1.08 - 0.97 (m, 2 H), 0.91 (t, *J* = 7.2 Hz, 3 H). ^{13}C NMR ($CDCl_3$, 400 MHz): δ 231.05, 230.22, 230.04, 229.22, 154.37,

154.61, 137.55, 137.21, 128.48, 128.40, 128.19, 127.70, 108.37, 106.99, 105.61, 67.33, 67.15, 66.92, 66.80, 66.71, 66.34, 52.25, 51.00, 50.86, 44.28, 39.78, 39.63, 38.38, 21.20, 21.01, 19.63, 19.59, 14.41.

Table 8. Crystal data and structure refinement for **compound (±)-52**.

Identification code	**compound (±)-52**	
Empirical formula	$C_{35}H_{34}BMoN_7O_6S$	
Formula weight	787.50	
Temperature	173(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P-1	
Unit cell dimensions	a = 11.859(7) Å	α= 69.749(9)°.
	b = 12.703(7) Å	β= 69.075(9)°.
	c = 13.506(8) Å	γ = 86.440(10)°.
Volume	1778.5(17) $Å^3$	
Z	2	
Density (calculated)	1.471 Mg/m^3	
Absorption coefficient	0.483 mm^{-1}	
F(000)	808	
Crystal size	0.31 x 0.24 x 0.20 mm^3	
Theta range for data collection	1.72 to 32.30°.	
Index ranges	-17<=h<=17, -18<=k<=18, -20<=l<=20	
Reflections collected	37653	
Independent reflections	11768 [R(int) = 0.0523]	
Completeness to theta = 32.30°	92.9 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.9113 and 0.8643	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	11768 / 0 / 465	
Goodness-of-fit on F^2	1.042	
Final R indices [I>2sigma(I)]	R1 = 0.0429, wR2 = 0.0979	
R indices (all data)	R1 = 0.0591, wR2 = 0.1065	
Largest diff. peak and hole	1.227 and -0.657 e.$Å^{-3}$	

Table 9. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **compound (±)-52**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
B(1)	-2585(2)	6317(2)	10128(2)	25(1)
C(1)	-745(2)	6412(2)	10733(2)	38(1)
C(2)	454(3)	6819(3)	10189(2)	45(1)
C(3)	629(2)	7162(2)	9037(2)	32(1)
C(4)	-3860(2)	8103(2)	9963(2)	28(1)
C(5)	-3891(2)	9065(2)	9078(2)	31(1)
C(6)	-2996(2)	8961(2)	8115(2)	26(1)
C(7)	-3512(2)	4573(2)	10027(2)	31(1)
C(8)	-3466(2)	4169(2)	9184(2)	36(1)
C(9)	-2618(2)	4914(2)	8194(2)	29(1)
C(10)	-1712(2)	7866(2)	6182(2)	20(1)
C(11)	-102(2)	8821(2)	6550(2)	19(1)
C(12)	1202(2)	7073(2)	6515(2)	20(1)
C(13)	433(2)	6193(2)	6652(2)	21(1)
C(14)	-194(2)	6442(2)	5878(2)	21(1)
C(15)	415(2)	7228(2)	4707(2)	19(1)
C(16)	63(2)	7343(2)	3828(2)	23(1)
C(17)	818(2)	8182(2)	2673(2)	26(1)
C(18)	2174(2)	8012(2)	2384(2)	27(1)
C(19)	2597(2)	7880(2)	3386(2)	20(1)
C(20)	1523(2)	7977(2)	4430(2)	18(1)
C(21)	2672(2)	8678(2)	5274(2)	20(1)
C(22)	3567(2)	9451(2)	6227(2)	34(1)
C(23)	3044(2)	9635(2)	7351(2)	28(1)
C(24)	3528(3)	9146(3)	8186(2)	47(1)
C(25)	3032(3)	9311(3)	9225(2)	58(1)
C(26)	2072(3)	9972(3)	9430(2)	47(1)
C(27)	1588(3)	10464(3)	8598(2)	45(1)
C(28)	2074(3)	10292(2)	7559(2)	39(1)

C(29)	-981(2)	6686(2)	3866(2)	33(1)
C(30)	4093(2)	6559(2)	4578(2)	23(1)
C(31)	5066(2)	7325(2)	4222(2)	31(1)
C(32)	5671(2)	7262(2)	4951(3)	41(1)
C(33)	5315(3)	6432(3)	6014(2)	44(1)
C(34)	4359(3)	5668(2)	6357(2)	42(1)
C(35)	3722(2)	5717(2)	5645(2)	31(1)
Mo(1)	-922(1)	7319(1)	7324(1)	16(1)
N(1)	-1237(2)	6491(2)	9953(2)	27(1)
N(2)	-382(2)	6958(2)	8884(1)	23(1)
N(3)	-2994(2)	7476(1)	9536(1)	22(1)
N(4)	-2445(2)	8002(1)	8389(1)	21(1)
N(5)	-2741(2)	5495(2)	9569(2)	26(1)
N(6)	-2174(2)	5715(1)	8424(2)	24(1)
N(7)	1891(2)	7833(1)	5409(1)	18(1)
O(1)	-2171(2)	8225(1)	5520(1)	29(1)
O(2)	371(2)	9722(1)	6071(1)	28(1)
O(3)	3200(1)	9411(1)	4376(1)	25(1)
O(4)	2791(1)	8567(1)	6271(1)	26(1)
O(5)	2467(2)	5638(1)	4154(1)	30(1)
O(6)	4295(2)	6696(1)	2548(1)	31(1)
S(1)	3355(1)	6590(1)	3629(1)	21(1)

Table 10. Bond lengths [Å] and angles [°] for **compound (±)-52**.

B(1)-N(5)	1.537(3)
B(1)-N(1)	1.548(3)
B(1)-N(3)	1.554(3)
B(1)-H(1)	1.09(2)
C(1)-N(1)	1.350(3)
C(1)-C(2)	1.382(4)
C(1)-H(1B)	0.9500
C(2)-C(3)	1.402(3)
C(2)-H(2A)	0.9500
C(3)-N(2)	1.343(3)
C(3)-H(3A)	0.9500
C(4)-N(3)	1.348(3)
C(4)-C(5)	1.392(3)
C(4)-H(4A)	0.9500
C(5)-C(6)	1.396(3)
C(5)-H(5A)	0.9500
C(6)-N(4)	1.346(3)
C(6)-H(6A)	0.9500
C(7)-N(5)	1.348(3)
C(7)-C(8)	1.386(4)
C(7)-H(7A)	0.9500
C(8)-C(9)	1.405(3)
C(8)-H(8A)	0.9500
C(9)-N(6)	1.345(3)
C(9)-H(9A)	0.9500
C(10)-O(1)	1.157(2)
C(10)-Mo(1)	1.987(2)
C(11)-O(2)	1.162(2)
C(11)-Mo(1)	1.950(2)
C(12)-C(13)	1.407(3)
C(12)-N(7)	1.435(2)
C(12)-Mo(1)	2.410(2)
C(12)-H(12A)	1.0000
C(13)-C(14)	1.429(3)
C(13)-Mo(1)	2.242(2)
C(13)-H(13A)	1.0000
C(14)-C(15)	1.484(3)

C(14)-Mo(1)	2.447(2)
C(14)-H(14A)	1.0000
C(15)-C(16)	1.353(3)
C(15)-C(20)	1.526(3)
C(16)-C(29)	1.512(3)
C(16)-C(17)	1.530(3)
C(17)-C(18)	1.534(3)
C(17)-H(17A)	0.9900
C(17)-H(17B)	0.9900
C(18)-C(19)	1.558(3)
C(18)-H(18A)	0.9900
C(18)-H(18B)	0.9900
C(19)-C(20)	1.564(3)
C(19)-S(1)	1.804(2)
C(19)-H(19A)	1.0000
C(20)-N(7)	1.484(2)
C(20)-H(20A)	1.0000
C(21)-O(3)	1.216(2)
C(21)-O(4)	1.362(2)
C(21)-N(7)	1.383(3)
C(22)-O(4)	1.467(3)
C(22)-C(23)	1.517(3)
C(22)-H(22A)	0.9900
C(22)-H(22B)	0.9900
C(23)-C(28)	1.382(4)
C(23)-C(24)	1.385(3)
C(24)-C(25)	1.400(4)
C(24)-H(24A)	0.9500
C(25)-C(26)	1.377(4)
C(25)-H(25A)	0.9500
C(26)-C(27)	1.382(4)
C(26)-H(26A)	0.9500
C(27)-C(28)	1.402(4)
C(27)-H(27A)	0.9500
C(28)-H(28A)	0.9500
C(29)-H(29A)	0.9800
C(29)-H(29B)	0.9800

C(29)-H(29C)	0.9800
C(30)-C(31)	1.389(3)
C(30)-C(35)	1.397(3)
C(30)-S(1)	1.783(2)
C(31)-C(32)	1.389(3)
C(31)-H(31A)	0.9500
C(32)-C(33)	1.388(4)
C(32)-H(32A)	0.9500
C(33)-C(34)	1.375(4)
C(33)-H(33A)	0.9500
C(34)-C(35)	1.403(4)
C(34)-H(34A)	0.9500
C(35)-H(35A)	0.9500
Mo(1)-N(4)	2.2126(19)
Mo(1)-N(6)	2.295(2)
Mo(1)-N(2)	2.305(2)
N(1)-N(2)	1.378(2)
N(3)-N(4)	1.374(2)
N(5)-N(6)	1.380(3)
O(5)-S(1)	1.4503(17)
O(6)-S(1)	1.4529(17)

N(5)-B(1)-N(1)	110.76(19)
N(5)-B(1)-N(3)	108.08(18)
N(1)-B(1)-N(3)	107.33(17)
N(5)-B(1)-H(1)	110.9(11)
N(1)-B(1)-H(1)	111.2(11)
N(3)-B(1)-H(1)	108.4(11)
N(1)-C(1)-C(2)	109.1(2)
N(1)-C(1)-H(1B)	125.5
C(2)-C(1)-H(1B)	125.5
C(1)-C(2)-C(3)	104.2(2)
C(1)-C(2)-H(2A)	127.9
C(3)-C(2)-H(2A)	127.9
N(2)-C(3)-C(2)	111.3(2)
N(2)-C(3)-H(3A)	124.4
C(2)-C(3)-H(3A)	124.4

N(3)-C(4)-C(5)	108.26(19)
N(3)-C(4)-H(4A)	125.9
C(5)-C(4)-H(4A)	125.9
C(4)-C(5)-C(6)	105.0(2)
C(4)-C(5)-H(5A)	127.5
C(6)-C(5)-H(5A)	127.5
N(4)-C(6)-C(5)	110.41(19)
N(4)-C(6)-H(6A)	124.8
C(5)-C(6)-H(6A)	124.8
N(5)-C(7)-C(8)	109.0(2)
N(5)-C(7)-H(7A)	125.5
C(8)-C(7)-H(7A)	125.5
C(7)-C(8)-C(9)	104.6(2)
C(7)-C(8)-H(8A)	127.7
C(9)-C(8)-H(8A)	127.7
N(6)-C(9)-C(8)	110.6(2)
N(6)-C(9)-H(9A)	124.7
C(8)-C(9)-H(9A)	124.7
O(1)-C(10)-Mo(1)	177.39(17)
O(2)-C(11)-Mo(1)	178.42(18)
C(13)-C(12)-N(7)	120.72(18)
C(13)-C(12)-Mo(1)	65.98(12)
N(7)-C(12)-Mo(1)	118.65(12)
C(13)-C(12)-H(12A)	114.3
N(7)-C(12)-H(12A)	114.3
Mo(1)-C(12)-H(12A)	114.3
C(12)-C(13)-C(14)	115.99(17)
C(12)-C(13)-Mo(1)	79.06(12)
C(14)-C(13)-Mo(1)	80.28(12)
C(12)-C(13)-H(13A)	121.3
C(14)-C(13)-H(13A)	121.3
Mo(1)-C(13)-H(13A)	121.3
C(13)-C(14)-C(15)	118.61(18)
C(13)-C(14)-Mo(1)	64.57(11)
C(15)-C(14)-Mo(1)	115.21(13)
C(13)-C(14)-H(14A)	116.1
C(15)-C(14)-H(14A)	116.1

Mo(1)-C(14)-H(14A)	116.1
C(16)-C(15)-C(14)	124.66(19)
C(16)-C(15)-C(20)	115.54(17)
C(14)-C(15)-C(20)	119.81(17)
C(15)-C(16)-C(29)	126.2(2)
C(15)-C(16)-C(17)	117.31(19)
C(29)-C(16)-C(17)	116.46(18)
C(16)-C(17)-C(18)	111.65(17)
C(16)-C(17)-H(17A)	109.3
C(18)-C(17)-H(17A)	109.3
C(16)-C(17)-H(17B)	109.3
C(18)-C(17)-H(17B)	109.3
H(17A)-C(17)-H(17B)	108.0
C(17)-C(18)-C(19)	112.67(17)
C(17)-C(18)-H(18A)	109.1
C(19)-C(18)-H(18A)	109.1
C(17)-C(18)-H(18B)	109.1
C(19)-C(18)-H(18B)	109.1
H(18A)-C(18)-H(18B)	107.8
C(18)-C(19)-C(20)	111.13(17)
C(18)-C(19)-S(1)	106.88(14)
C(20)-C(19)-S(1)	115.82(13)
C(18)-C(19)-H(19A)	107.6
C(20)-C(19)-H(19A)	107.6
S(1)-C(19)-H(19A)	107.6
N(7)-C(20)-C(15)	114.43(15)
N(7)-C(20)-C(19)	112.55(16)
C(15)-C(20)-C(19)	111.35(16)
N(7)-C(20)-H(20A)	105.9
C(15)-C(20)-H(20A)	105.9
C(19)-C(20)-H(20A)	105.9
O(3)-C(21)-O(4)	124.56(19)
O(3)-C(21)-N(7)	124.16(18)
O(4)-C(21)-N(7)	111.27(17)
O(4)-C(22)-C(23)	107.50(18)
O(4)-C(22)-H(22A)	110.2
C(23)-C(22)-H(22A)	110.2

O(4)-C(22)-H(22B)	110.2
C(23)-C(22)-H(22B)	110.2
H(22A)-C(22)-H(22B)	108.5
C(28)-C(23)-C(24)	119.0(2)
C(28)-C(23)-C(22)	120.5(2)
C(24)-C(23)-C(22)	120.6(2)
C(23)-C(24)-C(25)	120.3(3)
C(23)-C(24)-H(24A)	119.9
C(25)-C(24)-H(24A)	119.9
C(26)-C(25)-C(24)	120.8(3)
C(26)-C(25)-H(25A)	119.6
C(24)-C(25)-H(25A)	119.6
C(25)-C(26)-C(27)	119.1(3)
C(25)-C(26)-H(26A)	120.4
C(27)-C(26)-H(26A)	120.4
C(26)-C(27)-C(28)	120.3(3)
C(26)-C(27)-H(27A)	119.8
C(28)-C(27)-H(27A)	119.8
C(23)-C(28)-C(27)	120.6(2)
C(23)-C(28)-H(28A)	119.7
C(27)-C(28)-H(28A)	119.7
C(16)-C(29)-H(29A)	109.5
C(16)-C(29)-H(29B)	109.5
H(29A)-C(29)-H(29B)	109.5
C(16)-C(29)-H(29C)	109.5
H(29A)-C(29)-H(29C)	109.5
H(29B)-C(29)-H(29C)	109.5
C(31)-C(30)-C(35)	121.4(2)
C(31)-C(30)-S(1)	119.60(17)
C(35)-C(30)-S(1)	118.88(18)
C(30)-C(31)-C(32)	119.2(2)
C(30)-C(31)-H(31A)	120.4
C(32)-C(31)-H(31A)	120.4
C(33)-C(32)-C(31)	120.2(3)
C(33)-C(32)-H(32A)	119.9
C(31)-C(32)-H(32A)	119.9
C(34)-C(33)-C(32)	120.3(2)

C(34)-C(33)-H(33A)	119.8
C(32)-C(33)-H(33A)	119.8
C(33)-C(34)-C(35)	120.8(2)
C(33)-C(34)-H(34A)	119.6
C(35)-C(34)-H(34A)	119.6
C(30)-C(35)-C(34)	118.0(2)
C(30)-C(35)-H(35A)	121.0
C(34)-C(35)-H(35A)	121.0
C(11)-Mo(1)-C(10)	82.51(8)
C(11)-Mo(1)-N(4)	89.43(8)
C(10)-Mo(1)-N(4)	85.53(8)
C(11)-Mo(1)-C(13)	104.73(9)
C(10)-Mo(1)-C(13)	102.71(8)
N(4)-Mo(1)-C(13)	164.33(7)
C(11)-Mo(1)-N(6)	169.12(7)
C(10)-Mo(1)-N(6)	96.23(8)
N(4)-Mo(1)-N(6)	79.70(7)
C(13)-Mo(1)-N(6)	86.11(8)
C(11)-Mo(1)-N(2)	94.60(8)
C(10)-Mo(1)-N(2)	164.71(7)
N(4)-Mo(1)-N(2)	79.41(7)
C(13)-Mo(1)-N(2)	92.55(8)
N(6)-Mo(1)-N(2)	83.76(7)
C(11)-Mo(1)-C(12)	73.37(8)
C(10)-Mo(1)-C(12)	113.11(8)
N(4)-Mo(1)-C(12)	151.95(7)
C(13)-Mo(1)-C(12)	34.96(7)
N(6)-Mo(1)-C(12)	116.75(7)
N(2)-Mo(1)-C(12)	80.08(7)
C(11)-Mo(1)-C(14)	103.28(8)
C(10)-Mo(1)-C(14)	67.80(8)
N(4)-Mo(1)-C(14)	148.21(7)
C(13)-Mo(1)-C(14)	35.15(7)
N(6)-Mo(1)-C(14)	86.10(7)
N(2)-Mo(1)-C(14)	127.33(7)
C(12)-Mo(1)-C(14)	59.35(7)
C(1)-N(1)-N(2)	109.69(19)

C(1)-N(1)-B(1)	128.50(19)
N(2)-N(1)-B(1)	120.96(17)
C(3)-N(2)-N(1)	105.72(17)
C(3)-N(2)-Mo(1)	134.44(15)
N(1)-N(2)-Mo(1)	119.70(14)
C(4)-N(3)-N(4)	109.93(17)
C(4)-N(3)-B(1)	130.51(18)
N(4)-N(3)-B(1)	119.55(17)
C(6)-N(4)-N(3)	106.36(17)
C(6)-N(4)-Mo(1)	130.44(14)
N(3)-N(4)-Mo(1)	123.18(13)
C(7)-N(5)-N(6)	109.60(18)
C(7)-N(5)-B(1)	128.33(19)
N(6)-N(5)-B(1)	121.60(17)
C(9)-N(6)-N(5)	106.27(17)
C(9)-N(6)-Mo(1)	133.77(15)
N(5)-N(6)-Mo(1)	119.60(13)
C(21)-N(7)-C(12)	120.62(17)
C(21)-N(7)-C(20)	115.96(15)
C(12)-N(7)-C(20)	120.74(17)
C(21)-O(4)-C(22)	115.47(16)
O(5)-S(1)-O(6)	118.03(10)
O(5)-S(1)-C(30)	108.83(10)
O(6)-S(1)-C(30)	107.13(11)
O(5)-S(1)-C(19)	109.45(10)
O(6)-S(1)-C(19)	105.50(9)
C(30)-S(1)-C(19)	107.41(10)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for **compound (±)-52**. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
B(1)	28(1)	27(1)	13(1)	-3(1)	-3(1)	-4(1)
C(1)	42(2)	54(2)	17(1)	-8(1)	-14(1)	1(1)
C(2)	39(2)	78(2)	25(1)	-19(1)	-20(1)	6(1)
C(3)	29(1)	47(1)	23(1)	-13(1)	-11(1)	-1(1)
C(4)	24(1)	34(1)	22(1)	-14(1)	0(1)	-4(1)
C(5)	29(1)	31(1)	30(1)	-14(1)	-4(1)	4(1)
C(6)	28(1)	24(1)	24(1)	-9(1)	-8(1)	4(1)
C(7)	30(1)	25(1)	26(1)	-3(1)	-1(1)	-6(1)
C(8)	32(1)	31(1)	39(1)	-14(1)	-3(1)	-10(1)
C(9)	29(1)	28(1)	30(1)	-13(1)	-6(1)	-5(1)
C(10)	19(1)	20(1)	19(1)	-7(1)	-4(1)	-1(1)
C(11)	21(1)	20(1)	17(1)	-8(1)	-7(1)	5(1)
C(12)	23(1)	21(1)	15(1)	-6(1)	-7(1)	5(1)
C(13)	27(1)	16(1)	17(1)	-5(1)	-6(1)	5(1)
C(14)	25(1)	19(1)	19(1)	-8(1)	-6(1)	0(1)
C(15)	20(1)	19(1)	17(1)	-7(1)	-5(1)	3(1)
C(16)	25(1)	26(1)	20(1)	-11(1)	-8(1)	2(1)
C(17)	31(1)	31(1)	17(1)	-6(1)	-10(1)	3(1)
C(18)	31(1)	32(1)	16(1)	-7(1)	-9(1)	3(1)
C(19)	24(1)	18(1)	14(1)	-4(1)	-5(1)	1(1)
C(20)	22(1)	19(1)	14(1)	-5(1)	-9(1)	4(1)
C(21)	19(1)	25(1)	18(1)	-10(1)	-6(1)	4(1)
C(22)	33(1)	46(1)	23(1)	-13(1)	-8(1)	-12(1)
C(23)	29(1)	36(1)	19(1)	-7(1)	-7(1)	-10(1)
C(24)	37(2)	77(2)	31(1)	-21(1)	-17(1)	16(1)
C(25)	47(2)	108(3)	27(1)	-25(2)	-21(1)	16(2)
C(26)	40(2)	80(2)	31(1)	-31(1)	-11(1)	3(1)
C(27)	45(2)	54(2)	42(2)	-24(1)	-18(1)	13(1)
C(28)	46(2)	44(1)	32(1)	-11(1)	-23(1)	6(1)
C(29)	39(1)	34(1)	30(1)	-13(1)	-16(1)	-4(1)
C(30)	23(1)	26(1)	19(1)	-8(1)	-8(1)	7(1)

C(31)	26(1)	28(1)	34(1)	-5(1)	-11(1)	2(1)
C(32)	34(1)	45(1)	56(2)	-22(1)	-26(1)	6(1)
C(33)	44(2)	61(2)	43(2)	-25(1)	-29(1)	22(1)
C(34)	45(2)	49(2)	25(1)	-7(1)	-13(1)	21(1)
C(35)	28(1)	30(1)	27(1)	-5(1)	-6(1)	7(1)
Mo(1)	19(1)	17(1)	12(1)	-4(1)	-5(1)	0(1)
N(1)	33(1)	31(1)	15(1)	-4(1)	-9(1)	-2(1)
N(2)	24(1)	27(1)	16(1)	-5(1)	-7(1)	-2(1)
N(3)	23(1)	26(1)	14(1)	-7(1)	-2(1)	-4(1)
N(4)	22(1)	23(1)	15(1)	-5(1)	-3(1)	0(1)
N(5)	29(1)	23(1)	19(1)	-4(1)	-4(1)	-4(1)
N(6)	27(1)	23(1)	20(1)	-7(1)	-6(1)	-3(1)
N(7)	20(1)	20(1)	13(1)	-6(1)	-6(1)	2(1)
O(1)	32(1)	35(1)	28(1)	-11(1)	-18(1)	6(1)
O(2)	31(1)	20(1)	30(1)	-6(1)	-9(1)	-2(1)
O(3)	29(1)	26(1)	17(1)	-6(1)	-7(1)	-3(1)
O(4)	28(1)	32(1)	17(1)	-7(1)	-9(1)	-5(1)
O(5)	31(1)	23(1)	34(1)	-8(1)	-9(1)	-2(1)
O(6)	30(1)	39(1)	22(1)	-15(1)	-4(1)	8(1)
S(1)	22(1)	21(1)	18(1)	-8(1)	-4(1)	2(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for **compound (±)-52**.

	x	y	z	U(eq)
H(1B)	-1156	6122	11529	45
H(2A)	1027	6858	10521	54
H(3A)	1369	7495	8442	39
H(4A)	-4363	7921	10735	33
H(5A)	-4409	9662	9120	37
H(6A)	-2804	9493	7372	31
H(7A)	-4007	4252	10803	37
H(8A)	-3909	3531	9257	43
H(9A)	-2390	4860	7465	35
H(12A)	1635	6875	7062	24
H(13A)	471	5402	7136	25
H(14A)	-733	5814	5967	26
H(17A)	670	8957	2675	32
H(17B)	560	8089	2085	32
H(18A)	2638	8664	1724	32
H(18B)	2354	7332	2171	32
H(19A)	3212	8513	3130	24
H(20A)	1284	8768	4191	22
H(22A)	3584	10155	5602	40
H(22B)	4404	9216	6097	40
H(24A)	4198	8698	8052	56
H(25A)	3363	8963	9796	70
H(26A)	1746	10089	10134	57
H(27A)	924	10920	8731	54
H(28A)	1733	10631	6994	47
H(29A)	-1379	6158	4636	49
H(29B)	-677	6269	3345	49
H(29C)	-1564	7207	3642	49
H(31A)	5315	7886	3490	37
H(32A)	6330	7788	4720	49
H(33A)	5734	6391	6508	53

H(34A)	4127	5100	7084	50
H(35A)	3058	5194	5882	37
H(1)	-3148(19)	6027(17)	11023(18)	16(5)

Table 6. Torsion angles [°] for **compound (±)-52**.

N(1)-C(1)-C(2)-C(3)	1.0(3)
C(1)-C(2)-C(3)-N(2)	-1.2(3)
N(3)-C(4)-C(5)-C(6)	0.0(3)
C(4)-C(5)-C(6)-N(4)	-0.3(3)
N(5)-C(7)-C(8)-C(9)	-0.1(3)
C(7)-C(8)-C(9)-N(6)	0.3(3)
N(7)-C(12)-C(13)-C(14)	-36.8(3)
Mo(1)-C(12)-C(13)-C(14)	73.41(16)
N(7)-C(12)-C(13)-Mo(1)	-110.23(17)
C(12)-C(13)-C(14)-C(15)	33.5(3)
Mo(1)-C(13)-C(14)-C(15)	106.14(17)
C(12)-C(13)-C(14)-Mo(1)	-72.68(16)
C(13)-C(14)-C(15)-C(16)	164.22(19)
Mo(1)-C(14)-C(15)-C(16)	-122.26(19)
C(13)-C(14)-C(15)-C(20)	-15.6(3)
Mo(1)-C(14)-C(15)-C(20)	57.9(2)
C(14)-C(15)-C(16)-C(29)	-1.4(3)
C(20)-C(15)-C(16)-C(29)	178.41(19)
C(14)-C(15)-C(16)-C(17)	-178.82(18)
C(20)-C(15)-C(16)-C(17)	1.0(3)
C(15)-C(16)-C(17)-C(18)	49.0(3)
C(29)-C(16)-C(17)-C(18)	-128.7(2)
C(16)-C(17)-C(18)-C(19)	-46.3(3)
C(17)-C(18)-C(19)-C(20)	-1.0(2)
C(17)-C(18)-C(19)-S(1)	126.24(17)
C(16)-C(15)-C(20)-N(7)	-179.93(17)
C(14)-C(15)-C(20)-N(7)	-0.1(2)
C(16)-C(15)-C(20)-C(19)	-50.9(2)
C(14)-C(15)-C(20)-C(19)	128.94(18)
C(18)-C(19)-C(20)-N(7)	178.92(16)
S(1)-C(19)-C(20)-N(7)	56.7(2)
C(18)-C(19)-C(20)-C(15)	48.9(2)
S(1)-C(19)-C(20)-C(15)	-73.30(19)
O(4)-C(22)-C(23)-C(28)	-80.7(3)
O(4)-C(22)-C(23)-C(24)	99.2(3)

C(28)-C(23)-C(24)-C(25)	0.5(4)
C(22)-C(23)-C(24)-C(25)	-179.3(3)
C(23)-C(24)-C(25)-C(26)	-1.0(5)
C(24)-C(25)-C(26)-C(27)	0.8(5)
C(25)-C(26)-C(27)-C(28)	-0.2(5)
C(24)-C(23)-C(28)-C(27)	0.1(4)
C(22)-C(23)-C(28)-C(27)	180.0(2)
C(26)-C(27)-C(28)-C(23)	-0.3(4)
C(35)-C(30)-C(31)-C(32)	-0.9(3)
S(1)-C(30)-C(31)-C(32)	-177.09(19)
C(30)-C(31)-C(32)-C(33)	0.9(4)
C(31)-C(32)-C(33)-C(34)	-0.2(4)
C(32)-C(33)-C(34)-C(35)	-0.5(4)
C(31)-C(30)-C(35)-C(34)	0.3(3)
S(1)-C(30)-C(35)-C(34)	176.45(18)
C(33)-C(34)-C(35)-C(30)	0.4(4)
O(2)-C(11)-Mo(1)-C(10)	0(7)
O(2)-C(11)-Mo(1)-N(4)	-85(7)
O(2)-C(11)-Mo(1)-C(13)	102(7)
O(2)-C(11)-Mo(1)-N(6)	-84(7)
O(2)-C(11)-Mo(1)-N(2)	-165(7)
O(2)-C(11)-Mo(1)-C(12)	117(7)
O(2)-C(11)-Mo(1)-C(14)	65(7)
O(1)-C(10)-Mo(1)-C(11)	-36(4)
O(1)-C(10)-Mo(1)-N(4)	54(4)
O(1)-C(10)-Mo(1)-C(13)	-139(4)
O(1)-C(10)-Mo(1)-N(6)	133(4)
O(1)-C(10)-Mo(1)-N(2)	44(4)
O(1)-C(10)-Mo(1)-C(12)	-104(4)
O(1)-C(10)-Mo(1)-C(14)	-144(4)
C(12)-C(13)-Mo(1)-C(11)	26.83(13)
C(14)-C(13)-Mo(1)-C(11)	-92.25(13)
C(12)-C(13)-Mo(1)-C(10)	112.31(12)
C(14)-C(13)-Mo(1)-C(10)	-6.77(13)
C(12)-C(13)-Mo(1)-N(4)	-127.1(2)
C(14)-C(13)-Mo(1)-N(4)	113.8(3)
C(12)-C(13)-Mo(1)-N(6)	-152.17(12)

C(14)-C(13)-Mo(1)-N(6)	88.75(12)
C(12)-C(13)-Mo(1)-N(2)	-68.61(12)
C(14)-C(13)-Mo(1)-N(2)	172.31(11)
C(14)-C(13)-Mo(1)-C(12)	-119.08(16)
C(12)-C(13)-Mo(1)-C(14)	119.08(16)
C(13)-C(12)-Mo(1)-C(11)	-152.90(13)
N(7)-C(12)-Mo(1)-C(11)	-39.71(15)
C(13)-C(12)-Mo(1)-C(10)	-78.88(13)
N(7)-C(12)-Mo(1)-C(10)	34.31(17)
C(13)-C(12)-Mo(1)-N(4)	152.75(13)
N(7)-C(12)-Mo(1)-N(4)	-94.05(19)
N(7)-C(12)-Mo(1)-C(13)	113.2(2)
C(13)-C(12)-Mo(1)-N(6)	31.44(13)
N(7)-C(12)-Mo(1)-N(6)	144.63(14)
C(13)-C(12)-Mo(1)-N(2)	109.21(12)
N(7)-C(12)-Mo(1)-N(2)	-137.59(16)
C(13)-C(12)-Mo(1)-C(14)	-35.79(11)
N(7)-C(12)-Mo(1)-C(14)	77.40(15)
C(13)-C(14)-Mo(1)-C(11)	96.80(13)
C(15)-C(14)-Mo(1)-C(11)	-14.43(16)
C(13)-C(14)-Mo(1)-C(10)	172.86(14)
C(15)-C(14)-Mo(1)-C(10)	61.63(15)
C(13)-C(14)-Mo(1)-N(4)	-152.02(13)
C(15)-C(14)-Mo(1)-N(4)	96.75(18)
C(15)-C(14)-Mo(1)-C(13)	-111.2(2)
C(13)-C(14)-Mo(1)-N(6)	-88.78(12)
C(15)-C(14)-Mo(1)-N(6)	159.98(15)
C(13)-C(14)-Mo(1)-N(2)	-9.67(14)
C(15)-C(14)-Mo(1)-N(2)	-120.91(14)
C(13)-C(14)-Mo(1)-C(12)	35.60(11)
C(15)-C(14)-Mo(1)-C(12)	-75.63(15)
C(2)-C(1)-N(1)-N(2)	-0.5(3)
C(2)-C(1)-N(1)-B(1)	-169.8(2)
N(5)-B(1)-N(1)-C(1)	-129.2(2)
N(3)-B(1)-N(1)-C(1)	113.0(2)
N(5)-B(1)-N(1)-N(2)	62.5(2)
N(3)-B(1)-N(1)-N(2)	-55.3(3)

C(2)-C(3)-N(2)-N(1)	0.9(3)
C(2)-C(3)-N(2)-Mo(1)	176.43(18)
C(1)-N(1)-N(2)-C(3)	-0.3(3)
B(1)-N(1)-N(2)-C(3)	170.0(2)
C(1)-N(1)-N(2)-Mo(1)	-176.59(16)
B(1)-N(1)-N(2)-Mo(1)	-6.3(3)
C(11)-Mo(1)-N(2)-C(3)	-40.6(2)
C(10)-Mo(1)-N(2)-C(3)	-119.0(3)
N(4)-Mo(1)-N(2)-C(3)	-129.2(2)
C(13)-Mo(1)-N(2)-C(3)	64.4(2)
N(6)-Mo(1)-N(2)-C(3)	150.2(2)
C(12)-Mo(1)-N(2)-C(3)	31.6(2)
C(14)-Mo(1)-N(2)-C(3)	69.9(2)
C(11)-Mo(1)-N(2)-N(1)	134.41(15)
C(10)-Mo(1)-N(2)-N(1)	56.0(3)
N(4)-Mo(1)-N(2)-N(1)	45.85(15)
C(13)-Mo(1)-N(2)-N(1)	-120.59(16)
N(6)-Mo(1)-N(2)-N(1)	-34.79(15)
C(12)-Mo(1)-N(2)-N(1)	-153.39(16)
C(14)-Mo(1)-N(2)-N(1)	-115.04(16)
C(5)-C(4)-N(3)-N(4)	0.3(2)
C(5)-C(4)-N(3)-B(1)	-178.6(2)
N(5)-B(1)-N(3)-C(4)	121.3(2)
N(1)-B(1)-N(3)-C(4)	-119.2(2)
N(5)-B(1)-N(3)-N(4)	-57.6(2)
N(1)-B(1)-N(3)-N(4)	61.9(2)
C(5)-C(6)-N(4)-N(3)	0.5(2)
C(5)-C(6)-N(4)-Mo(1)	-177.74(15)
C(4)-N(3)-N(4)-C(6)	-0.5(2)
B(1)-N(3)-N(4)-C(6)	178.56(19)
C(4)-N(3)-N(4)-Mo(1)	177.90(14)
B(1)-N(3)-N(4)-Mo(1)	-3.0(2)
C(11)-Mo(1)-N(4)-C(6)	41.9(2)
C(10)-Mo(1)-N(4)-C(6)	-40.60(19)
C(13)-Mo(1)-N(4)-C(6)	-163.2(2)
N(6)-Mo(1)-N(4)-C(6)	-137.8(2)
N(2)-Mo(1)-N(4)-C(6)	136.7(2)

C(12)-Mo(1)-N(4)-C(6)	93.1(2)
C(14)-Mo(1)-N(4)-C(6)	-72.9(2)
C(11)-Mo(1)-N(4)-N(3)	-136.09(16)
C(10)-Mo(1)-N(4)-N(3)	141.38(16)
C(13)-Mo(1)-N(4)-N(3)	18.8(3)
N(6)-Mo(1)-N(4)-N(3)	44.21(15)
N(2)-Mo(1)-N(4)-N(3)	-41.30(15)
C(12)-Mo(1)-N(4)-N(3)	-85.0(2)
C(14)-Mo(1)-N(4)-N(3)	109.09(17)
C(8)-C(7)-N(5)-N(6)	-0.1(3)
C(8)-C(7)-N(5)-B(1)	171.9(2)
N(1)-B(1)-N(5)-C(7)	129.0(2)
N(3)-B(1)-N(5)-C(7)	-113.7(2)
N(1)-B(1)-N(5)-N(6)	-59.8(2)
N(3)-B(1)-N(5)-N(6)	57.5(3)
C(8)-C(9)-N(6)-N(5)	-0.4(3)
C(8)-C(9)-N(6)-Mo(1)	-173.23(16)
C(7)-N(5)-N(6)-C(9)	0.3(2)
B(1)-N(5)-N(6)-C(9)	-172.4(2)
C(7)-N(5)-N(6)-Mo(1)	174.39(14)
B(1)-N(5)-N(6)-Mo(1)	1.7(3)
C(11)-Mo(1)-N(6)-C(9)	127.4(4)
C(10)-Mo(1)-N(6)-C(9)	44.7(2)
N(4)-Mo(1)-N(6)-C(9)	129.0(2)
C(13)-Mo(1)-N(6)-C(9)	-57.7(2)
N(2)-Mo(1)-N(6)-C(9)	-150.7(2)
C(12)-Mo(1)-N(6)-C(9)	-75.1(2)
C(14)-Mo(1)-N(6)-C(9)	-22.5(2)
C(11)-Mo(1)-N(6)-N(5)	-44.7(4)
C(10)-Mo(1)-N(6)-N(5)	-127.44(16)
N(4)-Mo(1)-N(6)-N(5)	-43.15(15)
C(13)-Mo(1)-N(6)-N(5)	130.18(16)
N(2)-Mo(1)-N(6)-N(5)	37.18(15)
C(12)-Mo(1)-N(6)-N(5)	112.75(15)
C(14)-Mo(1)-N(6)-N(5)	165.41(16)
O(3)-C(21)-N(7)-C(12)	-173.08(18)
O(4)-C(21)-N(7)-C(12)	8.1(2)

O(3)-C(21)-N(7)-C(20)	-11.5(3)
O(4)-C(21)-N(7)-C(20)	169.70(16)
C(13)-C(12)-N(7)-C(21)	-178.12(18)
Mo(1)-C(12)-N(7)-C(21)	104.30(18)
C(13)-C(12)-N(7)-C(20)	21.2(3)
Mo(1)-C(12)-N(7)-C(20)	-56.4(2)
C(15)-C(20)-N(7)-C(21)	-163.80(16)
C(19)-C(20)-N(7)-C(21)	67.8(2)
C(15)-C(20)-N(7)-C(12)	-2.2(2)
C(19)-C(20)-N(7)-C(12)	-130.68(18)
O(3)-C(21)-O(4)-C(22)	3.5(3)
N(7)-C(21)-O(4)-C(22)	-177.70(18)
C(23)-C(22)-O(4)-C(21)	146.20(19)
C(31)-C(30)-S(1)-O(5)	173.81(17)
C(35)-C(30)-S(1)-O(5)	-2.4(2)
C(31)-C(30)-S(1)-O(6)	45.2(2)
C(35)-C(30)-S(1)-O(6)	-131.10(17)
C(31)-C(30)-S(1)-C(19)	-67.8(2)
C(35)-C(30)-S(1)-C(19)	115.96(18)
C(18)-C(19)-S(1)-O(5)	-72.90(16)
C(20)-C(19)-S(1)-O(5)	51.53(17)
C(18)-C(19)-S(1)-O(6)	55.06(16)
C(20)-C(19)-S(1)-O(6)	179.49(14)
C(18)-C(19)-S(1)-C(30)	169.10(14)
C(20)-C(19)-S(1)-C(30)	-66.47(17)

Symmetry transformations used to generate equivalent atoms:

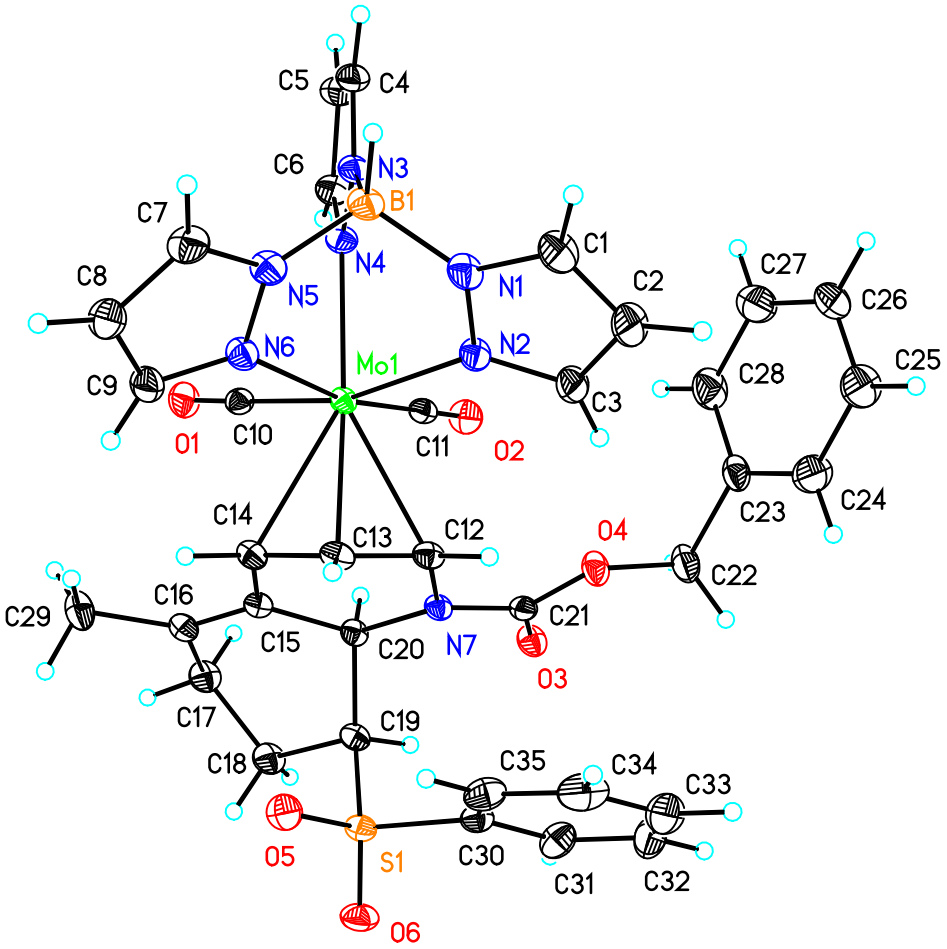


Figure 7: X-Ray structure of 52