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New Chemistry of Donor-Acceptor Cycloalkanes and Studies Towards the Synthesis of Streptorubin B

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Abstract and Keywords

Abstract

This dissertation presents two separate chapters within the broad area of synthetic organic chemistry. The first chapter describes the annelation chemistry of donor-acceptor (DA) cyclopropanes and cyclobutanes for the synthesis of heterocycles. The $Yb(OTf)_3$-catalyzed [4+2] cycloaddition between DA cyclobutanes and nitrosoarenes facilitated the synthesis of tetrahydro-1,2-oxazines in good to excellent yields as single diastereomers. Additionally, an unexpected deoxygenation occurred with electron-rich nitrosoarenes under MgI_2-catalysis that afforded pyrrolidine products. The $GaCl_3$-catalyzed [4+2] cycloaddition of DA cyclobutanes and *cis*-diazenes provided hexahydropyridazine derivatives in good to excellent yields as single diastereomers. Furthermore, a procedure to make spiroketals from the [4+2] cycloaddition of spirocyclic DA cyclobutanes and aldehydes is also disclosed. Lastly, a cascade reaction of DA cyclopropanes with nitrosoarenes is discussed. The reaction results in formation of tetrahydro-1,2-oxazine instead of normal cycloadduct isoxazolidine *via* a tandem ring opening, elimination, and cycloaddition sequence. A detailed discussion of the results along with associated mechanisms is presented.

The second chapter describes multiple strategies applied towards the synthesis of the prodigiosin alkaloid streptorubin B. The key aspect of the strategies is utilization of our group developed [3+2] cycloaddition between DA cyclopropanes and nitriles. An overview of this methodology and its application towards the synthesis of natural products is presented.

Keywords

donor-acceptor cyclopropane, donor-acceptor cyclobutane, annelation, annulation, cycloaddition, Lewis acid, catalysis, nitrosoarene, *cis*–diazene, tetrahydro-1,2-oxazine, pyrrolidine, hexahydropyridazine, spiroketal, pyrroles, streptorubin B, cascade reaction, methodology, total synthesis, thiabenzene 1-oxide.

Co-Authorship Statement

Chapter 1 involves collaborative work with Andrew C. Stevens (Ph.D. 2013), Tyler B. Schon (B.Sc. 2011), and Tristan Chidley (M.Sc. 2015). In section 1.2.1.1, Dr. Stevens and Mr. Schon were responsible for reaction discovery, optimization, and some substrate scope examples. Mr. Chidley was responsible for a major portion of the experimental of the results presented in sections 1.2.1.2 and 1.2.2.

For my lost self

Acknowledgments

There are many great people and experiences that helped me to become who I am today. First and foremost, I am indebted to my mother Suguna Vemula, who has been my inspiration, strength, and best friend. There was a time, due to extreme poverty, that I decided to give up on studies, and it was my uneducated mother who insisted I pursue higher studies. Now, I am scared to imagine how my life would have been without education.

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List of Abbreviations

18-C-6	1,4,7,10,13,16-hexaoxacyclooctadecane
A	electron-acceptor
Å	Angstrom
AACD	alkoxy-activated cyclobutane-1,1-dicarboxylate
Ac	acetyl
AIBN	2,2′-azo-*bis*(2-methylpropionitrile)
anhyd	anhydrous
app	apparent
aq	aqueous
Ar	aryl
BIAB	*bis*(acetoxy)iodobenzene
BINAP	2,2′-*bis*(diphenylphosphino)-1,1′-binaphthalene
Bn	benzyl
Boc	*tert*-butyloxycarbonyl
br	broad
Bu	butyl
bp	boiling point
Calcd	calculated
CAM	cerium ammonium molybdate
Cat	catalytic
Chloramine-T	*N*-chloro-*para*-toluenesulfonamide sodium salt

D	electron-donor
d	doublet
DA	donor-acceptor
dd	doublet of doublets
dba	dibenzylideneacetone
ddd	doublet of doublet of doublets
dddd	doublet of doublet of doublet of doublets
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DCE	1,2-dichloroethane
DCM	dichloromethane
de	diastereomeric excess
DEF	*N*,*N*-diethylformamide
DIBAL-H	diisobutylaluminum hydride
DMAP	4-(dimethylamino)pyridine
DME	1,2-dimethoxyethane
DMF	*N*,*N*-dimethylformamide
DMP	Dess-Martin periodinane (1,1,1-*tris*(acetyloxy)-1,1-dihydro-1,2-benziodoxol-3-(1*H*)-one)
DMS	dimethyl sulfide
DMSO	dimethyl sulfoxide
dq	doublet of quartets
dr	diastereomeric ratio
dt	doublet of triplets
ee	enantiomeric excess

E^+	electrophile
Et	ethyl
eq	equation
equiv	equivalent
g	gram (s)
Grubbs II	(1,3-*bis*(2,4,6-trimethylphenyl)-2-imidazolidinylidene)dichloro(phenylmethylene)(tricyclohexylphosphine)ruthenium
h	hour (s)
HMBC	heteronuclear multiple-bond correlation spectroscopy
HRMS	high-resolution mass spectrometry
Hz	hertz
imid	imidazole
*i*Pr	isopropyl
J	coupling constant
KAPA	potassium 3-aminopropylamide
Kcal	kilogram calorie (s)
KHMDS	potassium *bis*(trimethylsilyl)amide
m	multiplet
MAD	methylaluminum *bis*(2,6-di-*tert*-butyl-4-methylphenoxide)
mbar	millibar
Me	methyl
mg	milligram (s)
MHz	megahertz

min	minute (s)
mL	milliliter (s)
mol	mole (s)
MRs	medium-sized rings
MS	molecular sieves
Ms	methanesulfonyl
ms	millisecond (s)
m/z	mass to charge ratio
*n*Bu	*n*-butyl
Nu^-	nucleophile
NMR	nuclear magnetic resonance
NTf_2	*N,N-bis*(trifluoromethylsulfonyl)imide
nOe	nuclear Overhauser effect
ORTEP	Oak Ridge Thermal Ellipsoid Plot
OTf	trifluoromethanesulfonate
Ph	phenyl
PMP	*para*-methoxyphenyl
ppm	parts per million
PTAD	4-phenyl-1,2,4-triazoline-3,5-dione
Py	pyridine
PCC	pyridinium chlorochromate
q	quartet
qd	quartet of doublets
quin	quintet

rac	racemic
RBF	round bottom flask
RM	reaction mixture
rt	room temperature
s	singlet
Satd	saturated
t	triplet
TBDPS	*tert*-butyldiphenylsilyl
TBS	*tert*-butyldimethylsilyl
*t*Bu	*tert*-butyl
td	triplet of doublets
temp	temperature
TEMPO	2,2,6,6-tetramethyl-1-piperidinyloxy, free radical
THF	tetrahydrofuran
TLC	thin layer chromatography
TMS	trimethylsilyl
Ts	*para*-toluenesulfonyl
tt	triplet of triplets
µM	micromolar
µw	microwave irradiation

Preface

It is every synthetic organic chemist's vision to make a complex product from trivial starting materials in a manner that absolutely controls regio- and stereoselectivity. Intermolecular cycloaddition chemistry offers a tool which assists in turning this vision into a reality. One manner of facilitating cycloaddition chemistry is through exploitation of ring strain in carbocycles. In this regard cyclopropanes, typically bearing vicinally substituted electron donating and electron accepting groups, suitably named as donor-acceptor (DA) cyclopropanes, are extensively studied. While this area continues to mature, reports on extending similar synthetic transformations to the homologous cyclobutanes are comparatively limited. Recently, the Pagenkopf group has begun exploring application of DA cyclobutanes in cycloaddition chemistry. While exploring this reaction space in collaboration with co-workers, new modes of reactivity were discovered.

The first chapter of this thesis will discuss several novel reactions of DA cyclobutanes and cyclopropanes. We have disclosed the first example of a [4+2] cycloaddition between DA cyclobutanes and nitrosoarenes. The reaction proceeds well with electron neutral and deficient nitrosoarenes, but electron-rich nitrosoarenes required a stronger Lewis acid, MgI_2. Interestingly, with electron-rich nitrosoarenes, a deoxygenation process was observed resulting in the formation of pyrrolidines from tetrahydro-1,2-oxazines in MgI_2 conditions. We have also developed the first example of a [4+2] cycloaddition between DA cyclobutanes and *cis*-diazenes. The reaction proceeds smoothly with alkoxy activated cyclobutanes as well as aryl activated cyclobutanes to form hexahydropyridazines in good to excellent yields. Furthermore, a procedure to make spiroketals from [4+2] cycloaddition of spirocyclic DA cyclobutanes with aldehydes was also developed. In

addition, we have discovered a cascade reaction of DA cyclopropanes with nitrosoarenes to form tetrahydro-1,2-oxazines. The cascade reaction proceeds through a ring opening of DA cyclopropane, followed by fragmentation to a nitrone intermediate and cycloaddition with second equivalent of DA cyclopropane to generate the tetrahydro-1,2-oxazines as single diastereomers in good to excellent yields.

The second chapter discusses the different strategies applied towards the synthesis of the biologically active prodigiosin alkaloid streptorubin B, using our group's [3+2] cycloaddition of DA cyclopropanes and nitriles.

It is my sincere hope that the reader, through the results discussed throughout the thesis, can arrive at a better understanding of the chemistry of DA cyclopropanes and cyclobutanes.

-Naresh Vemula

Chapter 1. New Chemistry of Donor-Acceptor Cycloalkanes

This chapter discusses new reactions of DA cyclopropanes and cyclobutanes. In collaboration with fellow graduate student Andrew C. Stevens (Ph.D. 2013) and undergrad Tyler B. Schon (B.Sc. 2011), we have developed the first example of a [4+2] cycloaddition of DA cyclobutanes and nitrosoarenes. In an attempt to extend this methodology to DA cyclopropanes, we discovered a novel cascade reaction that ultimately generated tetrahydro1,2-oxazines. In collaboration with fellow graduate student Tristan Chidley, we studied the mechanism through crossover experiments. The first example of a [4+2] cycloaddition of DA cyclobutanes and *cis*-diazenes was also developed, in collaboration with Tristan Chidley. Additionally, a procedure to make spiroketals from spirocyclic DA cyclobutanes was also developed.

1.1 Introduction

1.1.1 General Introduction to Cyclopropanes and Cyclobutanes

Cyclopropanes and cyclobutanes are highly strained carbocycles.[1] The strain in any cyclic compound is a composite of three types of individual strain: transannular strain due to Van der Waals interactions between atoms across the ring, torsional strain (also called as Pitzer strain) due to eclipsing conformations between adjacent atoms, and angle strain (also called as Baeyer strain) due to distorted bond angles from the ideal for a given hybridization.[2] While transannular strain is predominant in medium-sized rings (see, section 2.4), cyclopropanes, and cyclobutanes experience severe Baeyer and Pitzer strains. Although, these two strained carbocycles have similar ring strain (27.5 kcal/mol for cyclopropane and 26.3 kcal/mol for cyclobutane), there are notable differences in their structures.[3] While cyclopropane has 60° C-C-C bond angles, similar to a planar equatorial triangle, cyclobutanes adopt a puckered conformation to reduce the Pitzer strain, but at the expense of Baeyer strain, and thus the C-C-C bond angle is <90° (Figure 1-1). Also the strain energy in cyclobutane is distributed over four carbons (6.6 kcal/mol/C–C bond) compared to three carbons in case of cyclopropane (9.2 kcal/mol/C-C bond).

Figure 1-1. Pictorial representation of puckering conformation of cyclobutane.

1.1.2 Donor-Acceptor Cyclopropanes

The reactivity of the cyclopropanes can be predictable by the substitution pattern around the ring (Figure 1-2). Electron-donating groups (**D**, such as amino or alkoxy) activate the

cyclopropane and increase its ability to react with electrophiles (eq 1, Figure 1-2). Likewise, electron-acceptor groups (**A**, such as carbonyl or nitro) increase the electrophilicity of the cyclopropane ring allowing homo-Michael type additions (eq 2, Figure 1-2). Interestingly, when both electron donating and electron-accepting groups are vicinally substituted, the strained C-C bond becomes polarized through a push-pull mechanism resulting in a 1,3-zwitterionic intermediate.[4] This can be trapped by appropriate dipolarophiles, such as aldehydes or nitrones, to access annulated compounds (eq 3, Figure 1-2). These three types of substitution patterns on cyclopropanes, classifies them into three categories, namely, donor cyclopropanes, acceptor cyclopropanes, and donor-acceptor (DA) cyclopropanes.[5]

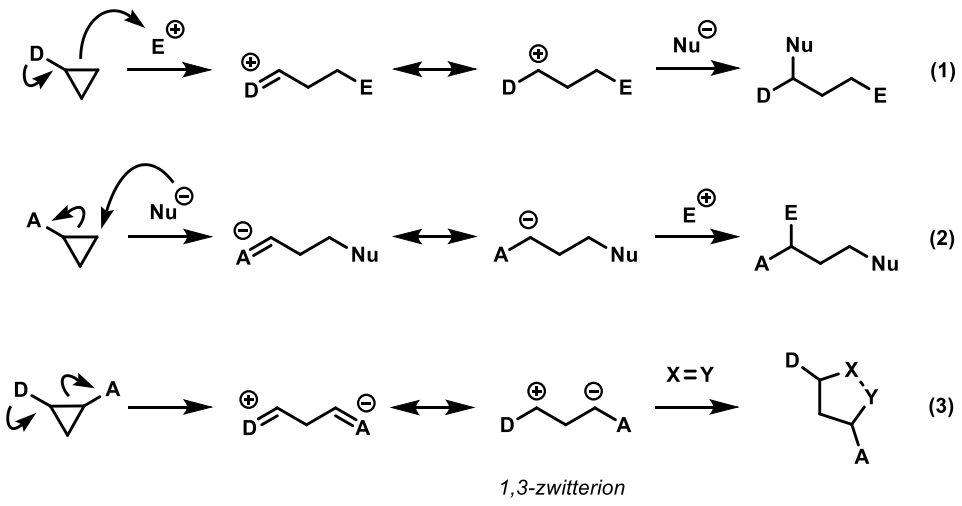
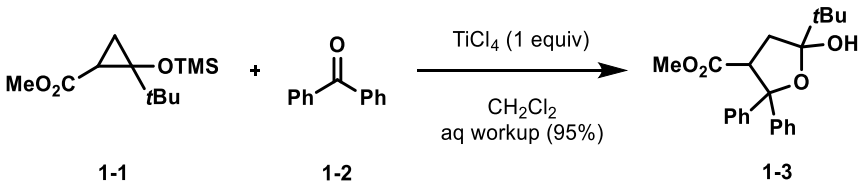


Figure 1-2. Modes of cyclopropane reactivity.

Substituent-activated chemistry of cyclopropanes was pioneered by the groups of Wenkert (on donor cyclopropanes),[6] Danishefsky (on acceptor cyclopropanes),[7] and Reissig (on DA cyclopropanes).[9a-b] The first formal cycloaddition of DA cyclopropanes was reported by Reissig (Scheme 1-1).[8] In this seminal report, Reissig reported the

annulation of DA cyclopropane **1-1** with benzophenone (**1-2**), mediated by $TiCl_4$, which resulted in tetrahydrofuran **1-3** in almost quantitative yield.



1-1 1-2 1-3

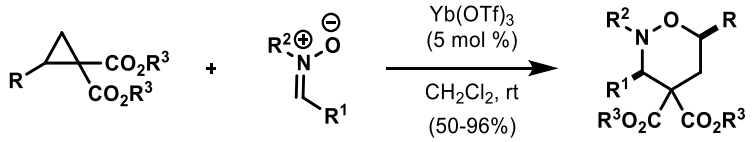
Scheme 1-1. First cycloaddition of DA cyclopropane **1-1** with benzophenone (**1-2**).

Since this seminal report, a plethora of discoveries have been published in this area.[9] Two of the finest reactions in this field relevant to this thesis are, the [3+2] cycloaddition of DA cyclopropanes with nitriles[10] (which is reviewed in section 2.3) and the [3+3] cycloaddition of DA cyclopropanes with nitrones.[11]

1.1.2.1 The [3+3] Cycloaddition of Nitrones and Donor-Acceptor Cyclopropanes

1.1.2.1.1 The Reaction Discovery and Development

The first example of a [3+3] cycloaddition of DA cyclopropanes with nitrones[12] was reported by Kerr and Young in 2003.[11a] The reaction of an aldehyde-derived nitrone **1-5** with DA cyclopropane **1-4** in presence of catalytic $Yb(OTf)_3$ resulted in tetrahydro-1,2-oxazine **1-6** in good to excellent yields and diastereoselectivity (Scheme 1-2).



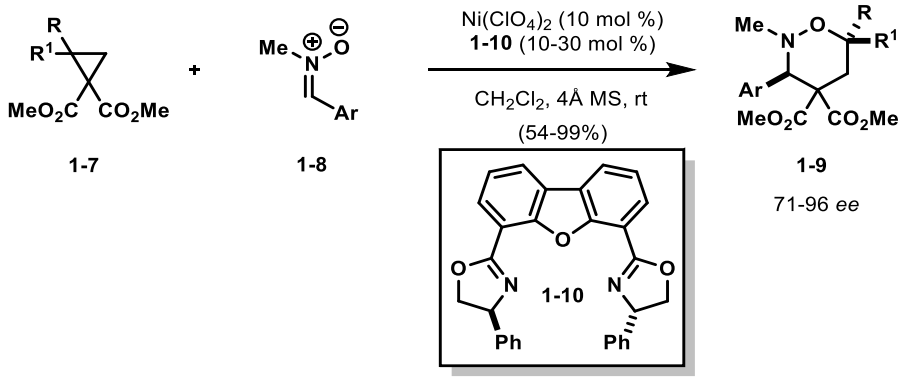
1-4 1-5 1-6

10 examples

Scheme 1-2. The [3+3] cycloaddition of DA cyclopropanes and nitrones.

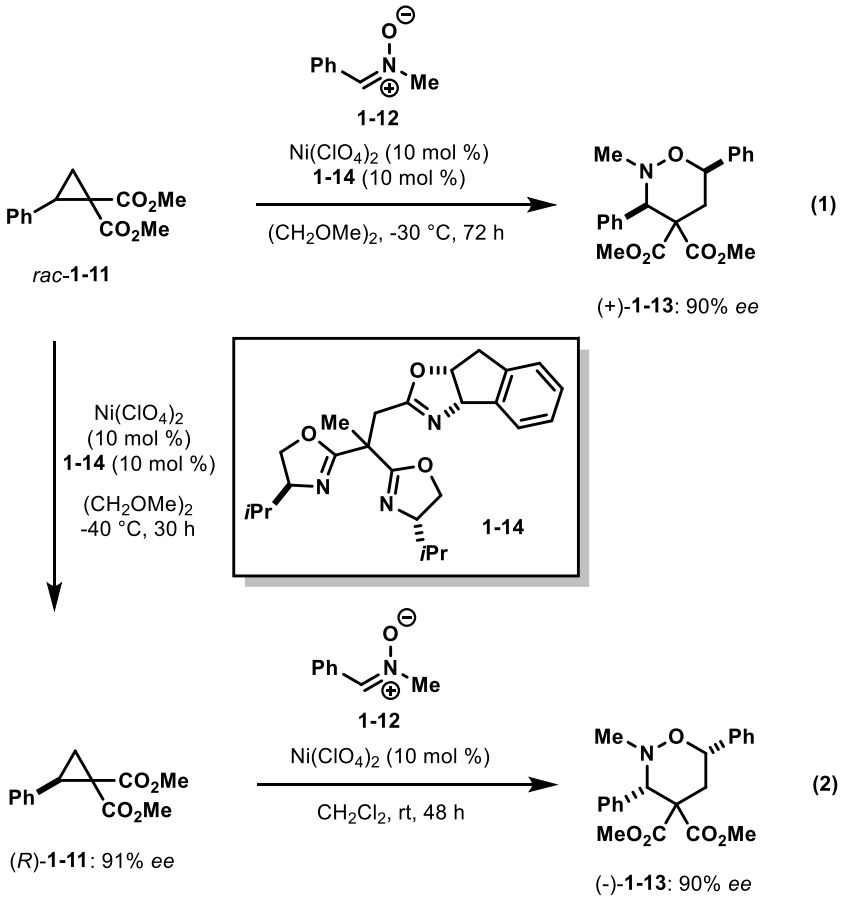
In 2004, Kerr and co-workers further developed this reaction to encompass unstable nitrones *via* a three-component coupling of hydroxylamines, aldehydes, and DA cyclopropanes.[11c] This multicomponent reaction allows the formation of a diverse array of tetrahydro-1,2-oxazines, which can then be transformed into congeners of FR900482 (similar to Scheme 1-5).

In 2005, Sibi and co-workers reported an asymmetric variant of this cycloaddition using bisoxazoline ligand **1-10** catalyzed by $Ni(ClO_4)_2$ (Scheme 1-3).[11d] Excellent yields and enantiomeric excess was observed, but kinetic resolution remained elusive while using racemic cyclopropanes.



Scheme 1-3. Sibi's asymmetric [3+3] cycloaddition of DA cyclopropanes and nitrones.

A few years later, in 2007, Tang and co-workers addressed the kinetic resolution problem using trisoxazoline ligand **1-14** in the $Ni(ClO_4)_2$–catalyzed asymmetric [3+3] cycloaddition of nitrones with DA cyclopropanes.[11g] As shown in the example in Scheme 1-4, both enantiomers of tetrahydro-1,2-oxazine **1-13** can be prepared from racemic DA cyclopropane **1-11** by either a direct cycloaddition with nitrone **1-12** in the presence of catalytic **1-14**/$Ni(ClO_4)_2$ (eq 1, Scheme 1-4) or a **1-14**/$Ni(ClO_4)_2$-catalyzed kinetic resolution followed by cycloaddition with nitrone **1-12** (eq 2, Scheme 1-4).



Scheme 1-4. Kinetic resolution of racemic DA cyclopropane for the synthesis of both enantiomers of tetarahydro-1,2-oxazine.

1.1.2.1.2 Application in Target-oriented Synthesis

Although, the tetrahydro-1,2-oxazine structure is not abundant in nature, the core can be found in a few natural products[13] as well as in pharmaceutical drugs[14] (Figure 1-3).

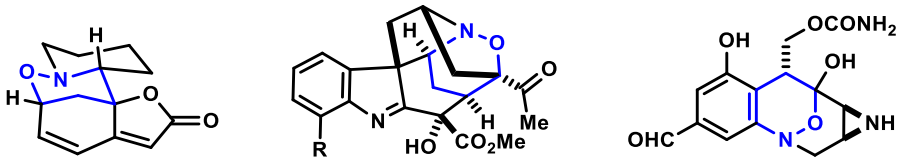
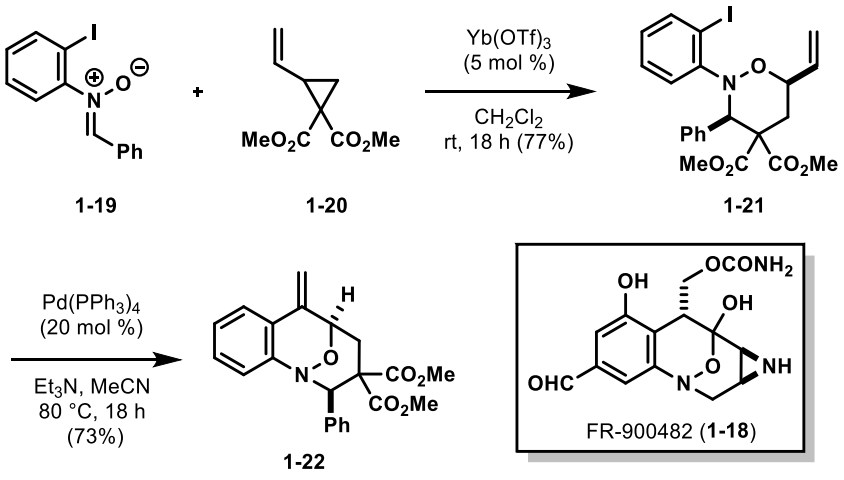


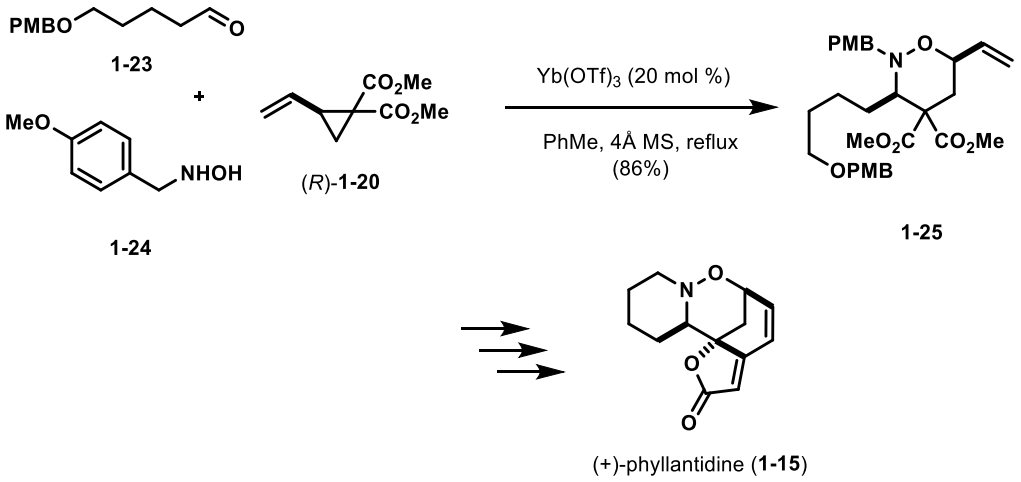
Figure 1-3. Representative examples of tetrahydro-1,2-oxazine core in natural products and pharmaceutical drugs.

Although multiple methods exist for the synthesis of tetrahydro-1,2-oxazines,[15] the [3+3] cycloaddition allows for the rapid generation of structural complexity from simple starting materials. For instance, in the same methodology paper,[11a] the authors demonstrated the utility of this elegant reaction in the synthesis of tricyclic skeleton of the antitumor agent FR-900482 (**1-18**).[16] As shown in Scheme 1-5, nitrone **1-19** underwent a [3+3] cycloaddition with DA cyclopropane **1-20** to afford tetrahydro-1,2-oxazine **1-21** in 77% yield. In a similar manner to Danishefsky's synthesis,[16b] oxazine **1-21** was converted into the desired tricyclic core **1-22** in 73% yield.



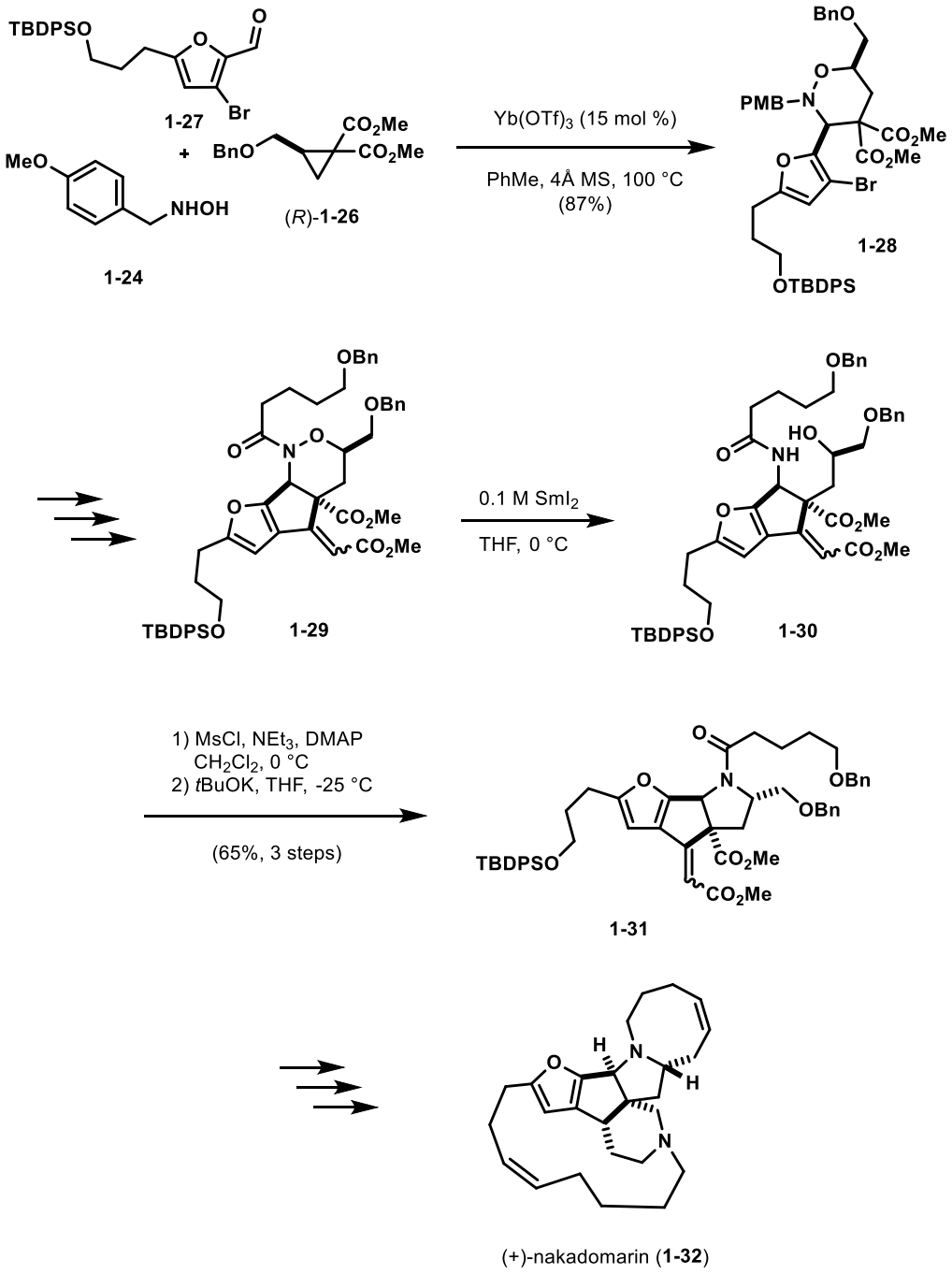
Scheme 1-5. Synthesis of the FR-900482 skeleton *via* [3+3] cycloaddition.

In 2006, Kerr and Carson showcased the [3+3] cycloaddition of nitrones with DA cyclopropanes, in their elegant total synthesis of a securinega alkaloid, (+)-phyllantidine (**1-15**, Scheme 1-6).[11e] The tetrahydro-1,2-oxazine core structure of (+)-phyllantidine (**1-15**) was efficiently accessed from a three component coupling of aldehyde **1-23**, hydroxylamine **1-24**, and enantiopure DA cyclopropane (*R*)-**1-20** in 86% yield (Scheme 1-6). Oxazine **1-25** was then converted into the natural product (+)-phyllantidine (**1-15**) in a series of transformations. Thus the synthesis of (+)-phyllantidine was achieved in 6% overall yield over 12 linear steps from DA cyclopropane (*R*)-**1-20**.



Scheme 1-6. Total synthesis of (+)-phyllantidine *via* [3+3] cycloaddition.

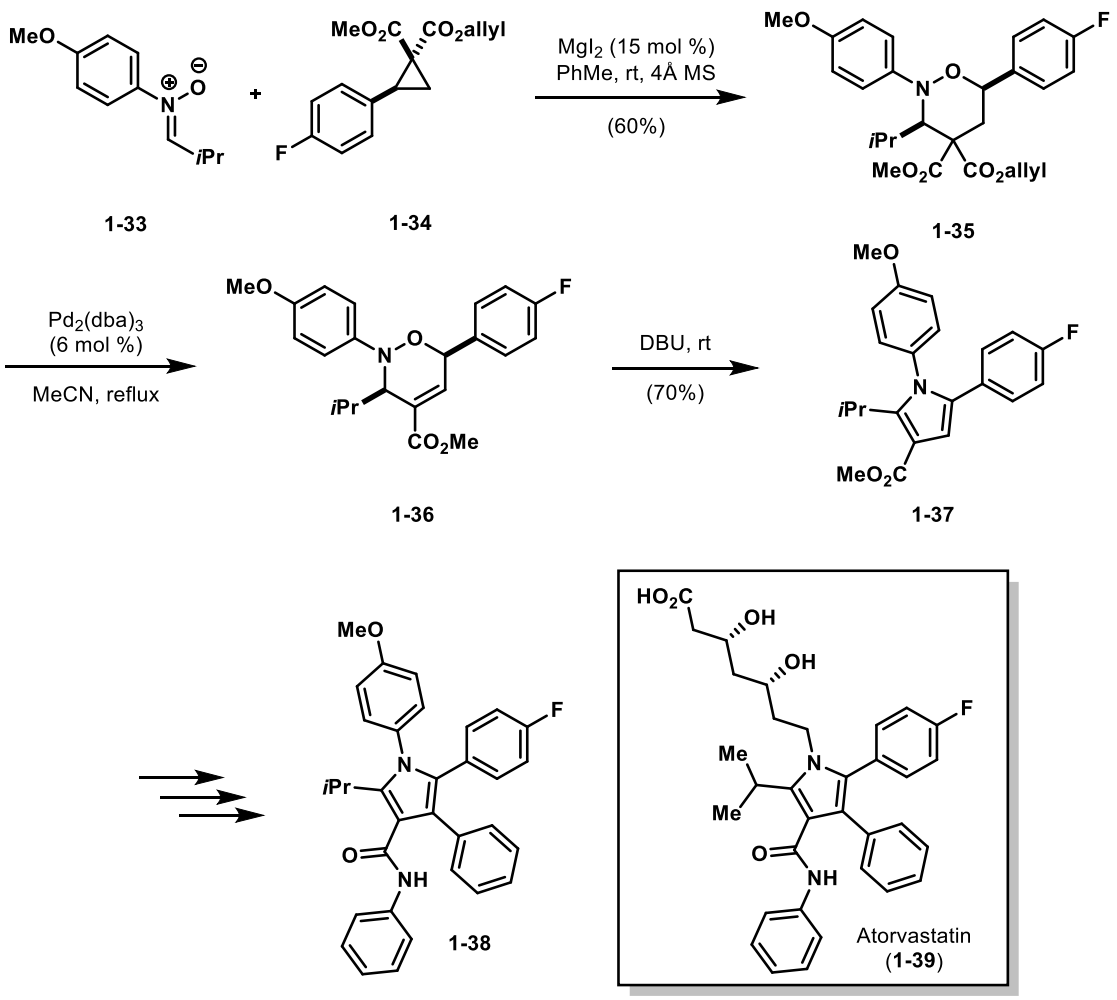
Reissig and co-workers demonstrated the application of tetrahydro-1,2-oxazines in synthesis of pyrrolidines *via* a reductive cleavage of the N-O bond, followed by cyclization.[17] Kerr and co-workers applied this strategy on tetrahydro-1,2-oxazine **1-28** accessed from a three component coupling of aldehyde **1-27**, hydroxylamine **1-24**, and enantiopure DA cyclopropane (*R*)-**1-26** for the enantioselective synthesis of manzamine alkaloid (+)-nakadomarin A (**1-32**, Scheme 1-7).[18]



Scheme 1-7. Enantioselective synthesis of (+)-nakadomarin A *via* [3+3] cycloaddition of nitrone and DA cyclopropane.

As shown in Scheme 1-7 the three component coupling of aldehyde **1-27**, hydroxylamine **1-24**, and enantiopure DA cyclopropane (*R*)-**1-26** (derived from D-mannose) gave oxazine **1-28** in 87% yield. The oxazine **1-28** was then converted into an advanced intermediate **1-29** through a series of transformations. Hydrogenolytic cleavage of the N-O bond of oxazine **1-29** gave the amino alcohol **1-30**, which was selectively converted into *O*-mesylate and treated with base to afford pyrrolidine **1-31** in a 65% yield over three steps with inversion of configuration at reaction center. The pyrrolidine **1-31** was then carried on to (+)-nakadomarin A through a series of reactions. Thus the synthesis of (+)-nakadomarin A was achieved in 23 steps from DA cyclopropane (*R*)-**1-26**.

In 2012, Kerr and co-workers extended the applications of tetrahydro-1,2-oxazines towards synthesis Atorvastatin pyrrole (**1-38**, Scheme 1-8).[19] As described in Scheme 1-8, the synthesis began with the [3+3] cycloaddition of nitrone **1-33** and DA cyclopropane **1-34** to afford oxazine **1-35** in 60% yield. Tsuji dehydrocarbonylation on the oxazine **1-35** provided the enolate **1-36** which was immediately treated with DBU to obtain pyrrole **1-37** in 70% yield over two steps.[20] The pyrrole **1-37** was then converted into an advanced intermediate **1-38** through a series of transformations. Thus conversion of tetrahydro-1,2-oxazines to pyrroles was showcased in synthesis of Atorvastatin pyrrole (**1-38**).[21]



Scheme 1-8. Synthesis of Atorvastatin pyrrole **1-38** *via* [3+3] cycloaddition of nitrone and DA cyclopropane.

In summary, the [3+3] cycloaddition of nitrones and DA cyclopropanes has proven to be an excellent method to construct tetrahydro-1,2-oxazines. The efficiency of the reaction has been well demonstrated in synthesis of natural products (+)-phyllantidine (**1-15**) and (+)-nakadomarin A (**1-32**). The tetrahydro-1,2-oxazines were also manipulated to congeners of pharmaceutical drug FR-900482 (**1-18**) and Atorvastatin pyrrole (**1-38**).

1.1.3 Donor-Acceptor Cyclobutanes

While the chemistry of DA cyclopropanes continues to mature, reports extending similar synthetic transformations to the homologous cyclobutanes are comparatively limited (Figure 1-4).[22]

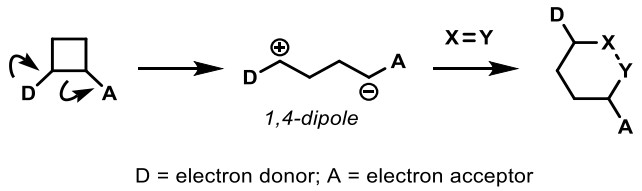
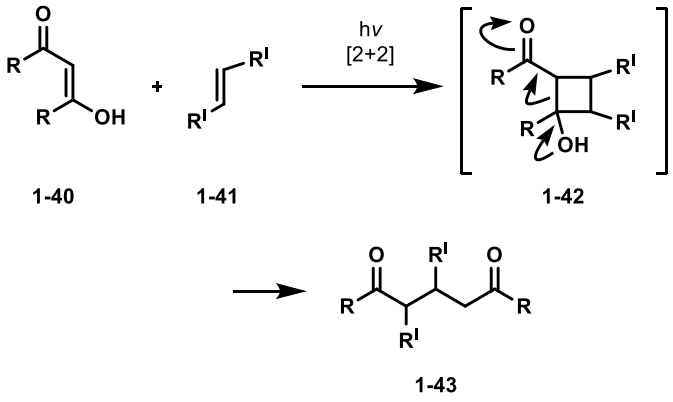


Figure 1-4. Potential reactivity of DA cyclobutanes with generic dipolarophile **X=Y**.

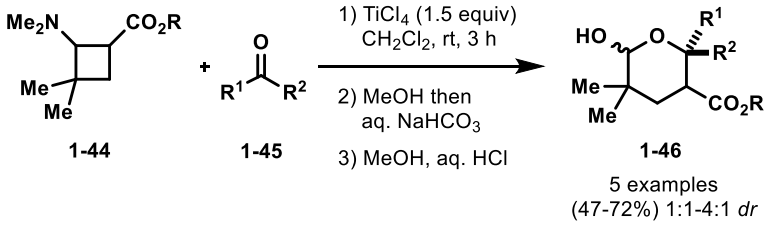
1.1.3.1 Seminal Reports in DA Cyclobutane Chemistry

Even though the de Mayo reaction, in which the transient cyclobutane **1-42** undergoes a rapid ring opening to give 1,5-dicarbonyl compound **1-43**, has been known in the literature since the 1960s (Scheme 1-9),[23] attempts to explore the reactivity of DA cyclobutanes was not made until early 1990s.



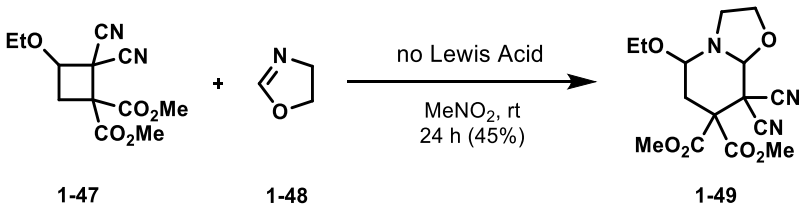
Scheme 1-9. Ring opening of the transient cyclobutane **1-42** in the de Mayo reaction.

The first report of formal cycloaddition of DA cyclobutanes was disclosed by Saigo and co-workers in 1991.[24] In this work, amino-activated DA cyclobutanes **1-44** underwent [4+2] cycloadditions with carbonyl compounds **1-45** to generate tetrahydropyrans **1-46**, albeit with low diastereoselectivity and modest yield (Scheme 1-10).



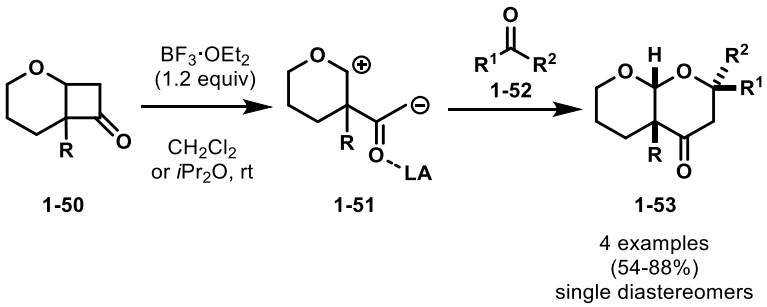
Scheme 1-10. The [4+2] cycloaddition of amino-activated DA cyclobutanes with carbonyl compounds.

A few years later, in 1997, Suzuki and co-workers observed a [4+2] cycloaddition of highly activated DA cyclobutane **1-47** with 2-oxazoline (**1-48**) without the need for a catalyst (Scheme 1-11).[25]



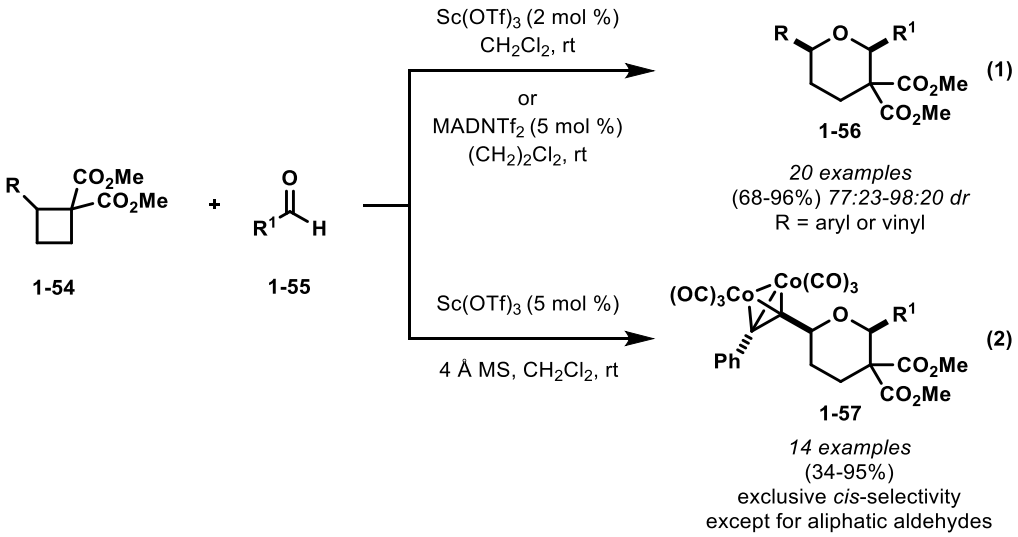
Scheme 1-11. The [4+2] cycloaddition of DA cyclobutane **1-47** with 2-oxazoline (**1-48**).

The field remained relatively dormant for a decade, until 2008, when Matsuo and co-workers observed a conceptually similar [4+2] cycloaddition[26] with 3-alkoxycyclobutanones **1-50** and carbonyl compounds **1-52** (Scheme 1-12).[27]



Scheme 1-12. The [4+2] cycloaddition of 3-alkoxycyclobutanones **1-50** with carbonyl compounds **1-52**.

Shortly after the disclosure by Matsuo, the first catalytic cycloaddition of DA cyclobutanes with aldehydes that possessed a significantly broad substrate scope was reported by the research groups of Johnson[28] and of Christie and Pritchard.[31] The [4+2] cycloaddition with aldehydes **1-55** was found to proceed under mild conditions with good to excellent yields. In contrast to the work conducted by Saigo (Scheme 1-10), the DA cyclobutanes in these reports used carbon-based electron-donating groups (aryl, vinyl or cobalt-alkyne complex) and 1,1-diester substituents as the electron-accepting groups (Scheme 1-13).



Scheme 1-13. The [4+2] cycloaddition of carbon-activated cyclobutane-1,1-dicarboxylates **1-54** with aldehydes **1-55**.

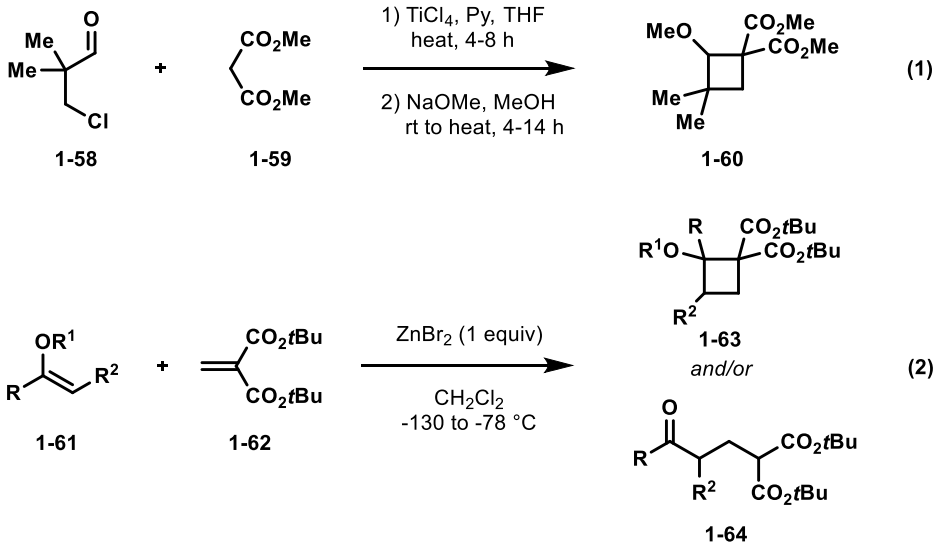
Johnson found that $Sc(OTf)_3$ was able to catalyze the cycloaddition with loadings as low as 2 mol % (eq 1, Scheme 1-13).[28] The cycloaddition was highly diastereoselective for the 2,6-*cis*-diastereomer with the majority of the aryl aldehydes investigated, but when cinnamaldehyde was used the diastereoselectivity dropped to 77:23, possibly due to the slow reactivity.[29] The group was able to encompass aliphatic aldehydes with the more reactive and bulky Lewis acid, $MADNTf_2$.[30]

The work by Christie and Pritchard reported a similar reactivity of cyclobutanes with a cobalt–alkyne complex as an electron-donor and 1,1-diesters as electron-acceptors (eq 2, Scheme 1-13).[31] The group also found $Sc(OTf)_3$ as the best catalyst for this transformation. Most of the aryl aldehydes and other electron-rich aldehydes underwent the cycloaddition in good to excellent yields, forming the tetrahydropyran products as single diastereomers. When aliphatic aldehydes were used, the diastereoselectivity significantly dropped to 20-23% *de*.

It became apparent from the preceding examples that having 1,1-diesters as electron-acceptors enhanced the reactivity as well as the diastereoselectivity in cycloadditions as compared to a monoester. Inspired by these seminal reports and ongoing interest of Pagenkopf group (referred hereinafter as "we" or "our") in alkoxy-activated cyclopropane chemistry,[32] we were motivated to investigate the reactivity alkoxy-activated cyclobutane-1,1-dicarboxylates (AACDs).

1.1.3.2 Synthesis of Alkoxy-activated Cyclobutane-1,1-dicarboxylates

At the outset of our work, only two literature methods were available for the synthesis of AACDs (Scheme 1-14).

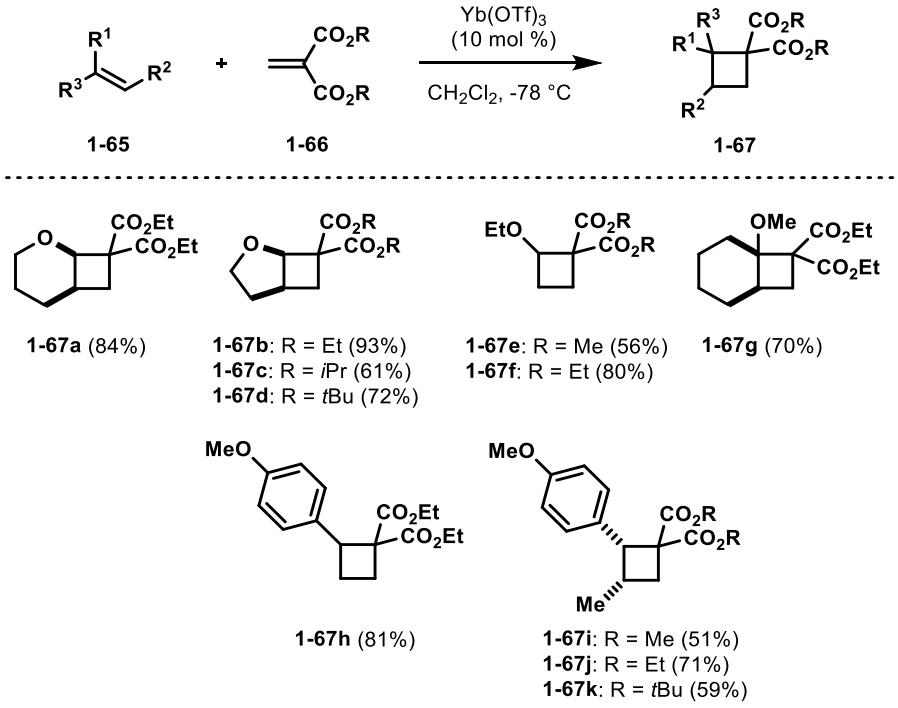


Scheme 1-14. Literature methods for the synthesis of AACDs.

The use of a Michael induced ring closure of acyclic substrates (eq 1, Scheme 1-14) was not selected as a preparative route as it offers limited control over the stereochemistry, and requires multiple steps.[33] On the other hand, a $ZnBr_2$-promoted [2+2] annulation reported by Roberts in 1986 appeared much more promising since the

required alkyl enol ethers are commercially available or can be readily prepared, and the methylidene malonates can be easily accessed through Knoevenagel condensation (eq 2, Scheme 1-14).[34] Although this procedure could be utilized to prepare a number of AACDs containing 1,1-di-*tert*-butyl esters, this methodology could not be extended to prepare the more reactive ethyl- or methyl-substituted AACDs.[35] To circumvent this challenge, a catalyst screening was explored, and it was revealed $Yb(OTf)_3$ as the best catalyst for this [2+2] cycloaddition. With the optimized conditions in hand, the scope of the cyclobutane synthesis was explored (Table 1-1).[38]

Table 1-1. The synthesis of AACDs.



A range of cyclic and acyclic enol ethers were found to undergo cycloaddition with a variety of dialkyl methylidene malonates to generate AACDs in good to excellent yields as single diastereomers (**1-67a**-**1-67g**, Table 1-1). In addition to enol ethers,

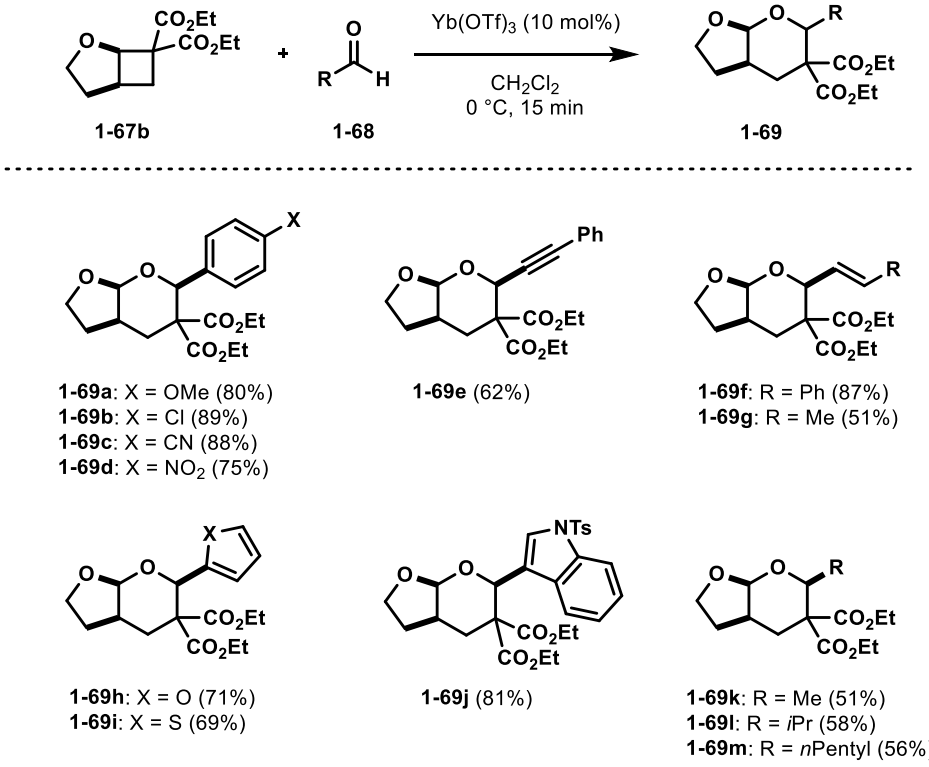
electron-rich styrenes were also found to undergo efficient cycloaddition to yield AACDs in good yields (**1-67h**-**1-67k**, Table 1-1). With the AACDs at hand, the reactivity was explored with a variety of dipolarophiles

1.1.3.3 Reactivity of Alkoxy-activated Cyclobutane-1,1-dicarboxylates

1.1.3.3.1 The [4+2] Cycloaddition of AACDs with Aldehydes

Interestingly, initial investigations established that $Yb(OTf)_3$, which was used for the synthesis of AACDs (Table 1-1), was also a competent catalyst for the [4+2] cycloaddition with aldehydes.[36] A wide range of aldehydes were found to undergo cycloadditions with AACDs in good to excellent yields, forming tetrahydropyrans as single diastereomers (Table 1-2). Aryl, heteroaryl, vinyl, and alkynyl aldehydes underwent smooth cycloadditions to afford tetrahydropyrans **1-69** in good to excellent yields (**1-69a**-**1-69j**). Finally, aliphatic aldehydes were also found to engage in cycloadditions, but only modest yields were observed (**1-69k**-**1-69m**).

Table 1-2. The [4+2] cycloaddition of AACDs with aldehydes.

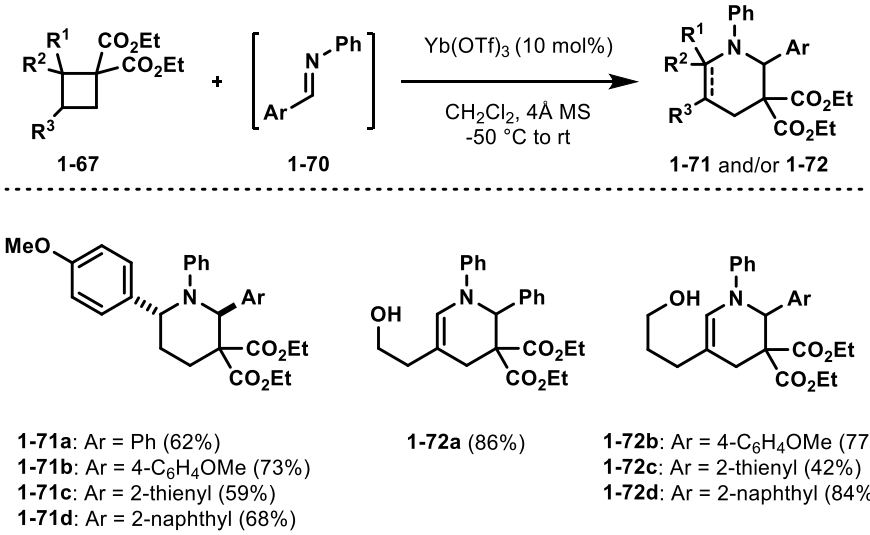


1.1.3.3.2 The [4+2] Cycloaddition of AACDs with Imines

With the above example, the feasibility of cycloaddition chemistry with AACDs was confirmed. Our interest then shifted to further explore other possible dipolarophiles which could lead to desirable or novel structural architectures. Although imines were excellent dipolarophiles in cycloadditions with DA cyclopropanes,[37] their reactivity with DA cyclobutanes was unexplored. Thus, we set out to investigate the reactivity of imines with AACDs. Upon exposure of cyclobutane **1-67** and imine **1-70** (prepared *in situ*) to catalytic $Yb(OTf)_3$ at -50 °C, a mixture of bicyclic piperidine **1-71** and piperideine **1-72** were formed (Table 1-3).[38] In order to converge on the piperideine product **1-72**, the reaction was simply warmed to rt after the cyclobutane was consumed.[39] Electron-rich

styrene derived cyclobutanes were also found to undergo cycloaddition to afford exclusive 2,6-*trans*-piperidines, but longer reaction times were necessary (**1-71a**-**1-71d**).

Table 1-3. The [4+2] cycloaddition of AACDs with imines.



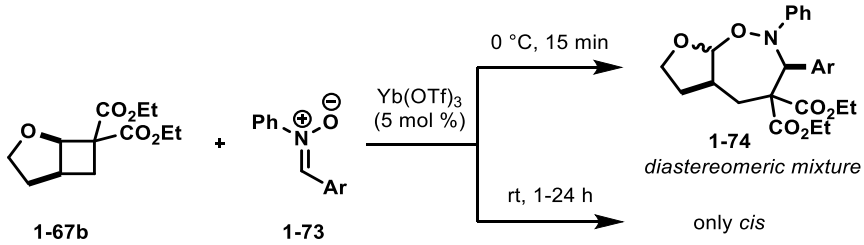
1.1.3.3.3 The [4+3] Cycloaddition of AACDs with Nitrones

Having successfully expanded the reactivity of AACDs to imines, our interest turned to explore 3-atom dipolarophiles. Nitrones have previously been reported as excellent dipolarophiles in cycloadditions with DA cyclopropanes (see Section 1.1.2.1). Given this precedent, we investigated the reactivity of nitrones with AACDs.

After brief optimization studies, 5 mol % $Yb(OTf)_3$ was determined to be the best catalyst for this cycloaddition.[40] Interestingly, *cis*-diastereomers were formed as thermodynamic products when the reaction was performed at rt; however a diastereomeric mixture containing significant amounts of the kinetic *trans*-diastereomer could be obtained at lower temperatures (Table 1-4).[41] Additionally, when electron-deficient nitrone **1-73d** was used, an inseparable third diastereomer was observed (entry

4),[42] however, all three diastereomers would eventually converge to the single thermodynamic product. The heterocycle, 1,2-oxazepanes, are intriguing and unique structural motifs that are not naturally occurring, but they do display interesting antiviral[43] and antiproliferative[44] activity.

Table 1-4. The [4+3] cycloaddition of AACDs with nitrones.

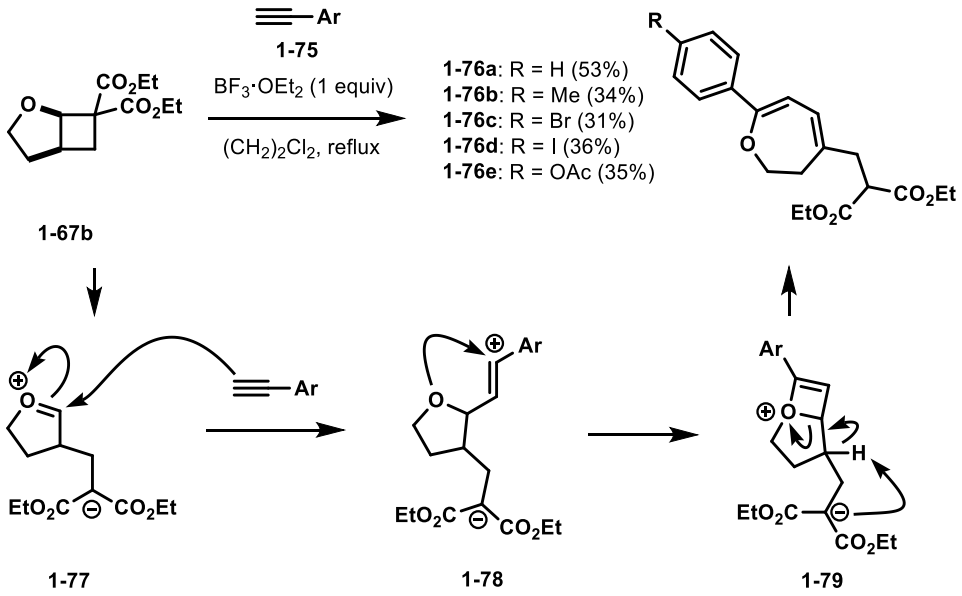


entry	1,2-oxazepane	at 0 °C yield (*cis:trans:3rd*)	at rt yield (*cis*)
1	**1-73a**: Ar = C_6H_5	91% (31:69)	76%
2	**1-73b**: Ar = 4-C_6H_4Cl	82% (29:71)	73%
3	**1-73c**: Ar = 4-C_6H_4OMe	88% (37:63)	74%
4	**1-73d**: Ar = 4-C_6H_4CN	95% (15:57:27)	76%

1.1.3.3.4 BF_3·OEt_2-promoted Reaction of AACDs with Terminal Alkynes

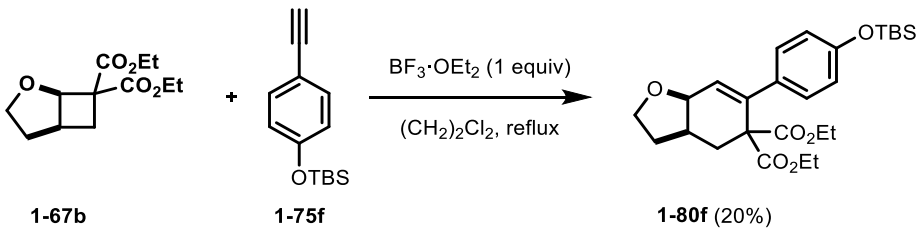
Intrigued with the success of above discussed cycloadditions, we were then interested to study an all carbon dipolarophile, such as the alkynes. Terminal alkynes have previously been reported to undergo efficient [3+2] cycloadditions with DA cyclopropanes.[45] After a multitude of unsuccessful attempts, it was discovered that stoichiometric BF_3·OEt_2 could promote the reaction to generate a peculiar 2,3-dihydrooxepine structure **1-76**. This

structure originated from an addition/rearrangement sequence *via* a highly strained bicyclic intermediate **1-79** (Scheme 1-15).[46]



Scheme 1-15. $BF_3{\cdot}OEt_2$-promoted reaction of AACDs with terminal alkynes.

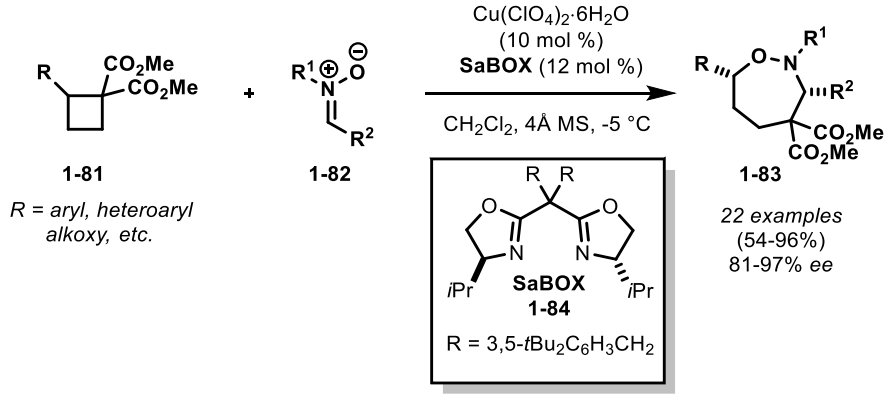
Only arylacetylenes with electron-neutral and moderately electron-rich substituents proceeded through a productive reaction manifold, albeit in low yields (**1-76a**-**1-76e**, Scheme 1-15). Substrates with strong electron-donating substituents rapidly polymerized upon exposure to $BF_3{\cdot}OEt_2$, whereas, electron-deficient alkynes failed to react.[47] Interestingly, when silyloxy substituted phenylacetylene **1-75f** was used, the reaction resulted in the expected [4+2] cycloadduct **1-80f** (Scheme 1-16). This was the only case we observed cycloaddition instead of rearrangement, which could be due to the increased bulk on the aryl ring inhibiting the polymerization and/or rearrangement.



Scheme 1-16. The [4+2] cycloaddition of alkyne **1-75f** with AACD **1-67b**.

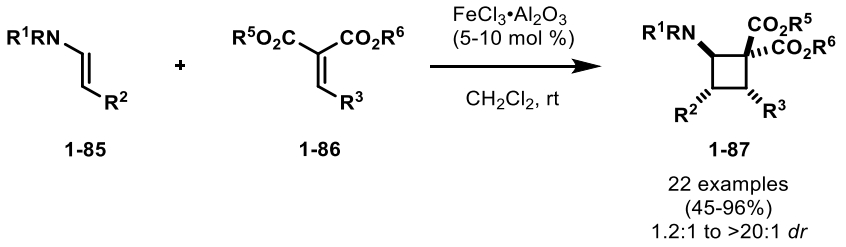
1.1.3.4 Additional Cyclobutane-1,1-dicarboxylates

In recent years, several other groups have reported interesting cycloadditions of DA cyclobutanes. Most recently, Tang and co-workers reported the enantioselective [4+3] cycloaddition of DA cyclobutanes and nitrones (Scheme 1-17).[48] While contributing the first enantioselective variant, the group also added several new DA cyclobutanes to the library.



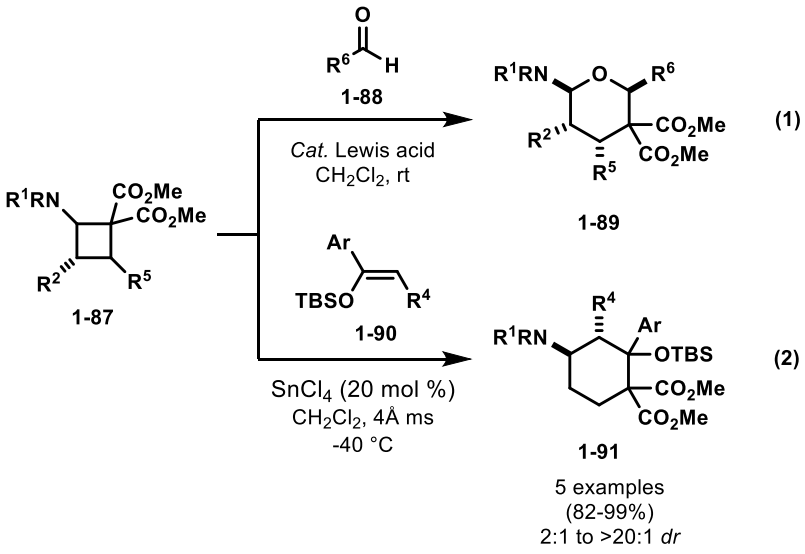
Scheme 1-17. Enantioselective [4+3] cycloaddition of DA cyclobutanes **1-81** with nitrones **1-83**.

Waser and co-workers enhanced the family of DA cyclobutanes by developing a Fe(III)-catalyzed [2+2] cycloaddition of enimides **1-85** and alkylidene malonates **1-86** to access amino-activated cyclobutane-1,1-dicarboxylates **1-87** (Scheme 1-18).[49]



Scheme 1-18. Waser's synthesis of amino-activated cyclobutane-1,1-dicarboxylates.

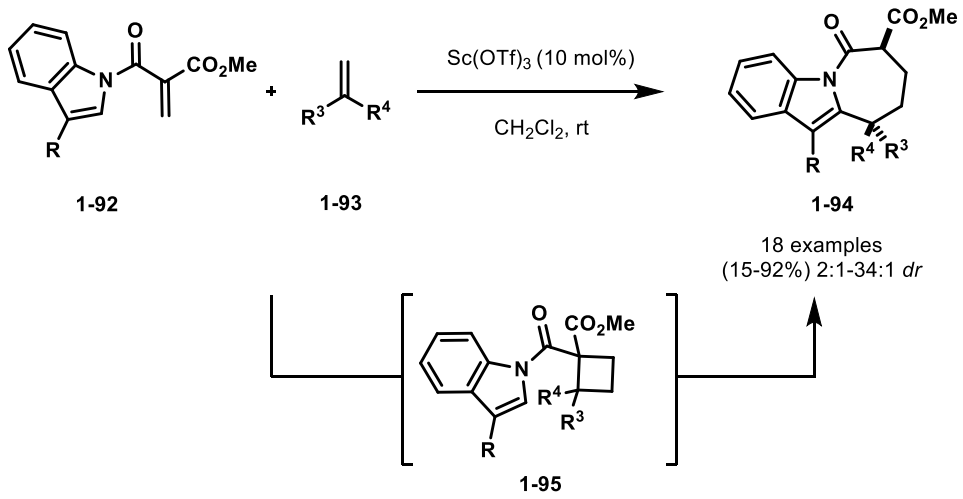
The group also disclosed the reactivity of these DA cyclobutanes with aldehydes and silyl enolethers (Scheme 1-19).[50] Interestingly, in the reaction with aldehydes **1-88** (eq 1, Scheme 1-19), the less substituted DA cyclobutanes **1-87** ($R^2 = R^3 = H$) could be activated with $Sc(OTf)_3$, but the more substituted **1-87** ($R^2 = R^3 \neq H$) required $FeCl_3 \cdot Al_2O_3$. More interestingly, thymine- or fluorouracil-substituted cyclobutanes were also found to undergo cycloaddition with aldehydes under $Hf(OTf)_4$ catalysis to access six-membered ring carbonucleoside analogues. In reaction with silyl enolethers, only less



Scheme 1-19. [4+2] cycloadditions of amino-activated cyclobutane-1,1-dicarboxylates **1-87** with aldehydes **1-88** and silyl enolethers **1-90**.

substituted DA cyclobutanes **1-87** (R^2 = R^3 = H) were found to undergo cycloadditions (eq 2, Scheme 1-19).

The first intramolecular cycloaddition of DA cyclobutanes[51] was recently reported by France and co-workers.[52,53] The authors described a $Sc(OTf)_3$-catalyzed [5+2] cycloaddition approach for the synthesis of azepino[1,2-*a*]indoles **1-94** *via* DA cyclobutane intermediates **1-95** (Scheme 1-20).



Scheme 1-20. The [5+2] cycloaddition approach for synthesis of azepino[1,2-*a*]indoles **1-94** *via* DA cyclobutane intermediates **1-95**.

In summary, application of the long ignored DA cyclobutanes in cycloaddition chemistry have recently garnered significant attention. A number of reaction partners have been found to undergo efficient annulations with DA cyclobutanes to facilitate rapid access to structurally intriguing carbo- and heterocyclic frameworks. While initial examples lacked scope and stereochemical control, more recent examples have broadened the scope of the transformations, and have demonstrated the possibility of high level of stereo-control. Recently, asymmetric and intramolecular cycloaddition variants

have been reported, yet the chemistry of DA cyclobutanes is only in its infancy and further studies will surely prove fruitful.

Motivated by the successful cycloadditions of AACDs with aldehydes, imines, and nitrones, we became interested in exploring the reactivity of other dipolarophiles, as this would allow a better understanding of these fascinating systems. A successful cycloaddition would result in diverse structural motifs, depending on the dipolarophile, and would thus be useful in accessing a library of compounds for biological screening. In addition, as many natural products contain these cycloadducts as core structures, it would be very efficient to elaborate these cycloadducts for complex natural product synthesis. Thus, we chose nitrosoarenes as annulation partners to investigate it's reactivity with AACDs.

1.2 Results and Discussion

1.2.1 Reactivity of Donor-Acceptor Cycloalkanes with Nitrosoarenes

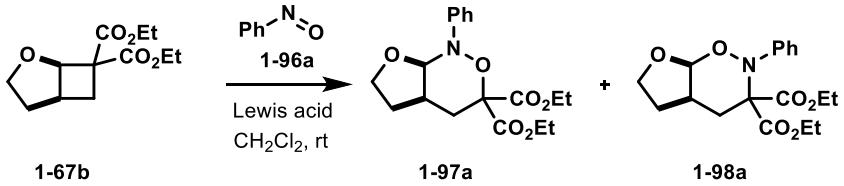
Nitrosoarenes[54] have been utilized in a variety of transformations[55] such as dienophiles in hetero Diels-Alder cycloadditions[56] and as enophiles in nitroso-ene reactions.[57] The dichotomous capacity of nitroso functional group, to act as either nitrogen or oxygen transfer reagents, has been well studied in nitroso-aldol chemistry.[58] Although the insertion of NO into the cyclopropane ring is known,[59] surprisingly, nitrosoarenes have not yet seen application in annelation[60] chemistry with either DA cyclopropanes or cyclobutanes.

1.2.1.1 The [4+2] Cycloaddition of AACDs with Nitrosoarenes

In collaboration with fellow grad student Andrew C. Stevens (Ph.D. 2013) and undergrad Tyler B. Schon (B.Sc. 2011), investigations into the reactivity of AACDs with nitrosoarenes began with the examination of the reaction between cyclobutane **1-67b** and nitrosobenzene (**1-96a**) (Table 1-5).[61] While a variety of Lewis acids were found to catalyze the reaction, maximum yields were obtained with $Yb(OTf)_3$. Additionally, the product yield was dramatically improved by decreasing the catalyst loading from 10 to 2 mol % (compare entries 1, 6 and 8). The reaction could be effected with catalyst loadings as low as 0.5 mol % but in low yield (entry 9). Thus, 2 mol % $Yb(OTf)_3$ was selected as the optimized catalysts system for this reaction. Interestingly, among the two possible regioisomers (**1-97a** and **1-98a**), the product obtained was always **1-97a**, and no noticeable amount of **1-98a** was observed, irrespective of the Lewis acid used. Thereby

demonstrating that the nitrogen of the nitroso functional group was acting as a nucleophile rather than oxygen.[62]

Table 1-5. Catalyst screening for [4+2] cycloaddition of AACDs with nitrosoarenes.



1-67b 1-97a 1-98a

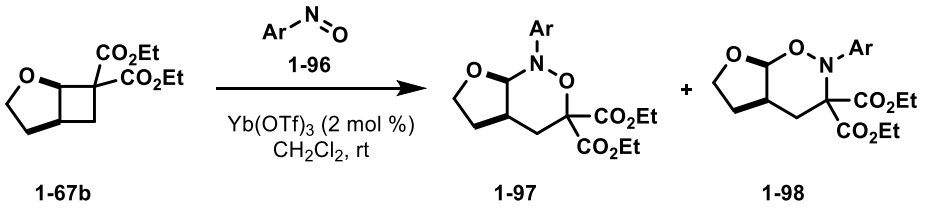
entry[a]	Lewis acid	mol %	yield (%)[b]	product
1	$Yb(OTf)_3$	10	60	**1-97a**
2	$Sc(OTf)_3$	10	55	**1-97a**
3	$La(OTf)_3$	10	22	**1-97a**
4	$Zn(OTf)_2$	10	61	**1-97a**
5	$Pr(OTf)_3$	10	63	**1-97a**
6	$Yb(OTf)_3$	5	72	**1-97a**
7	$Sc(OTf)_3$	5	61	**1-97a**
8	$Yb(OTf)_3$	2	92	**1-97a**
9	$Yb(OTf)_3$	0.5	80	**1-97a**

[a]**Typical reaction conditions**: To a solution of Lewis acid in CH_2Cl_2 (3 mL) at rt, was added nitrosobenzene **1-96a** (0.30 mmol) followed by cyclobutane **1-67b** (0.36 mmol). Reactions were monitored until **1-96a** was consumed by TLC. [b]Isolated yield.

With optimal conditions in hand, the scope of the reaction was examined (Table 1-6). It was discovered that nitrosoarenes with halogen substituents were excellent reaction partners regardless of the position on the aryl ring (entries 2-7).[63] Substrates with moderately deactivating ketone (entries 8 and 9) or ester (entry 10) substituents were

competent in the reaction affording the product in good yields. Electron-deficient nitrosoarenes afforded moderate yields (entries 11 and 12); however, the other possible regioisomer (Figure 1-6) was also formed, comprising up to 25% of the isolated yield. Nitrosoarene with a weakly electron donating methyl substituent resulted in a substantially decreased yield (entry 13). Upon incorporation of a strongly electron donating group no reaction was observed (entries 14 and 15). The arrest in reactivity is likely due to the sequestration of the ytterbium catalyst by the electron-rich nitrosoarene.

Table 1-6. Reaction scope of the [4+2] cycloaddition of AACDs with nitrosoarenes.



1-67b 1-97 1-98

entry	nitrosoarene	product	yield (%)[b]
1	Ar = C_6H_5	**1-97a**	92
2	Ar = 4-C_6H_4Br	**1-97b**	89
3	Ar = 4-C_6H_4Cl	**1-97c**	93
4	Ar = 3-C_6H_4Br	**1-97d**	87
5	Ar = 3-C_6H_4Cl	**1-97e**	95
6	Ar = 2,4-$C_6H_3Br_2$	**1-97f**	47
7	Ar = 3,4-$C_6H_3Cl_2$	**1-97g**	91
8	Ar = 4-$C_6H_4C(O)Me$	**1-97h**	69
9	Ar = 3-$C_6H_4C(O)Me$	**1-97i**	87
10	Ar = 4-$C_6H_4CO_2Et$	**1-97j**	76
11	Ar = 4-C_6H_4CN	**1-97k**, **1-98k** (3:1)[a]	61
12	Ar = 4-$C_6H_4NO_2$	**1-97l**, **1-98l** (4:1)[a]	59
13	Ar = 4-C_6H_4Me	**1-97m**	29
14	Ar = 4-C_6H_4OMe	-	no reaction[c]
15	Ar = 4- $C_6H_4NMe_2$	-	no reaction[c]

[a]Ratio of **1-97**:**1-98** of isolated overall yield, [b]Isolated yield.

[c]$Yb(OTf)_3$ 2 mol % or 10 mol %

Fortuitously, X-ray quality crystals of compounds **1-97b** (entry 2, Table 1-6) and **1-97k** (entry 11, Table 1-6) were obtained and the ORTEP structures are depicted in

Figure 1-5. These crystal structures unambiguously establish both the regiochemistry of the cyclization and the relative stereochemistry at the ring fusion.[64]

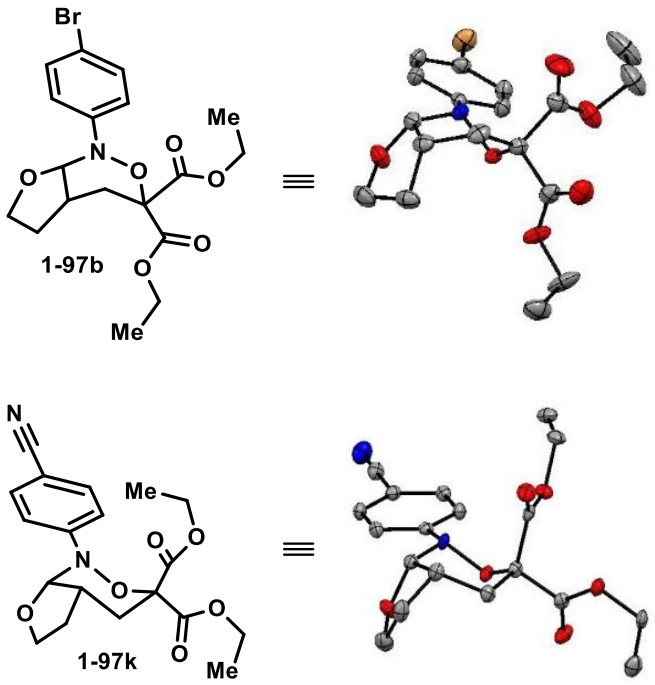


Figure 1-5. ORTEP structures of **1-97b** and **1-97k**.

(Reproduced with permissions from ref. 61)

Extensive 2D NMR analysis was used to support the structural assignments of the isomers formed with electron deficient nitrosoarenes (entries 11 and 12, Table 1-6). The major isomer in each case was found to have nOe and ^{1}H-^{15}N HMBC interactions that were consistent with those observed for **1-97b** and **1-97k** (Figure 1-6). The minor isomer showed nOe interactions suggesting a *cis* ring fusion, and ^{1}H-^{15}N HMBC data indicated that it is a regioisomer, rather than a diastereomer, was formed. Similar nOe and ^{1}H-^{15}N HMBC correlations were observed for **1-97l** and **1-98l** also. This lack of selectivity could be due to delocalization of the nitrogen lone pair of electrons into the aromatic ring, leading to competition between nitrogen and oxygen for dominant nucleophilicity.

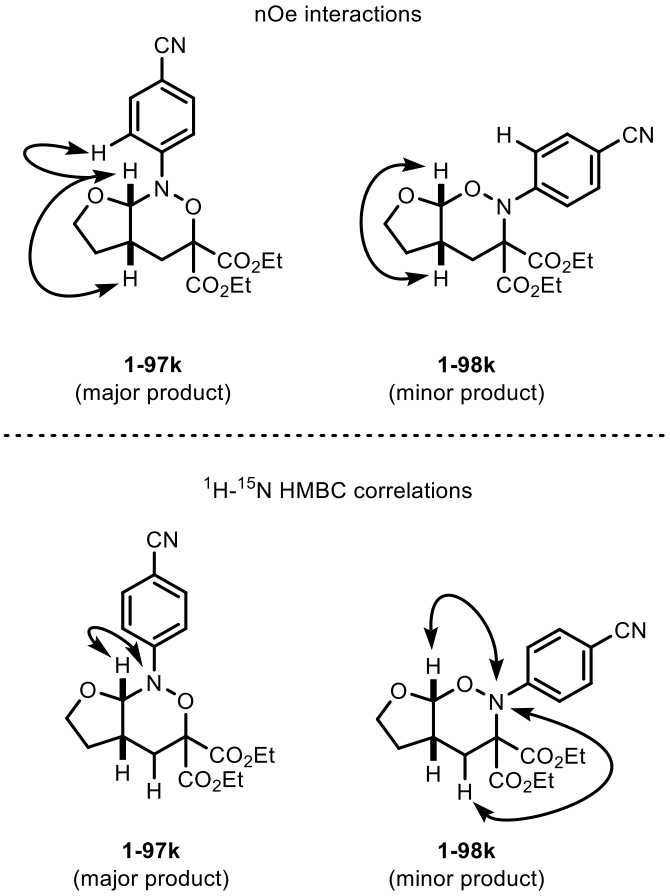
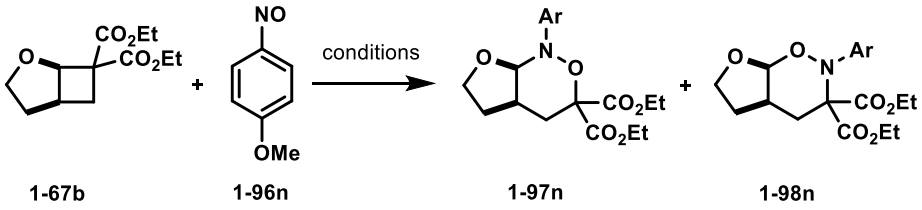


Figure 1-6. Key nOe and ^{1}H-^{15}N HMBC correlations for structural assignment of **1-97k** and **1-98k**.

As electron-rich nitrosoarenes were found not to participate in the $Yb(OTf)_3$-catalyzed cycloaddition, we reinvestigated the reaction conditions in attempts to find an alternative. Employing 1-methoxy-4-nitrosobenzene **1-96n** as a model substrate, a thorough screening of catalysts was undertaken. In most cases, either no reaction or decomposition of the cyclobutane was observed (Table 1-7).[65] However, a number of catalysts did afford the reaction product in small quantities.

Table 1-7. Catalyst screening for electron-rich nitrosoarenes.

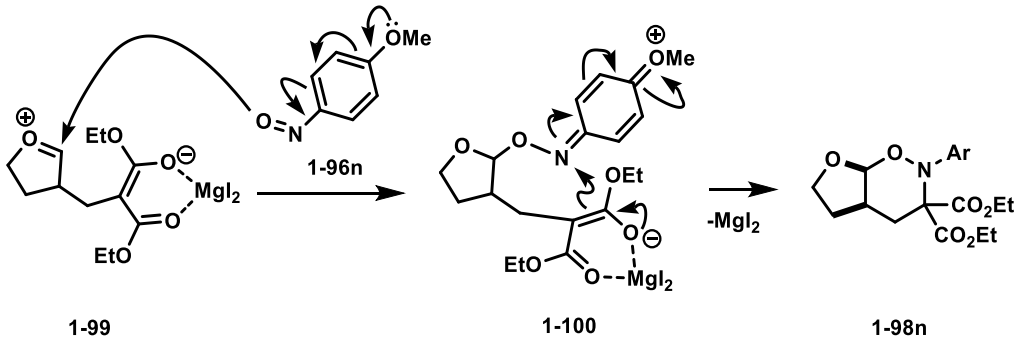


entry[a]	catalyst	mol %	temp, time	result[b]
1	$Yb(OTf)_3$	50	rt, 30 min	19%[c]
2	$Zn(OTf)_2$	10	rt, 20 h	13%[c]
3	$ZnCl_2$	10	rt, 6 h	26%[c]
4	$Zn(NTf_2)_2$	10	rt, 2 h	**1-98n**-15%
5	$AlCl_3$	10	rt, 23 h	**1-98n**-9%
6	$AlBr_3$	10	rt, 72 h	no reaction[f]
7	$AlMe_3$	20	rt, 24 h	no reaction[f]
8	$MADNTf_2$	100	rt, 72 h	no reaction[f]
9	Et_2AlCl	20	0 °C, 2 h; rt, 18 h	decomposition[e]
10	$Sc(OTf)_3$	10	rt, 30 min	decomposition[e]
11	CuI	10	rt, 52 h	no reaction[f]
12	$Cu(OTf)_2$	10	rt, 30 min	**1-98n**-14%
13	$SnCl_2$	10	rt, 46 h	no reaction[f]
14	$SnCl_4$	10	0 °C, 1 h	decomposition[f]
15	$Sn(OTf)_2$	10	rt, 18 h	**1-98n**-10%
16	Bu_2BOTf	10	0 °C, 2 h; rt, 30 min	decomposition[e]
17	$BF_3{\cdot}OEt_2$	10	0 °C, 4 h; rt, 18 h	decomposition[e]
18	AgOTf	10	rt, 15 min	decomposition[e]
19	AgCl	10	rt, 18 h	decomposition[e]
20	$ZrCl_4$	10	0 °C, 3 h; rt, 18 h	decomposition[e]
21	$TiCl_4$	10	0 °C, 3 h; rt, 18 h	decomposition[e]
22	$In(NTf_2)_3$	10	rt, 30 min	**1-98n**-20%

23	$In(OTf)_3$	10	rt, 3.5 h	**1-98n**-13%
24	$MgCl_2$	10	rt, 100 h	no reaction[f]
25	$MgBr_2$	10	rt, 120 h	**1-98n**-4%
26	$Mg(ClO_4)_2$	10	0 °C, 4 h; rt, 2 h	decomposition[e]
27	MgI_2	10	rt, 23 h	**1-98n**-20%
28	MgI_2	5	rt, 24 h	**1-98n**-17%
29	MgI_2	10	0 °C, 40 h	**1-98n**-30%
30	MgI_2	10	-20 °C, 72 h	**1-98n**-20%
31	MgI_2	50	0 °C, 15 min	**1-98n**-26%

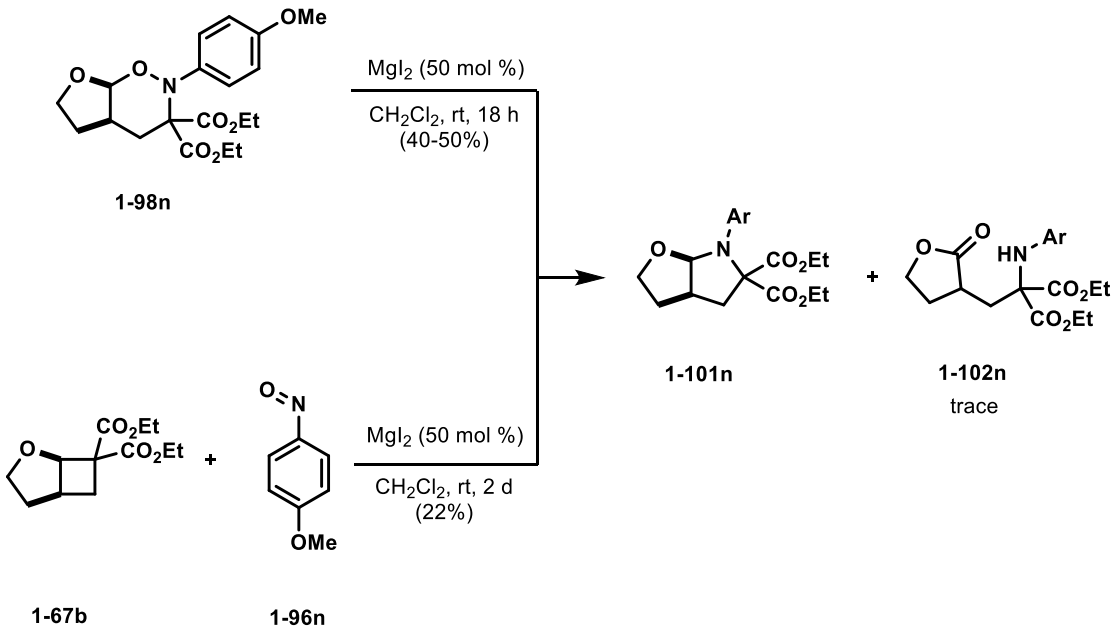
[a]**Typical reaction conditions**: To a solution of Lewis acid in CH_2Cl_2 (3 mL) at specified temp, was added nitrosoarene **1-96n** (0.30 mmol) followed by cyclobutane **1-67b** (0.36 mmol). Reactions were monitored until **1-96n** was consumed by TLC. [b]Isolated yields. [c]1:1 mixture **1-80n** and another unknown compound by ^{1}H NMR spectroscopy. [d]Microwave irradiation. [e]Cyclobutane **1-67b** consumed. [f]Cyclobutane **1-67b** recovered with some decomposition based on TLC and/or crude ^{1}H NMR spectroscopy.

Among all the Lewis acids tested, MgI_2 was found to be functional for this reaction; however only low yields of product were obtained (entries 27-31, Table 1-7). Interestingly the regioisomer isolated under these conditions was the acetal **1-98n** and not the aminal **1-97n** as expected (compare with Table 1-6). This reversal in regioselectivity could be rationalized by the proposed mechanism (Scheme 1-21), in which the electron donating methoxy group on the aryl ring enhances the nucleophilicity of the nitroso oxygen, causing the oxygen to act as the nucleophile instead of nitrogen. Nucleophilic addition of the oxygen of the nitroso on the oxocarbenium ion **1-99** followed by cyclization *via* intermediate **1-100** would yield **1-98n**.



Scheme 1-21. Proposed mechanism for the formation of **1-98n**.

During the course studying this reaction, a peculiar observation was noted. When the reaction was left to stir for 2 days at rt or when **1-98n** was treated with 50 mol % MgI_2 at rt overnight, pyrrolidine **1-101n** was formed with trace amounts of lactone **1-102n** (Scheme 1-22).



Scheme 1-22. Formation of pyrrolidine **1-101n** and lactone **1-102n**.

The structural assignment for the deoxygenated pyrrolidine product **1-101n** was made based on extensive 2D NMR analysis (Figure 1-7). The nOe correlations were

consistent with those observed for aminal regioisomer of oxazine **1-97** (See Figure 1-6) suggesting a *cis* ring fusion and an aminal linkage. The presence of ^{1}H-^{15}N HMBC correlations of nitrogen with all of the pyrrolidine protons, and a ^{1}H-^{13}C HMBC correlation between aminal proton and quaternary carbon supported the proposed structure which was in agreement with the observed mass in HRMS.

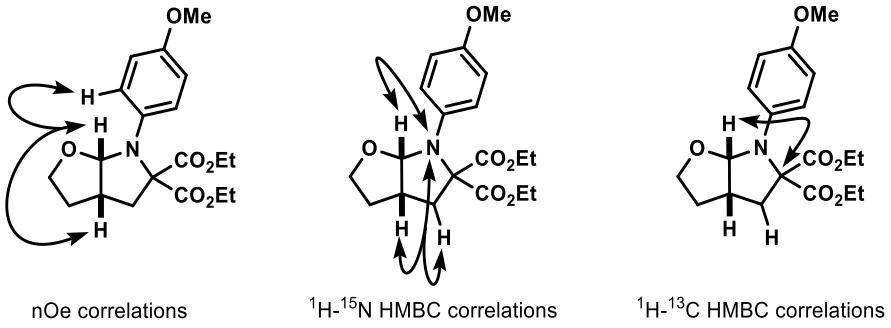
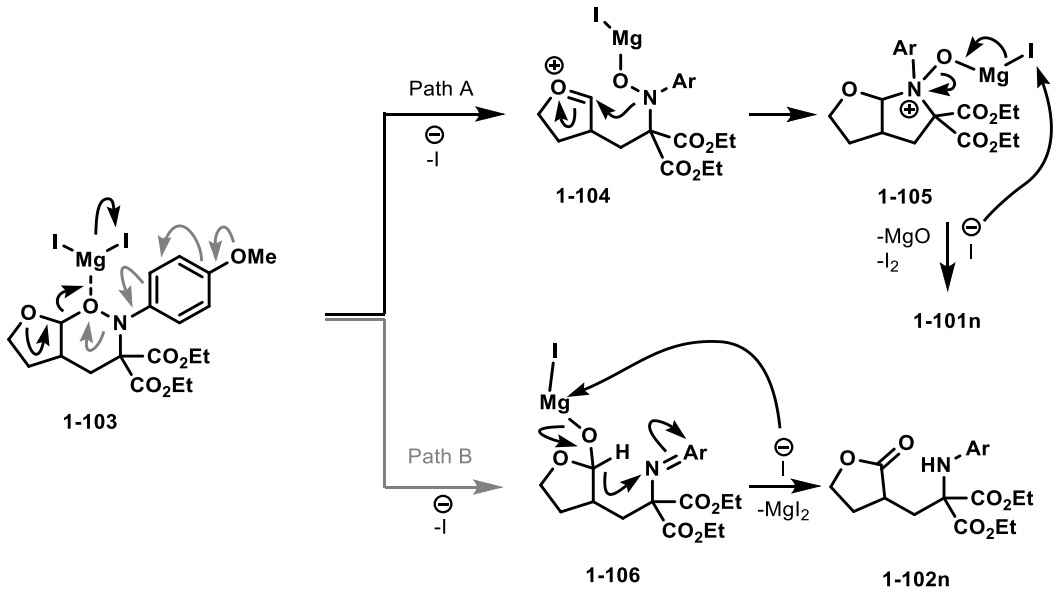


Figure 1-7. Key nOe, ^{1}H-^{15}N HMBC, and ^{1}H-^{13}C HMBC correlations for structural assignment of **1-101n**.

A postulated mechanism to explain this redox transformation is depicted in Scheme 1-23.



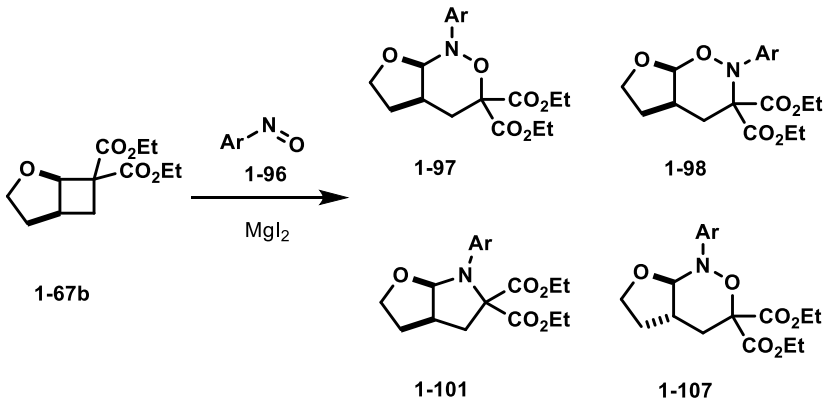
Scheme 1-23. Proposed mechanism for the formation of **1-101n** and **1-102n**.

Coordination of MgI_2 to the oxygen of tetrahydro-1,2-oxazine **1-103** polarizes both the C-O and N-O bonds indicated. Cleavage of the C-O bond (Path A, Scheme 1-23) generates an oxocarbenium ion **1-104**, which could then undergo nucleophilic attack by the pendant nitrogen, forming pyrrolidinium intermediate **1-105**. Finally, the initially displaced iodide reacts with the side chain on the nitrogen, resulting in N-O bond reduction, and concomitantly producing I_2, MgO, and pyrrolidine **1-101n**. Lactone **1-102n** can be formed *via* N-O bond cleavage of **1-103** (Path B) leading to intermediate **1-106** followed by 1,5-hydride shift.

Based on the proposed mechanism it is clear that stoichiometric MgI_2 was necessary for complete conversion of **1-98n** to **1-101n**, but disappointingly the yields were further lowered with considerable decomposition of cyclobutane under such conditions.

With these interesting results we proceeded to investigate if other nitrosoarenes would follow a similar reaction manifold under MgI_2-promoted conditions. Thus, the reaction of electron-rich nitrosoarene **1-96o** directly afforded pyrrolidine **1-101o** (entry 2, Table 1-8), without observation of the anticipated tetrahydro-1,2-oxazine **1-98o**. Interestingly, the substrate **1-96k**, which afforded aminal **1-97k** as the major product under $Yb(OTf)_3$ catalysis (entry 11, Table 1-6), resulted in reversal of regioselectivity albeit in low yield (entry 3, Table 1-8). Also, the isolated aminal **1-107k** was found to be the *trans*-diastereomer (confirmed by single-crystal X-ray diffraction; see, Figure 1-8), rather than *cis*. Nitrosobenzene **1-96a**, which is electronically sandwiched between **1-96n** and **1-96k**, produced aminal **1-97a** as the exclusive product, ruling out the possibility of Mg-enolate aldol reaction mechanism.[66] The nitroso-heteroarenes 2-nitrosopyridine (**1-96p**) and *N*-Boc-5-nitrosoindole (**1-96q**), which did not react under $Yb(OTf)_3$ conditions, provided exclusive acetal products (**1-98** and **1-98q** respectively) in low yields (entries 5 and 6, Table 1-8).

Table 1-8. Scope of MgI_2-promoted cycloaddition.



entry[a]	nitrosoarene	product	MgI_2 (mol %)	yield (%)[c]
1	**1-96n** Ar = 4-C_6H_4OMe	**1-101n**	50	26
2	**1-96o** Ar = 4-$C_6H_4NMe_2$	**1-101o**	50	22
3	**1-96k** Ar = 4-C_6H_4CN	**1-98k**, **1-107k** (2:1)[b]	10	35
4	**1-96a** Ar = C_6H_5	**1-97a**	10	56
5	**1-96p** Ar = 2-pyridine	**1-98p**	50	28
6	**1-96q** Ar = *N*-Boc-5-nitrosoindole	**1-98q**	10	19

[a]**Typical reaction conditions**: To a solution of MgI_2 in CH_2Cl_2 (3 mL) at specified temp, was added nitrosoarene **1-96** (0.30 mmol) followed by cyclobutane **1-67b** (0.36 mmol). Reactions were monitored until nitrosoarene **1-96** was consumed by TLC.

[b]Ratio of isolated overall yields. [c]Isolated yields.

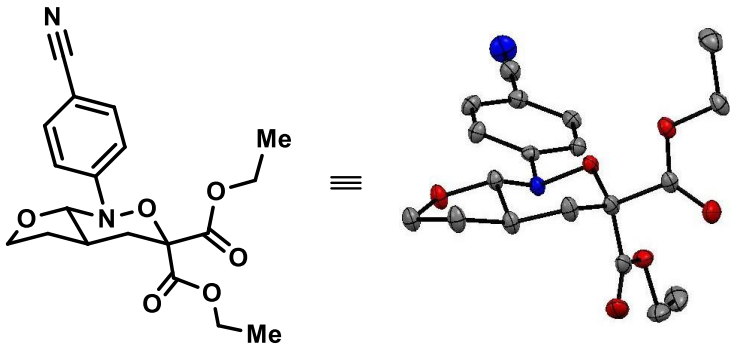
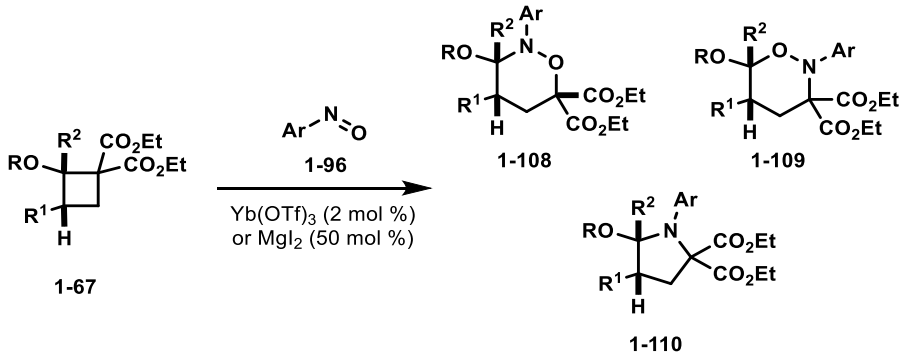
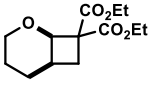
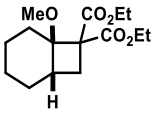
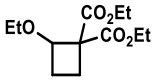


Figure 1-8. ORTEP structure of oxazine **1-107k**.

Additional AACDs were explored under both $Yb(OTf)_3$ and MgI_2 reaction conditions (Table 1-9). AACD **1-67a** gave a moderate yield with nitrosobenzene (**1-96a**) under $Yb(OTf)_3$ catalysis, while electron-rich nitrosoarenes **1-96n** and **1-96o** resulted in low yields of exclusive pyrrolidine products **1-110an** and **1-110ao** respectively (entries 2 and 3). The AACD **1-67g** smoothly reacted with nitrosobenzene (**1-96a**) and 1-chloro-4-nitrosobenzene **1-96c** to furnish tetrahydro-1,2-oxazines **1-108ga** and **1-108gc** respectively in good yields (entries 4 and 5). Disappointingly the AACD **1-67f** gave a poor yield with nitrosobenzene (**1-96a**), while electron-rich nitrosoarene **1-96n** resulted in a low yield of acetal product **1-109fn** (entry 7).

Table 1-9. Reaction scope of additional AACDs in [4+2] cycloaddition.



entry	cyclobutane	nitrosoarene	isolated yield	
			$Yb(OTf)_3$	**MgI_2**
1	 1-67a	**1-96a** Ar = C_6H_5	**1-108aa**, 45%	-
2		**1-96n** Ar = 4-C_6H_4OMe	-	**1-110an**, 35%
3		**1-96o** Ar = 4-$C_6H_4N(CH_3)_2$	-	**1-110ao**, 18%
4	 1-67g	**1-96a** Ar = C_6H_5	**1-108ga**, 73%	-
5		**1-96c** Ar = 4-C_6H_4Cl	**1-108gc**, 70%	-
6	 1-67f	**1-96a** Ar = C_6H_5	**1-108fa**, 21%	-
7		**1-96n** Ar = 4-C_6H_4OMe	-	**1-109fn**, 38%

Crystals of **1-110an** were obtained and the X-ray structure was able to unambiguously confirm the structure of the pyrrolidine product (Figure 1-9).

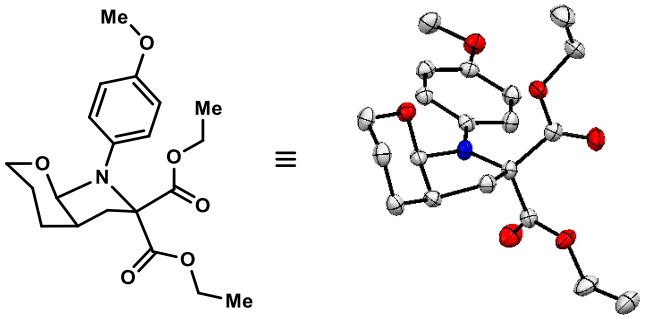
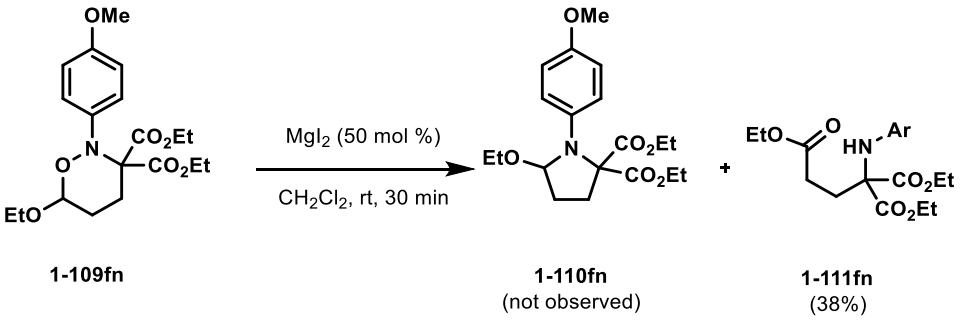


Figure 1-9. ORTEP structure of **1-110an**.

(Reproduced with permissions from ref. 65)

Knowing that **1-98n** could be converted into pyrrolidine **1-101n** *via* MgI_2 mediated reaction (Scheme 1-22), **1-109fn** was subjected 50 mol % of MgI_2 in attempts to form pyrrolidine **1-110fn**. However, ester **1-111fn** was the only product formed, and pyrrolidine **1-110fn** was not observed (Scheme 1-24).



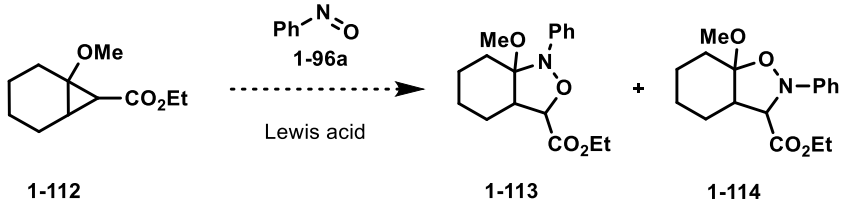
Scheme 1-24. Formation of ester **1-111fn**.

In summary, we have developed the first example of [4+2] cycloaddition between AACDs and nitrosoarenes. The regiochemistry and relative stereochemistry of aminal products have been assigned by 2D NMR spectroscopy correlations and ultimately confirmed by single crystal X-ray diffraction. The reaction proceeds well with electron-neutral and deficient nitrosoarenes but, electron-rich nitrosoarenes required much strong

Lewis acid, MgI_2. Furthermore, a procedure to convert tetrahydro-1,2-oxazines into pyrrolidines was discovered. The regiochemistry and stereochemistry of the unexpected pyrrolidine products was assigned based on 2D NMR correlations and ultimately confirmed by single-crystal X-ray diffraction. Future work includes gaining mechanistic insights into the formation of pyrrolidines which will surely bring about new and exciting opportunities for furthering the efficiency of the process.

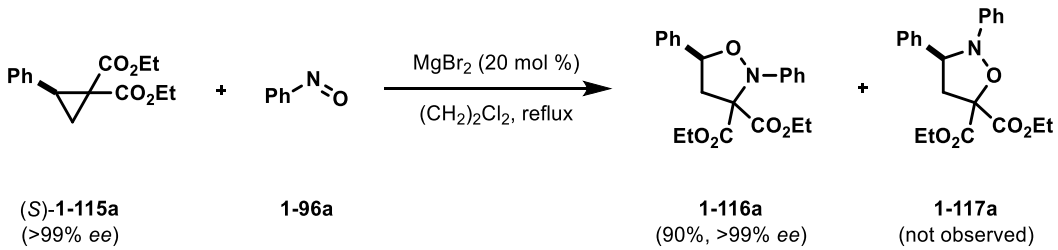
1.2.1.2 Cascade Reaction of Donor-Acceptor Cyclopropanes: Mechanistic Studies on Cycloadditions with Nitrosoarenes and *cis*-Diazenes

The interesting results observed in cycloadditions of nitrosoarenes with AACDs spurred the investigation of similar reactivity with alkoxy-activated cyclopropanes. Unfortunately, the initial investigation only resulted in either no reaction or decomposition of the cyclopropane **1-12** despite a variety of conditions employed (Scheme 1-25).[67]



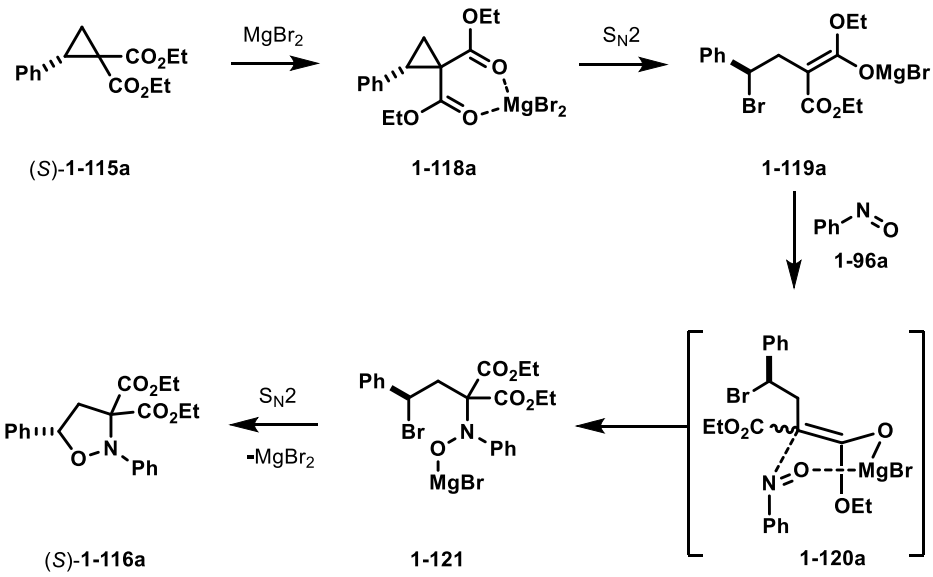
Scheme 1-25. Anticipated [3+2] cycloaddition of DA cyclopropane **1-112** with nitrosobenzene (**1-96a**).

While investigating for the best cycloaddition conditions, the Studer group reported an elegant [3+2] cycloaddition of DA cyclopropanes with nitrosoarenes.[68] The reaction proceeds with complete retention of configuration and perfect control of regioselectivity (an example shown in Scheme 1-26).



Scheme 1-26. Studer's [3+2] cycloaddition of DA cyclopropanes with nitrosoarenes.

The observed stereospecificity and regioselectivity (which is opposite to what was observed with AACDs, see Section 1.2.1.1), was rationalized by Studer and co-workers through the mechanism proposed below (Scheme 1-27).

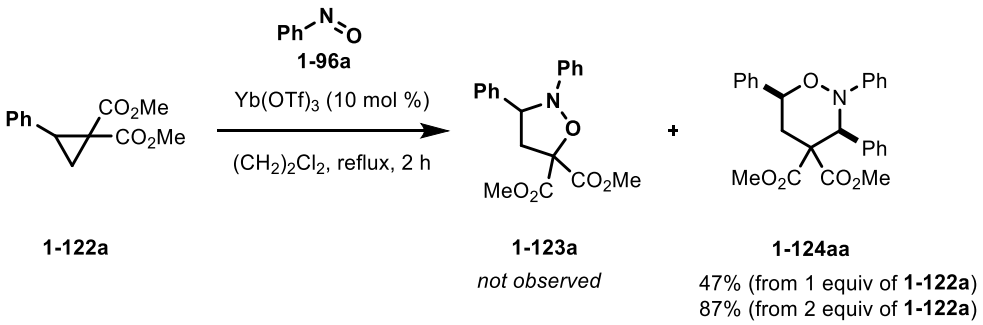


Scheme 1-27. Studer's proposed mechanism for the [3+2] cycloaddition.

As per the authors, the catalyst $MgBr_2$ first coordinates to the DA cyclopropane (*S*)-**1-115a**, providing the $MgBr_2$-activated cyclopropane **1-118a**. The bromide anion then opens the cyclopropane ring at the benzylic position in an S_N2 fashion, generating Mg-enolate **1-119a**. This enolate **1-119a** then undergoes a nitroso-aldol reaction with the nitrosobenzene (**1-96a**) likely *via* the 6-membered transition state **1-120a**, to generate magnesiated hydroxylamine **1-121**. Intermediate **1-121** then cyclizes through an intramolecular S_N2 substitution to close the catalytic cycle, providing the isoxazole (*S*)-**1-116a** with net retention at the stereogenic center with respect to the starting cyclopropane (*S*)-**1-115a**.

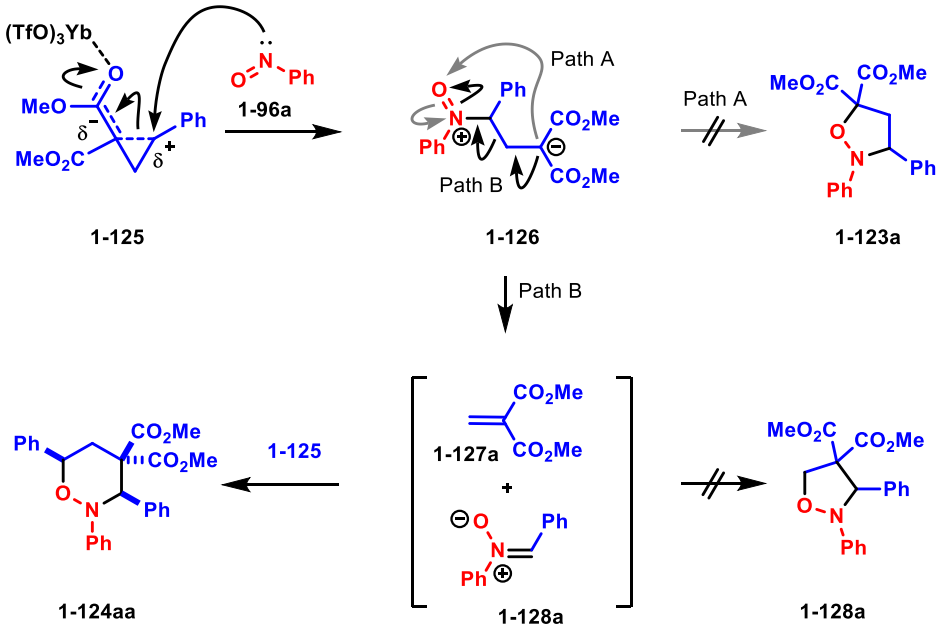
Motivated by this reaction and previously reported $Yb(OTf)_3$-catalyzed cycloadditions of DA cyclopropanes,[69] we set out to investigate alternative reactivity of

DA cyclopropanes with nitrosoarenes under $Yb(OTf)_3$ catalysis, aiming to secure the opposite regioisomer **1-123a**. To our surprise, the reaction resulted in the formation of tetrahydro-1,2-oxazine **1-124aa** instead of the anticipated isoxazolidine (**1-123a**, Scheme 1-28).



Scheme 1-28. $Yb(OTf)_3$-catalyzed reaction of nitrosobenzene (**1-96a**) with DA cyclopropane **1-122a**.

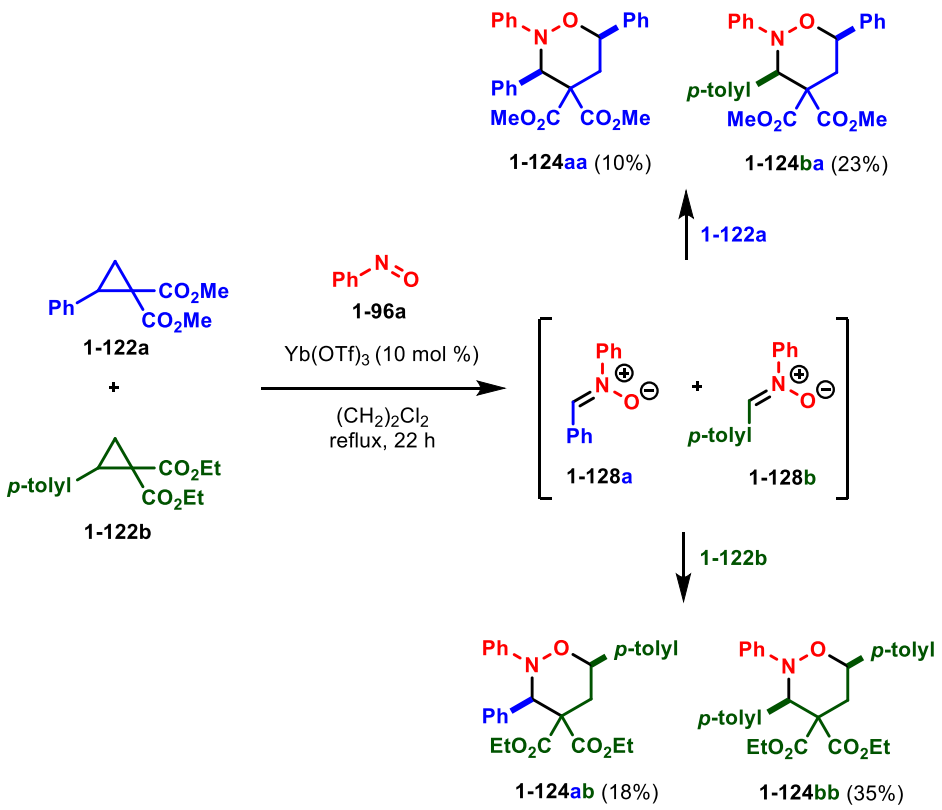
Interestingly, the yield of the reaction was slightly below 50%, but rose to 87% when two equiv of cyclopropane were used. After additional experimentation, it appeared that the reaction was consuming two equiv of the cyclopropane. A plausible mechanism that accounts for the observed stoichiometry requirements shown in Scheme 1-29.



Scheme 1-29. Proposed mechanism for the formation of tetrahydro-1,2-oxazine **1-124aa**.

As described in Scheme 1-29, the nitrogen of the nitrosobenzene (**1-96a**) opens the Yb(OTf)$_3$-activated DA cyclopropane **1-125** resulting in intermediate **1-126**, which instead of undergoing ring closure to give the expected cycloadduct isoxazolidine **1-123a** (Path A), expels dimethyl 2-methylenemalonate (**1-127a**) producing nitrone **1-128a** (Path B). This *in situ* generated nitrone **1-128a** then undergoes a well-known [3+3] cycloaddition with another equiv of Yb(OTf)$_3$-activated DA cyclopropane **1-125** to furnish tetrahydro-1,2-oxazine **1-124aa** (see Section 1.1.2.1). Interestingly, no evidence of recombination of nitrone **1-128a** and dimethyl 2-methylenemalonate (**1-127a**) to form isoxazolidine **1-128a** was observed. This could be due to the rapid polymerization of dimethyl 2-methylenemalonate (**1-127a**) under Yb(OTf)$_3$ conditions.

In order to substantiate the proposed mechanism and gain insights into this unique reaction, a crossover experiment was designed with two similar cyclopropanes, **1-122a** and **1-122b**, with nitrosobenzene (**1-96a**, Scheme 1-30).



Scheme 1-30. Crossover experiment for the reaction of DA cyclopropanes, **1-122a** and **1-122b**, with nitrosobenzene (**1-96a**).

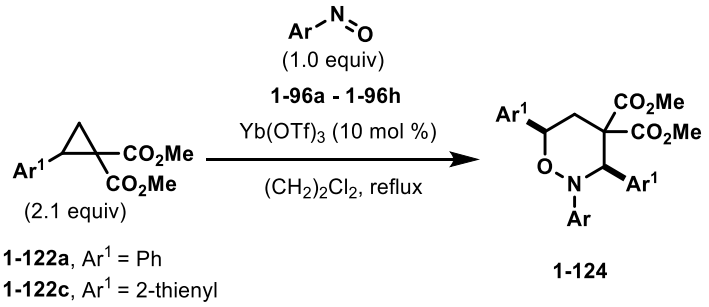
(Experiment was conducted by Tristan Chidley)

As expected, crossover products **1-124ba** and **1-124ab** were observed, supporting the formation of nitrone intermediates **1-128a** and **1-128b** (Scheme 1-30). These products were identical to standards independently synthesized from literature procedures.[11c]

It is interesting to note that this remarkable transformation has a reasonable substrate scope and could be used as a general method for the synthesis of tetrahydro-1,2-oxazines (Table 1-10).[13] Nitrosoarenes with halogen substituents resulted in good yields regardless of the position on the aryl ring (entries 2-4). Nitrosoarenes with a moderately

electron-withdrawing ketone (entry 5) or ester (entries 6-7) substituent were also found to be good reaction partners. Disappointingly, nitrosoarenes with strong electron-withdrawing (entry 8) or electron-donating (entry 9) substituent resulted in decomposition products.[70] Finally, a thiophene-substituted cyclopropane **1-122c** was also shown to be a suitable reaction partner (entry 10).

Table 1-10. Scope of the cascade reaction.



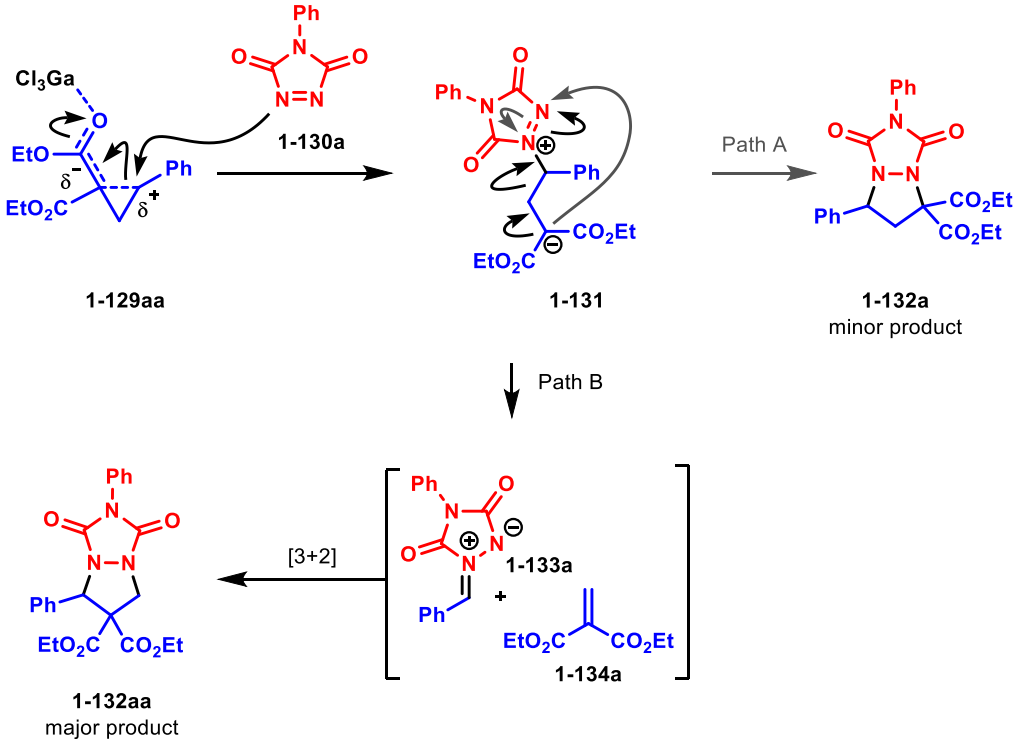
entry[a]	Ar^1	Ar	time (h)	yield (%)[b]
1	Ph	**1-96a**, C_6H_5	13	87
2	Ph	**1-96d**, 3-C_6H_4Br	24	73
3	Ph	**1-96b**, 4-C_6H_4Br	24	75
4	Ph	**1-96g**, 3,4-$C_6H_3Cl_2$	12	91
5	Ph	**1-96i**, 3-$C_6H_4C(O)Me$	20	68
6	Ph	**1-96r**, 3-$C_6H_4CO_2Et$	24	80
7	Ph	**1-96j**, 4-$C_6H_4CO_2Et$	23	78
8	Ph	**1-96k**, 4-C_6H_4CN	-	-
9	Ph	**1-96n**, 4-C_6H_4OMe	-	-
10	2-thienyl	**1-96a**, C_6H_5	7	69

(Conducted in collaboration with Tristan Chidley)

[a]Reaction conditions: To a solution of cyclopropane **1-122** and nitrosoarene **1-96** in $(CH_2)_2Cl_2$ at rt, was added $Yb(OTf)_3 \cdot H_2O$, and then heated at reflux for specified time.

[b]Isolated yields.

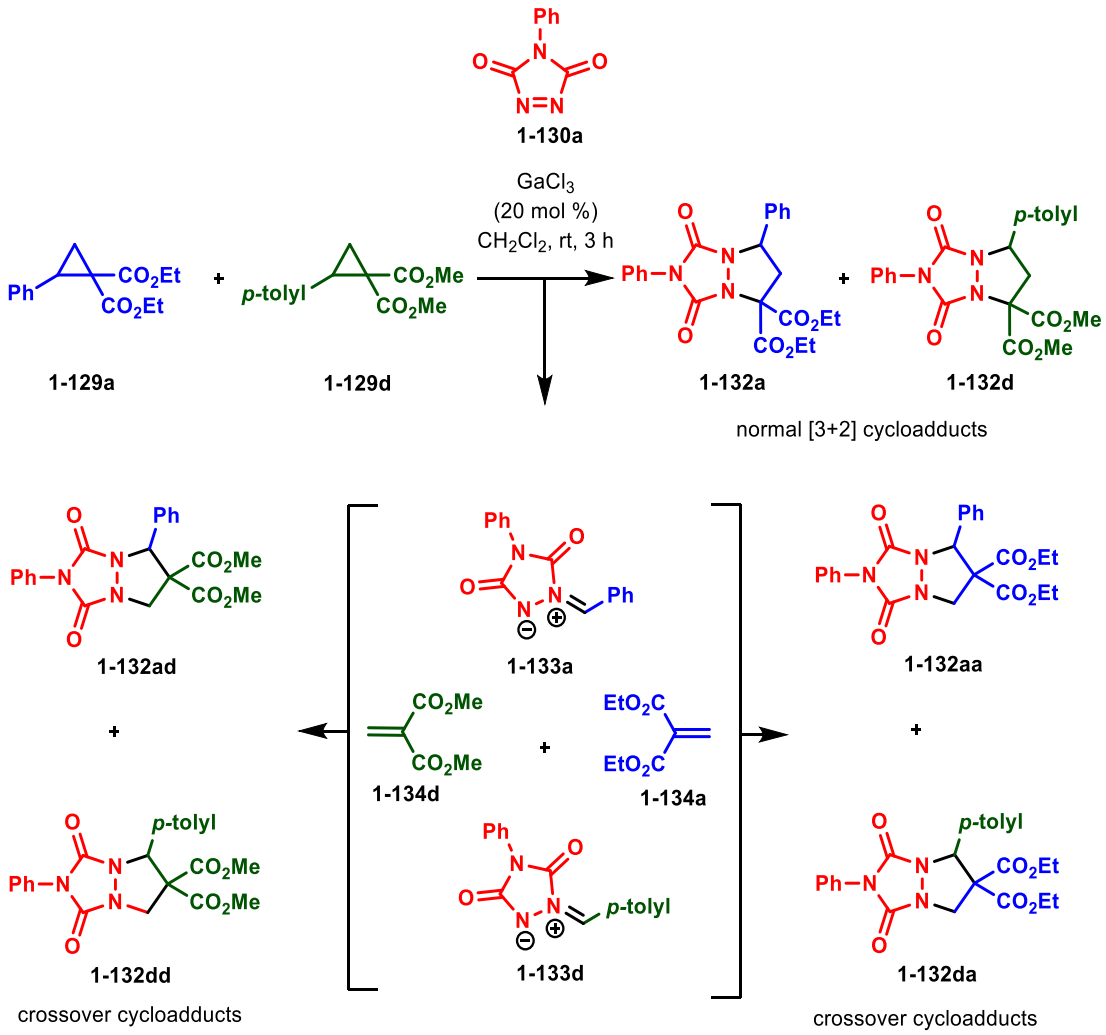
With the mechanistic insight in hand, we began to reconsider the curious products isolated by the de Meijere group in $GaCl_3$-catalyzed cycloadditions of diazene derivatives with DA cyclopropanes.[71] We believe that the unusual product **1-132aa** formed from *cis*-diazene, 4-phenyl-1,2,4-triazoline-3,5-dione (**1-130a**, PTAD) and DA cyclopropane **1-129a** might have resulted through a similar mechanism *via* azomethine imine intermediate **1-133a** (Scheme 1-31).



Scheme 1-31. Proposed mechanism for de Meijere's report on cycloaddition of *cis*-diazene **1-130a** with $GaCl_3$-activated DA cyclopropane **1-129aa**.

As depicted in Scheme 1-31, one of the nitrogens of PTAD **1-130a** opens the $GaCl_3$-activated cyclopropane **1-129aa** to form zwitterionic intermediate **1-131**. This intermediate could then undergo either a cyclization to yield normal cycloadduct **1-132a** (Path A) or fragment into azomethine imine **1-133a** and diethyl 2 methylenemalonate (**1-**

134a, Path B). Recombination of these latter two fragments would provide the cycloadduct **1-132aa**. To validate this hypothesized mechanism, a crossover experiment was designed with two similar cyclopropanes, **1-129a** and **1-129d**, with PTAD **1-130a** (Scheme 1-32).[72]



Scheme 1-32. Crossover experiment for the reaction of DA cyclopropanes, **1-129a** and **1-129b**, with *cis*-diazene **1-130a**.

(Experiment was conducted by Tristan Chidley)

As anticipated, the reaction did yield crossover products **1-132ad**, **1-132dd**, **1-132aa**, and **1-132da**, thus providing strong evidence for the formation of azomethine imines **1-133a** and **1-133d** in the reaction. All of the crossover products were identical with standards independently synthesized from de Meijere's method.[71] The gas chromatogram in Figure 1-10 shows relative ratios of all six products in the crude mixture of a representative crossover experiment.[73]

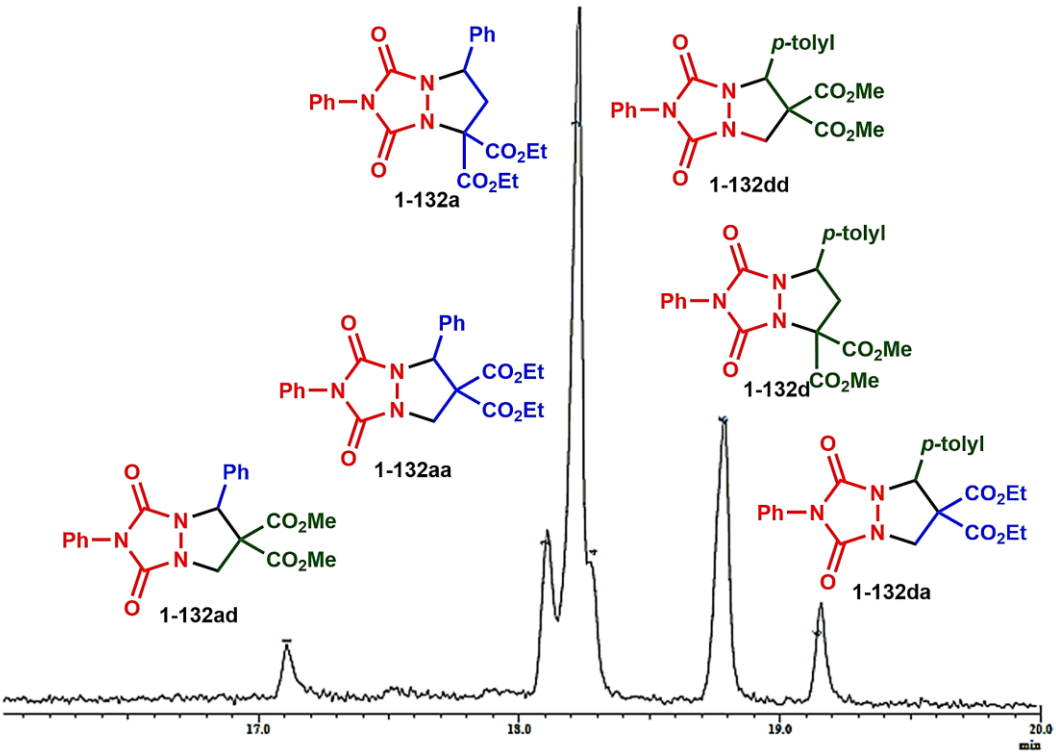


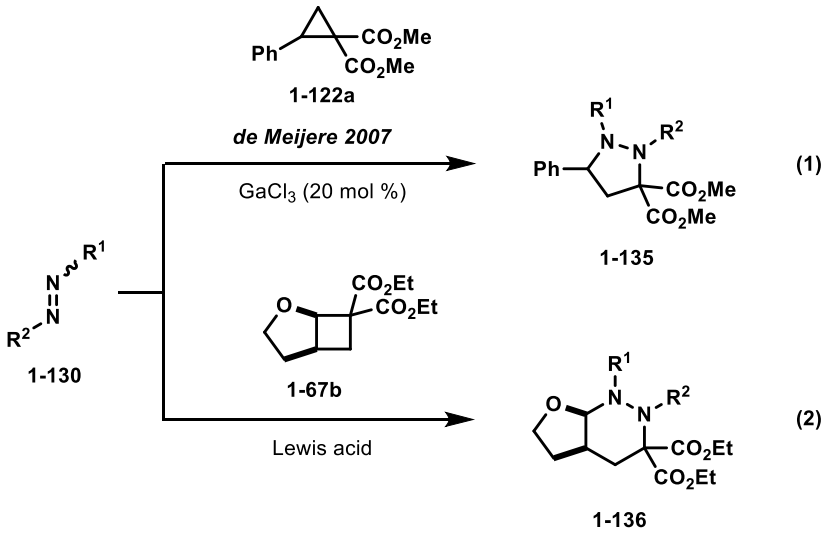
Figure 1-10. Gas chromatogram of the crude product of crossover experiment of cycloaddition of DA cyclopropanes, **1-129a** and **1-129d**, with *cis*-diazene **1-130a**.

In summary, we discovered a cascade process in reactions of DA cyclopropanes with nitrosoarenes. The reaction results in tetrahydro-1,2-oxazines *via* nitrone intermediates in good to excellent yields as single diastereomers. Mechanistic insights gained by crossover experiments on this unique transformation enabled a better rationale

for peculiar products formed in $GaCl_3$-catalyzed cycloaddition of PTAD with DA cyclopropanes. As the chemistry of DA cyclopropanes is constantly expanding, we believe this mechanistic observation serves as a caution for the cascade processes. Additionally, this study reveals new opportunities for reaction design in DA cyclopropane chemistry.

1.2.2 The [4+2] Cycloaddition of AACDs with *cis*-Diazenes

Diazenes are well-known in the literature largely for use as dienophiles for hetero Diels-Alder chemistry.[74] Also, diazenes are competent dipolarophiles in $GaCl_3$-catalyzed [3+2] cycloadditions with DA cyclopropanes furnishing pyrazolidine derivatives **1-135** (eq 1, Scheme 1-33).[71] Given this precedent, and our ongoing interest in DA cyclobutane chemistry (see Section 1.1.3.3), we sought to access hexahydropyridazines **1-136** through Lewis acid-catalyzed [4 + 2] cycloaddition of AACDs and diazenes (eq 2, Scheme 1-33). The resulting hexahydropyridazine derivatives[75] are of interest for their prevalence in biologically relevant and structurally interesting molecules (Figure 1-11).[76]



Scheme 1-33. Cycloaddition of diazenes with DA cyclopropanes and DA cyclobutanes.

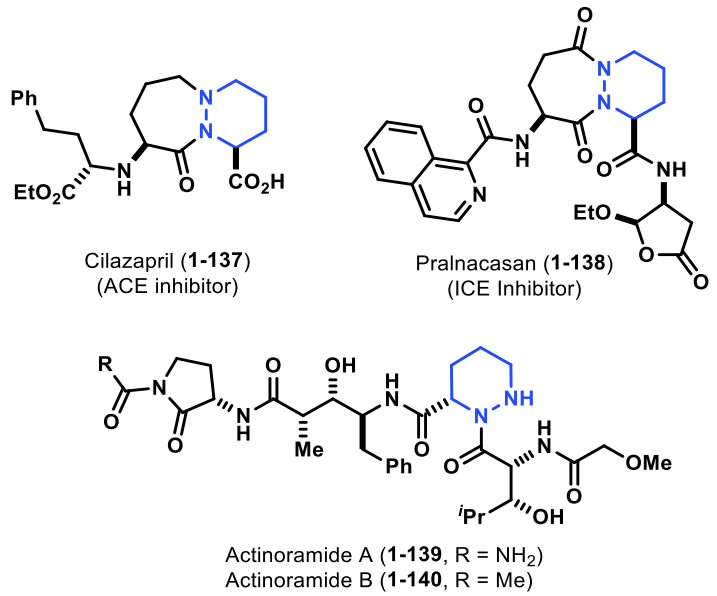
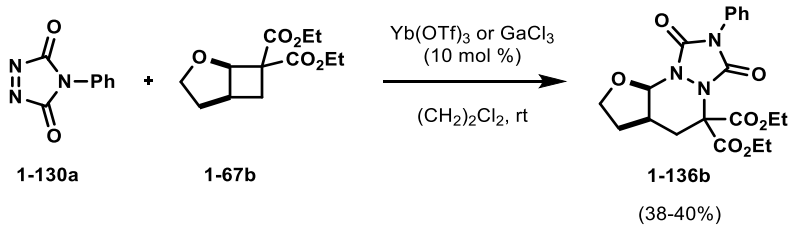


Figure 1-11. Representative examples of hexahydropyridazine core in synthetic pharmaceuticals and natural products.

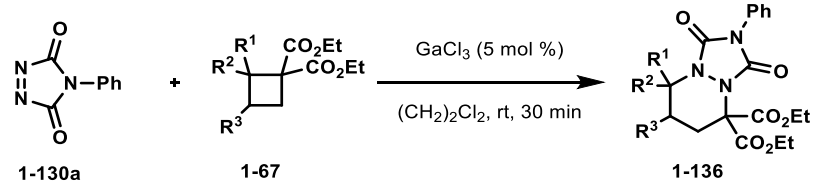
In collaboration with fellow graduate student Tristan Chidley, we began our studies by examining the reactivity of AACD **1-67b** with commercially available *trans*-diazenes diethyl azodicarboxylate (DEAD) and azobenzene, with either $Yb(OTf)_3$ or $GaCl_3$ catalysis with a variety of conditions, but unfortunately these attempts only resulted in slow decomposition of AACD **1-67b**. Fortunately, the *cis*-diazene PTAD (**1-130a**)[77] was found to engage in cycloaddition to yield hexahydropyridazine **1-136b** as a single diastereomer albeit in poor yield (Scheme 1-34).



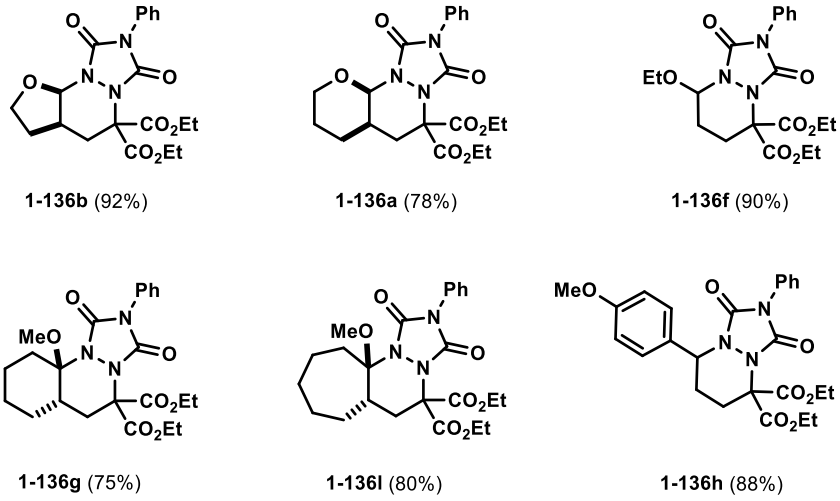
Scheme 1-34. Cycloaddition of *cis*-diazene **1-130a** with AACD **1-67b**.

Quick optimization established 5 mol % $GaCl_3$ as optimal to catalyze the reaction (Table 1-11). With the optimal conditions in hand, we then investigated the scope of the reaction using PTAD **1-130a** and a variety of AACDs (Table 1-11).

Table 1-11. The [4+2] cycloaddition of *cis*-diazene **1-130a** with AACDs.



1-130a + **1-67** → **1-136**



1-136b (92%) **1-136a** (78%) **1-136f** (90%)

1-136g (75%) **1-136l** (80%) **1-136h** (88%)

Reaction conditions: To a solution of cyclobutane **1-67** (0.40 mmol, 2.0 equiv) and PTAD **1-130a** (0.20 mmol, 1.0 equiv) in DCE (2 mL) at rt was added a solution of $GaCl_3$ (0.01 mmol, 0.05 equiv) in DCE (1 mL) and stirred until **1-130a** was fully consumed (by TLC).

The pyran-fused cyclobutane **1-67a** resulted in a 78% isolated yield while the ethoxy substituted cyclobutane **1-67f** afforded hexahydropyridazine in 90% yield. Densely functionalized cyclobutanes **1-67g** and **1-67l** also caused excellent conversions

to hexahydropyridazines **1-136g** and **1-136l** respectively. Finally, an aryl substituted cyclobutane **1-67h** was also found to engage in the cycloaddition.

Due to thermal instability and short shelf-life of the other reported *cis*-diazenes, we were unable to expand the scope of the reaction to additional *cis*-diazenes.

Fortuitously, X-ray quality crystals of cycloadduct **1-136a** (Table 1-11) were obtained and the ORTEP structure depicted in Figure 1-12.[78] The crystal structure shows the relative *cis* stereochemistry at the ring fusion.

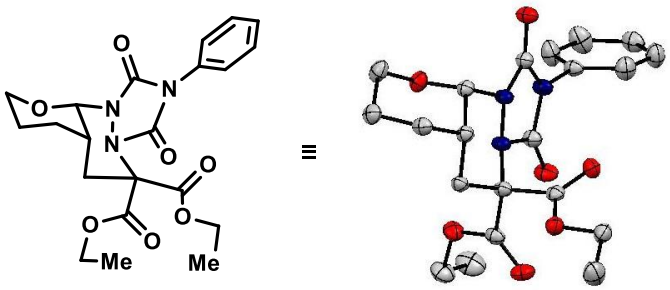


Figure 1-12. ORTEP structure of hexahydropyridazine **1-136a**.

In summary, we have developed the first example of a [4+2] cycloaddition between AACDs and *cis*-diazene. The relative *cis* stereochemistry at ring fusion has been assigned based on nOe correlations and confirmed by single crystal X-ray diffraction. The reaction proceeds smoothly with alkoxy activated cyclobutanes as well as aryl activated cyclobutanes to form hexahydropyridazines in good to excellent yields.

1.2.3 Spiroketals from AACDs

Spiroketals are abundant substructures of natural products from many sources, including but not limited to, insects, microbes, plants, fungi, and marine organisms (Figure 1-13).[79] Interesting pharmacological properties of these compounds resulted in significant research in both their synthesis and chemical reactivity.[80]

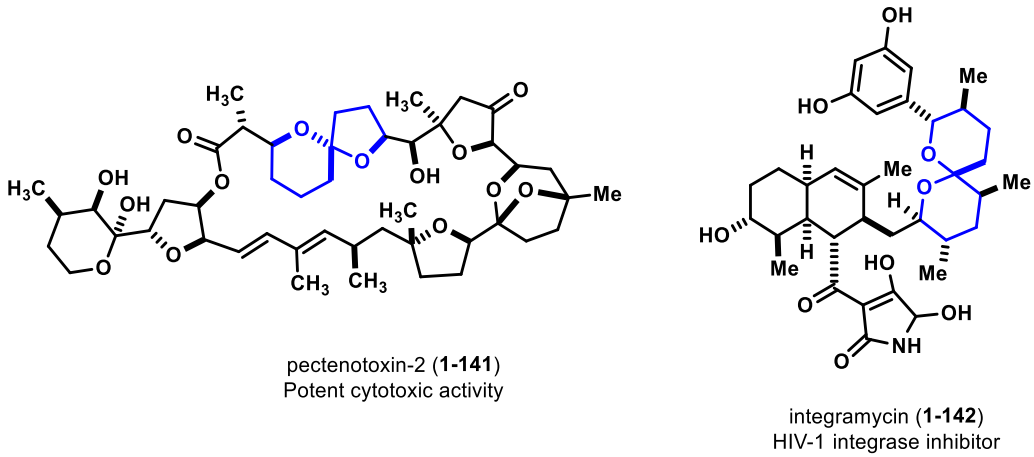
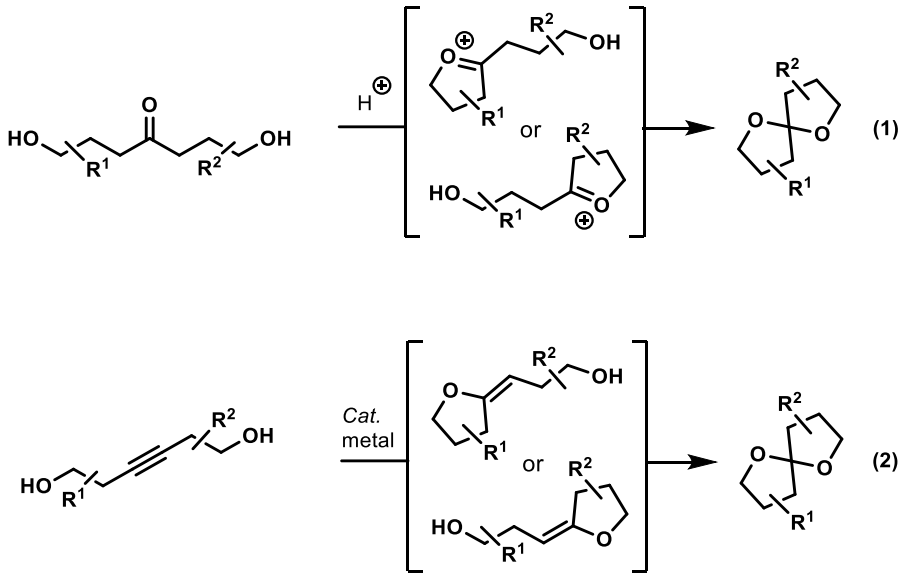


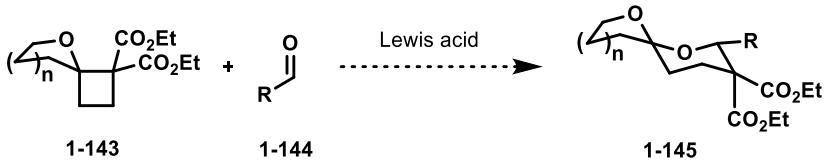
Figure 1-13. Representative examples of spiroketal-containing natural products.

Two of the most common strategies towards the synthesis of spiroketals is acid-catalyzed dehydration of dihydroxy ketones (eq 1, Scheme 1-35)[79e] and transition metal-mediated cyclizations of internal alkynes (eq 2, Scheme 1-35).[81] Although these methods efficiently construct spiroketals, additional methods would be desirable for regio- and stereoselective synthesis of spiroketals.



Scheme 1-35. Two common strategies towards the synthesis of spiroketal.

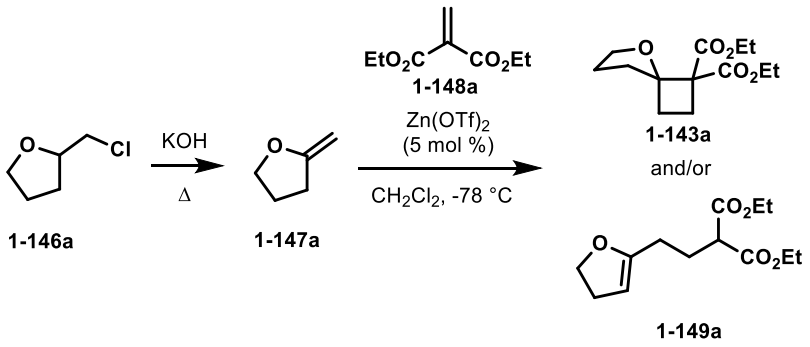
Recently, our group reported a cycloaddition between AACDs and a wide range of aldehydes under $Yb(OTf)_3$ catalysis to generate fused acetals with exclusive *cis*-stereochemistry (see Section 1.1.3.3.1). Now we anticipated that the same chemistry could be applied to spirocyclic AACDs to efficiently access spiroketals (Scheme 1-36).



Scheme 1-36. Proposed synthesis of spiroketals from spirocyclic AACDs.

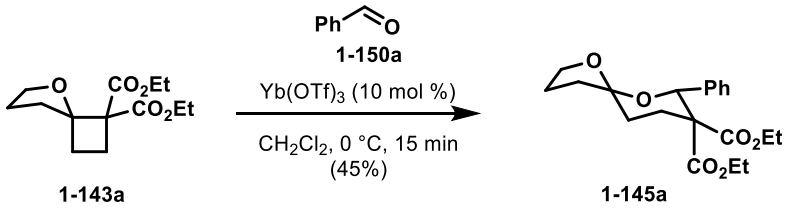
We set out to synthesize the spirocyclic AACDs under previously successful conditions with AACDs (see Section 1.1.3.2). The required enol ethers were prepared from β-elimination of corresponding chloroethyl ethers using literature procedures.[82] Initial investigation established 5 mol % of $Zn(OTf)_2$ at -78 °C in dichloromethane as the

best conditions for this reaction (Scheme 1-37). Nevertheless, both preventing the formation of the decomposition product **1-149a** in the reaction or purification of the product **1-143a** turned out to be insurmountable and ultimately partially purified product **1-143a** was carried forwarded to the next step.[83]



Scheme 1-37. Synthesis of spirocyclic AACD **1-143a**.

In order to examine the proposed synthesis of spiroketals, we tested the reactivity of partially purified **1-143a** with benzaldehyde (**1-150a**) under $Yb(OTf)_3$ conditions. Satisfyingly the reaction did produce the spiroketal as a single diastereomer in moderate 45% yield (Scheme 1-38).



Scheme 1-38. Synthesis of spiroketal **1-145a** *via* a [4+2] cycloaddition of AACD **1-143a** and benzaldehyde (**1-150a**).

In summary, we accomplished the spiroketal **1-145a** synthesis from spirocyclic AACD **1-143a**. Although the yield is moderate, this result serves as a proof of concept.

Efforts are now underway to isolate the AACD **1-143a** in pure form to further optimize the reaction conditions and to examine the reaction scope.

1.3 Conclusions and Outlook

In summary, we have developed the first example of a [4+2] cycloaddition between DA cyclobutanes and nitrosoarenes. The regiochemistry and relative stereochemistry of the cycloadducts have been assigned based on ^{1}H-^{15}N HMBC spectroscopy and confirmed by single crystal X-ray diffraction. The reaction proceeds well with electron neutral and deficient nitrosoarenes to form tetrahydro-1,2-oxazines. We have also discovered the formation of unexpected pyrrolidine products in the MgI_2 promoted [4+2] cycloaddition between DA cyclobutanes and electron-rich nitrosoarenes. Furthermore, a procedure to make pyrrolidines from tetrahydro-1,2-oxazines was reported. The regiochemistry and stereochemistry of the unexpected pyrrolidine product has been unambiguously assigned by single-crystal X-ray diffraction. Future work includes mechanistic insights into the unexpected formation of pyrrolidines, and to further increase the efficiency of this transformation. In short, the reaction of DA cyclobutanes and nitrosoarenes could be used as a general method to access either tetrahydro-1,2-oxazine or pyrrolidine products, depending on the electronics of the nitrosoarenes.

A cascade process was discovered in $Yb(OTf)_3$-catalyzed reactions of nitrosoarenes with DA cyclopropanes. The reaction underwent a tandem ring-opening, elimination, and cyclization sequence to form tetrahydro-1,2-oxazines *via* nitrone intermediates in good to excellent yields as single diastereomers. Mechanistic insights gained by crossover experiments on this unique transformation enabled a better rationale for peculiar products formed in $GaCl_3$-catalyzed cycloaddition of *cis*-diazene PTAD with DA cyclopropanes. Overall, this study serves as a warning for the cascade processes in DA cyclopropane chemistry and reveals new opportunities for reaction design.

We have also developed the first example of a [4+2] cycloaddition between AACDs and *cis*-diazenes. The relative *cis* stereochemistry of the cycloadducts has been assigned based on single crystal X-ray diffraction. The reaction proceeds efficiently with all the AACDs investigated to form hexahydropyridazines in good to excellent yields, suggesting the potential use as a general method. Expansion of the substrate scope to additional *cis*-diazenes and application towards the synthesis of synthetic pharmaceutical *Pralnacasan* are currently under investigation.

Finally, we demonstrated the application of spirocyclic AACD in spiroketal synthesis. Although, we only disclosed one example, this serves as a proof of concept to motivate further studies.

To conclude, exploitation of ring strain in carbocycles to generate dipolar intermediates for cycloaddition chemistry, has become an efficient strategy in modern organic synthesis. Despite the plethora of discoveries already made in DA cyclopropane chemistry, there are still opportunities for new chemistries to uncover (such as the cascade reaction we discovered). On the other hand, the long ignored DA cyclobutanes has only recently garnered attention. Regardless of the reactions disclosed, elaboration of these cycloaddition adducts remains to be exploited for the synthesis of complex natural products. Overall, the chemistry of DA cyclobutanes is only in its infancy and further investigation will surely benefit the synthetic community.

1.4 Experimental

1.4.1 General Considerations

All reactions were run under argon atmosphere unless otherwise indicated. Flasks were oven dried at approximately 120 °C and cooled in a dessicator prior to use. Solvents and reagents were purified by standard methods.[84] $Yb(OTf)_3$ used as mono hydrate as obtained from *Sigma-Aldrich*®. All other chemicals were of reagent quality and used as obtained from commercial sources unless otherwise noted. The progress of reactions were monitored by thin layer chromatography (TLC) performed on F254 silica gel plates. The plates were visualized by UV light (254 nm) or by staining with ceric ammonium molybdate (CAM). Column chromatography was performed with Silica Flash P60 60 Å silica gel from *SiliCycle*® according to the Still method.[85]

The ^{1}H and ^{13}C NMR data were obtained on either 400 or 600 MHz spectrometers. All spectra were obtained in deuterated chloroform and were referenced to the residual chloroform at 7.26 ppm for ^{1}H spectra and the center signal of the triplet at 77.0 ppm for ^{13}C spectra. Scalar coupling was eliminated from nOe experiments by using acquisition delays of 500 ms. Electron ionization mass spectra were obtained on a Finnigan MAT 8400 spectrometer at an ionizing voltage of 70 eV. GC/MS analyses of the samples were performed on a Shimadzu GCMS-QP2010 Chromatography-Ion trap mass spectrometer. A DB-5MS (J&W Scientific) (30 m X 0.25 mm i.d. and 0.25 (m film thickness) capillary column was used; carrier gas helium (1 mL/min). Temperature program for the oven: 200 °C (3 min), 320 °C at 6 °C/min. Ion source temp 250 °C; interface temp 250 °C; solvent cut time 0.5 min; time 2-28 min; scan, m/z 45-600. The microwave reaction was conducted in an Initiator reactor from *Biotage*®.

1.4.2 Cycloadditions of AACDs and Nitrosoarenes

Nitrosoarenes, which are not commercially available, were prepared from the corresponding anilines according to literature methods.[86] AACDs were prepared according to the literature procedure, except 5 mol % of $Zn(OTf)_2$ was used instead of 10 mol % $Yb(OTf)_3$.[87]

General Cycloaddition Procedure A

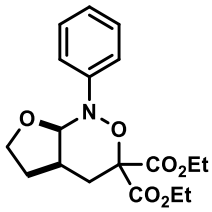
To a mixture of nitrosoarene (0.30 mmol, 1.0 equiv) and $Yb(OTf)_3 \cdot H_2O$ (4 mg, 0.006 mmol, 2 mol %) in CH_2Cl_2 (3 mL) at rt was added cyclobutane (0.36 mmol, 1.2 equiv). After complete consumption of the nitrosoarene (as indicated by TLC) the reaction mixture (RM) was layered directly onto a silica gel column and purified by flash chromatography (0-25% EtOAc/hexanes).

General Cycloaddition Procedure B

To a stirred solution of MgI_2 (41.5 mg, 0.15 mmol, 50 mol %) in CH_2Cl_2 (3 mL) at 0 °C was added nitrosoarene (0.30 mmol, 1.0 equiv) followed by cyclobutane (0.36 mmol, 1.2 equiv). After complete consumption of the nitrosoarene (as indicated by TLC) the RM was layered directly onto a silica gel column and purified by flash chromatography (0-25% EtOAc/hexanes).

Compounds **1-97b, 1-97f**, **1-97h**, and **1-97m** were prepared either by Andrew C. Stevens (Ph.D. 2013) or Tyler B. Schon (B.Sc. 2011) and are not shown below.

Characterization Data



Compound 1-97a

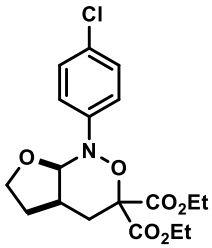
The title compound was prepared according to the general cycloaddition procedure A to afford pale yellow oil (96 mg, 92%).

R_f = 0.27 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26 - 7.35 (m, 4 H), 6.97 - 7.02 (m, 1 H), 5.44 (d, *J* = 5.9 Hz, 1 H), 4.25 - 4.33 (m, 2 H), 4.15 - 4.24 (m, 2 H), 4.09 (td, *J* = 6.8, 8.5 Hz, 1 H), 3.93 (td, *J* = 3.9, 8.2 Hz, 1 H), 2.80 - 2.90 (m, 1 H), 2.60 (dd, *J* = 6.6, 14.1 Hz, 1 H), 2.16 (dq, *J* = 8.2, 12.7 Hz, 1 H), 2.04 (dd, *J* = 8.6, 14.1 Hz, 1 H), 1.83 - 1.92 (m, 1 H), 1.29 (t, *J* = 7.2 Hz, 3 H), 1.18 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.9, 167.6, 146.7, 128.5, 123.0, 117.5, 88.6, 83.6, 67.0, 62.2, 62.0, 33.3, 30.6, 29.6, 14.0, 13.9.

HRMS (*m*/*z*): 349.1525 (calcd for $C_{18}H_{23}NO_6$, 349.1525).



Compound 1-97c

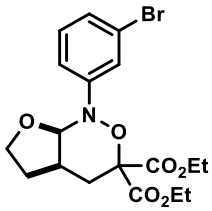
The title compound was prepared according to the general cycloaddition procedure A to afford colorless oil (109 mg, 93%).

R_f = 0.30 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.21 - 7.29 (m, 4 H), 5.37 (d, *J* = 5.9 Hz, 1 H), 4.14 - 4.33 (m, 4 H), 4.05 - 4.10 (m, 1 H), 3.92 (td, *J* = 8.3, 3.8 Hz, 1 H), 2.80 - 2.88 (m, 1 H), 2.58 (dd, *J* = 14.1, 6.4 Hz, 1 H), 2.15 (dq, *J* = 12.4, 8.2 Hz, 1 H), 2.07 (dd, *J* = 14.1, 8.2 Hz, 1 H), 1.85 - 1.92 (m, 1 H), 1.28 (t, *J* = 7.3 Hz, 3 H), 1.18 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.7, 167.5, 145.4, 128.5, 128.1, 118.9, 88.7, 83.6, 67.1, 62.2, 62.1, 33.4, 30.5, 29.4, 14.0, 14.0.

HRMS (*m/z*): 383.1128 (calcd for $C_{18}H_{22}ClNO_6$, 383.1136).



Compound 1-97d

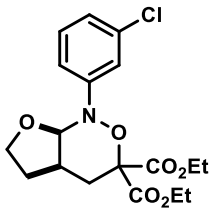
The title compound was prepared according to the general cycloaddition procedure A to afford a colorless thick mass (112 mg, 87%).

R_f = 0.32 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52 - 7.55 (m, 1 H), 7.17 - 7.23 (m, 1 H), 7.10 - 7.14 (m, 2 H), 5.40 (d, *J* = 5.9 Hz, 1 H), 4.25 - 4.36 (m, 2 H), 4.16 - 4.25 (m, 2 H), 4.09 (td, *J* = 8.3, 6.8 Hz, 1 H), 3.93 (td, *J* = 8.2, 3.9 Hz, 1 H), 2.78 - 2.90 (m, 1 H), 2.60 (dd, *J* = 14.3, 6.5 Hz, 1 H), 2.04 - 2.21 (m, 2 H), 1.84 - 1.93 (m, 1 H), 1.30 (t, *J* = 7.0 Hz, 3 H), 1.21 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.7, 167.4, 147.9, 129.8, 125.7, 122.5, 120.5, 115.5, 88.5, 83.6, 67.2, 62.3, 62.2, 33.3, 30.5, 29.3, 14.0, 13.9.

HRMS (*m/z*): 427.0621 (calcd for $C_{18}H_{22}BrNO_6$, 427.0631).



Compound 1-97e

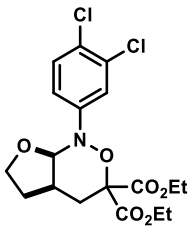
The title compound was prepared according to the general cycloaddition procedure A to afford pale yellow color oil (111 mg, 95%).

R_f = 0.30 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.38 - 7.41 (m, 1 H), 7.14 - 7.22 (m, 2 H), 6.97 (dd, *J* = 7.6, 1.8 Hz, 1 H), 5.42 (d, *J* = 5.9 Hz, 1 H), 4.26 - 4.36 (m, 2 H), 4.16 - 4.26 (m, 2 H), 4.07 - 4.13 (m, 1 H), 3.94 (td, *J* = 8.2, 4.1 Hz, 1 H), 2.82 - 2.89 (m, 1 H), 2.61 (dd, *J* = 14.1, 6.4 Hz, 1 H), 2.16 (dq, *J* = 12.6, 8.1 Hz, 1 H), 2.10 (dd, *J* = 14.1, 7.6 Hz, 1 H), 1.87 - 1.94 (m, 1 H), 1.31 (t, *J* = 7.0 Hz, 3 H), 1.21 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.7, 167.5, 147.9, 134.4, 129.5, 122.8, 117.8, 115.1, 88.6, 83.7, 67.2, 62.3, 62.2, 33.4, 30.5, 29.3, 14.0, 13.9.

HRMS (*m/z*): 383.1132 (calcd for $C_{18}H_{22}ClNO_6$, 383.1136).



Compound 1-97g

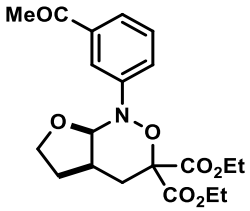
The title compound was prepared according to the general cycloaddition procedure A to afford a pale yellow color paste (114 mg, 91%).

R_f = 0.25 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 (d, *J* = 2.3 Hz, 1 H), 7.32 (d, *J* = 8.8 Hz, 1 H), 7.15 (dd, *J* = 8.8, 2.3 Hz, 1 H), 5.37 (d, *J* = 6.4 Hz, 1 H), 4.26 - 4.35 (m, 2 H), 4.17 - 4.26 (m, 2 H), 4.06 - 4.11 (m, 1 H), 3.94 (td, *J* = 8.3, 4.4 Hz, 1 H), 2.81 - 2.89 (m, 1 H), 2.59 (dd, *J* = 14.1, 6.4 Hz, 1 H), 2.09 - 2.20 (m, 2 H), 1.87 - 1.94 (m, 1 H), 1.31 (t, *J* = 7.3 Hz, 3 H), 1.22 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.6, 167.3, 146.3, 132.4, 130.0, 126.0, 119.5, 116.6, 88.7, 83.7, 67.3, 62.4, 62.2, 33.5, 30.4, 29.2, 14.0, 14.0.

HRMS (*m/z*): 417.0737 (calcd for $C_{18}H_{21}Cl_2NO_6$, 417.0746).



Compound 1-97i

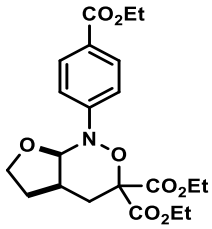
The title compound was prepared according to the general cycloaddition procedure A to afford pale yellow colored oil (103 mg, 87%).

R_f = 0.39 (30% EtOAc/hexanes, double elution).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 - 7.91 (m, 1 H), 7.55 - 7.62 (m, 2 H), 7.34 - 7.41 (m, 1 H), 5.49 (d, *J* = 5.9 Hz, 1 H), 4.25 - 4.35 (m, 2 H), 4.20 (q, *J* = 7.0 Hz, 2 H), 4.05 - 4.13 (m, 1 H), 3.94 (td, *J* = 8.4, 3.9 Hz, 1 H), 2.81 - 2.92 (m, 1 H), 2.59 - 2.65 (m, 1 H), 2.58 (s, 3 H), 2.02 - 2.23 (m, 2 H), 1.84 - 1.95 (m, 1 H), 1.30 (t, *J* = 7.0 Hz, 3 H), 1.18 (t, *J* = 5.9 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 198.0, 167.7, 167.4, 147.1, 137.5, 128.8, 122.9, 122.1, 117.0, 88.6, 83.7, 67.1, 62.3, 62.1, 33.3, 30.5, 29.4, 26.7, 14.0, 13.9.

HRMS (*m/z*): 391.1636 (calcd for $C_{20}H_{25}NO_7$, 391.1631).



Compound 1-97j

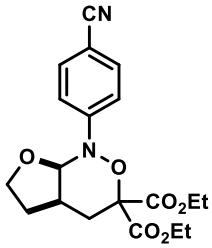
The title compound was prepared according to the general cycloaddition procedure A to afford pale yellow oil (104 mg, 76%).

R_f = 0.21 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.95 - 7.98 (m, 2 H), 7.31 - 7.34 (m, 2 H), 5.55 (d, *J* = 5.9 Hz, 1 H), 4.27 - 4.36 (m, 4 H), 4.15 - 4.24 (m, 2 H), 4.08 - 4.13 (m, 1 H), 3.94 (td, *J* = 8.2, 4.1 Hz, 1 H), 2.84 - 2.91 (m, 1 H), 2.63 (dd, *J* = 14.1, 6.5 Hz, 1 H), 2.17 (dq, *J* = 12.6, 8.1 Hz, 1H), 2.11 (dd, 14.4, 7.9 Hz, 1H), 1.88 - 1.94 (m, 1 H), 1.37 (t, *J* = 7.3 Hz, 3 H), 1.31 (t, *J* = 7.0 Hz, 3 H), 1.15 - 1.18 (m, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.6, 167.2, 166.4, 150.4, 130.3, 124.2, 115.8, 88.0, 83.6, 67.2, 62.3, 62.1, 60.5, 33.1, 30.5, 29.2, 14.3, 13.9, 13.9.

HRMS (*m*/*z*): 421.1742 (calcd for $C_{18}H_{23}NO_6$, 421.1737).



Compound 1-97k

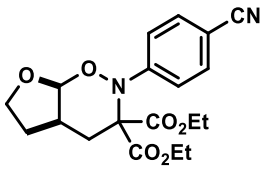
The title compound was prepared according to the general cycloaddition procedure A to afford a cream colored solid (67 mg, 46%).

R_f = 0.22 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.55 - 7.58 (m, 2 H), 7.37 - 7.40 (m, 2 H), 5.52 (d, *J* = 5.9 Hz, 1 H), 4.27 - 4.36 (m, 2 H), 4.16 - 4.25 (m, 2 H), 4.07 - 4.12 (m, 1 H), 3.94 (td, *J* = 8.2, 4.1 Hz, 1 H), 2.85 - 2.92 (m, 1 H), 2.61 (dd, *J* = 14.7, 6.5 Hz, 1 H), 2.14 - 2.22 (m, 2 H), 1.90 - 1.96 (m, 1 H), 1.31 (t, *J* = 7.0 Hz, 3 H), 1.18 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.4, 167.0, 150.2, 132.8, 119.3, 116.6, 105.1, 87.9, 83.7, 67.4, 62.5, 62.3, 33.3, 30.4, 29.0, 14.0, 13.9.

HRMS (*m*/*z*): 374.1482 (calcd for $C_{19}H_{22}N_2O_6$, 374.1478).



Compound 1-98k

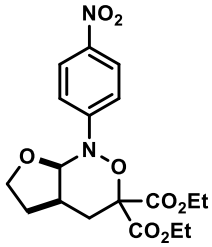
The title compound was isolated as a byproduct along with **1-97k** as yellow oil (22 mg, 15%).

R_f = 0.22 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.46 - 7.50 (m, 2 H), 7.09 - 7.13 (m, 2 H), 5.57 (d, *J* = 5.3 Hz, 1 H), 4.28 (q, *J* = 7.0, 2 H), 4.10 - 4.21 (m, 3 H), 4.02 (td, *J* = 8.2, 3.5 Hz, 1 H), 2.65 - 2.70 (m, 1 H), 2.60 - 2.65 (m, 1 H), 2.54 - 2.59 (m, 1 H), 2.08 - 2.18 (m, 1 H), 1.87 - 1.94 (m, 1 H), 1.25 (t, *J* = 7.0 Hz, 3 H), 1.13 (t, *J* = 7.3 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 168.2, 168.2, 150.6, 132.4, 119.5, 116.0, 104.9, 104.0, 72.9, 68.7, 62.7, 62.4, 35.4, 33.0, 29.6, 13.9, 13.8.

HRMS (*m*/*z*): 374.1489 (calcd for $C_{19}H_{22}N_2O_6$, 374.1478).



Compound 1-97l

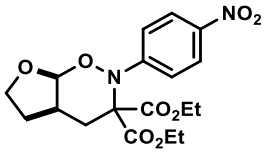
The title compound was prepared according to the general cycloaddition procedure A to afford a yellow solid (56 mg, 47%).

R_f = 0.19 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.14 - 8.20 (m, 2 H), 7.38 - 7.42 (m, 2 H), 5.58 (d, *J* = 6.3 Hz, 1 H), 4.28 - 4.36 (m, 2 H), 4.17 - 4.24 (m, 2 H), 4.11 (q, *J* = 7.9 Hz, 1 H), 3.95 (td, *J* = 8.2, 4.3 Hz, 1 H), 2.86 - 2.94 (m, 1 H), 2.63 (dd, *J* = 14.1, 6.3 Hz, 1 H), 2.15 - 2.24 (m, 2 H), 1.91 - 1.98 (m, 1 H), 1.32 (t, *J* = 7.2 Hz, 3 H), 1.18 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.3, 167.0, 152.0, 142.3, 124.7, 115.8, 88.0, 83.7, 67.5, 62.6, 62.4, 33.4, 30.3, 28.9, 14.0, 13.9.

HRMS (*m*/*z*): 394.1377 (calcd for $C_{18}H_{22}N_2O_8$, 394.1376).



Compound 1-98l

The title compound was isolated as a byproduct along with **1-97l** as yellow colored oil (14 mg, 12%).

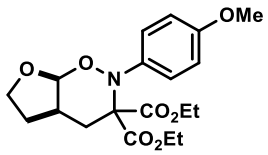
R_f = 0.19 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 8.08 - 8.11 (m, 2 H), 7.05 - 7.09 (m, 2 H), 5.59 (d, *J* = 5.3 Hz, 1 H), 4.26 - 4.34 (m, 2 H), 4.17 - 4.23 (m, 2 H), 4.10 - 4.15 (m, 1 H), 4.04 (td, *J* =

8.2, 3.5 Hz, 1 H), 2.63 - 2.69 (m, 2 H), 2.54 - 2.58 (m, 1H), 2.10 - 2.18 (m, 1 H), 1.88 - 1.92 (m, 1 H), 1.27 (t, *J* = 7.0 Hz, 3 H), 1.15 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.8, 167.8, 152.0, 140.9, 124.3, 114.2, 105.0, 72.4, 68.5, 62.8, 62.5, 35.3, 32.9, 29.7, 13.8, 13.7.

HRMS (*m*/*z*): 394.1377 (calcd for $C_{18}H_{22}N_2O_8$, 394.1376).



Compound 1-98n

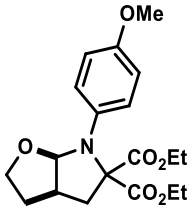
The title compound was prepared according to the general cycloaddition procedure B to afford a pale yellow paste (30 mg, 26%).

R_f = 0.41 (50% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.24 – 7.26 (m, 2 H), 6.75 – 6.77 (m, 2 H), 5.55 (d, *J* = 5.3 Hz, 1 H), 4.20 – 4.24 (m, 1 H), 4.15 – 4.19 (m, 1 H), 4.07 – 4.13 (m, 2 H), 4.01 – 4.06 (m, 1 H), 3.96 (td, *J* = 8.1, 5.0 Hz, 1 H), 3.76 (s, 3 H), 2.61 – 2.72 (m, 2 H), 2.50 – 2.57 (m, 1 H), 2.01 – 2.09 (m, 1 H), 1.95 (dq, *J* = 12.2, 6.3 Hz, 1 H), 1.14 (t, *J* = 7.0 Hz, 3 H), 1.10 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 169.0, 168.8, 156.6, 140.7, 122.7, 113.0, 104.5, 74.3, 68.8, 61.9, 61.6, 55.4, 35.1, 32.3, 28.9, 13.8, 13.8.

HRMS (*m*/*z*): 379.1635 (calcd for $C_{19}H_{25}NO_7$, 379.1631).



Compound 1-101n

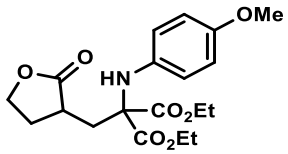
To a stirred solution of MgI_2 (44 mg, 0.16 mmol, 0.5 equiv) in 10 mL CH_2Cl_2 at rt was added **1-98n** (120 mg, 0.32 mmol). The RM was stirred for about 18 h at rt (complete consumption of starting material by TLC) then the RM was layered directly onto a silica gel column and purified by flash chromatography (0-25% EtOAc/hexanes) to a brown oil (57 mg, 50%).

R_f = 0.37 (50% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 6.90 – 6.94 (m, 2 H), 6.75 – 6.78 (m, 2 H), 5.62 (d, *J* = 5.9 Hz, 1 H), 4.15 – 4.25 (m, 4 H), 3.91 – 4.00 (m, 2 H), 3.74 (s, 3 H), 3.00 – 3.07 (m, 1 H), 2.70 (dd, *J* = 12.9, 8.8 Hz, 1 H), 2.39 (dd, *J* = 13.5, 8.8 Hz, 1 H), 2.00 – 2.08 (m, 1 H), 1.72 (dd, *J* = 12.6, 5.0 Hz, 1 H), 1.21 (t, *J* = 7.3 Hz, 3 H), 1.18 (t, *J* = 7.3 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 170.7, 169.9, 153.4, 138.3, 117.6, 113.9, 98.6, 74.8, 65.5, 61.8, 61.8, 55.5, 40.6, 40.1, 32.0, 14.0, 14.0.

HRMS (*m*/*z*): 363.1692 (calcd for $C_{19}H_{25}NO_6$, 363.1682).



Compound 1-102n

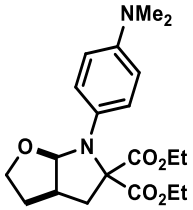
The title compound was isolated in trace amount along with **1-101n** as a pale brown oil.

R_f = 0.24 (70% hexanes /EtOAc).

^{1}H NMR (600 MHz, $CDCl_3$) δ 6.75 – 6.72 (m, 2 H), 6.65 – 6.62 (m, 2 H), 4.89 (s, 1 H), 4.29 – 4.15 (m, 5 H), 4.06 (ddd, *J* = 11.2, 9.1, 6.2 Hz, 1 H), 3.72 (s, 3 H), 3.09 (dd, *J* = 15.3, 3.5 Hz, 1 H), 2.67 – 2.60 (m, 1 H), 2.44 (dd, *J* = 15.3, 10.0 Hz, 1 H), 2.34 – 2.27 (m, 1 H), 1.78 (qd, *J* = 11.7, 8.8 Hz, 1 H), 1.21 – 1.16 (m, 6 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 178.8, 169.9, 169.2, 153.3, 137.5, 116.9, 114.7, 67.9, 66.4, 62.5, 62.5, 55.5, 35.2, 33.7, 29.7, 13.9.

HRMS (*m*/*z*): 379.1639 (calcd for $C_{19}H_{25}NO_7$, 379.1631).



Compound 1-101o

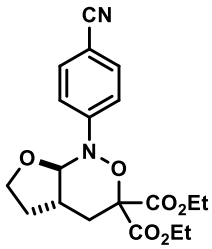
The title compound was prepared according to the general cycloaddition procedure B at rt for 4 h to afford a yellow colored oil (25 mg, 22%).

R_f = 0.33 (40% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 6.90 – 6.94 (m, 2 H), 6.66 – 6.70 (m, 2 H), 5.62 (d, *J* = 5.9 Hz, 1 H), 4.13 – 4.24 (m, 4 H), 3.91 – 3.98 (m, 2 H), 2.99 – 3.06 (m, 1 H), 2.82 (s, 6 H), 2.68 (dd, *J* = 13.5, 8.8 Hz, 1 H), 2.37 (dd, *J* = 13.2, 8.5 Hz, 1 H), 1.98 – 2.06 (m, 1 H), 1.70 (dd, *J* = 12.6, 4.4 Hz, 1 H), 1.15 – 1.21 (m, 6 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 170.9, 170.0, 145.3, 136.0, 118.2, 114.3, 98.7, 74.8, 65.4, 61.7, 61.6, 41.7, 40.5, 40.0, 32.2, 14.0, 14.0.

HRMS (*m*/*z*): 376.2044 (calcd for $C_{20}H_{28}N_2O_5$, 376.1998).



Compound 1-107k

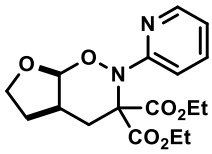
The title compound was prepared along with **1-98k** according to the general cycloaddition procedure B, employing MgI_2 (10 mol %) at rt for 2 h to afford a pale brown solid (15 mg, 13%).

R_f = 0.44 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.60 – 7.63 (m, 2 H), 7.54 – 7.59 (m, 2 H), 4.22 – 4.34 (m, 5 H), 4.06 – 4.15 (m, 2 H), 2.98 (dd, *J* = 12.9, 3.5 Hz, 1 H), 2.24 – 2.32 (m, 1 H), 2.19 – 2.24 (m, 1 H), 1.87 (t, *J* = 12.9 Hz, 1 H), 1.70 – 1.79 (m, 1 H), 1.30 (t, *J* = 7.0 Hz, 3 H), 1.24 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 167.0, 166.2, 151.9, 132.5, 119.4, 119.2, 107.2, 94.5, 84.0, 67.7, 62.6, 62.3, 41.4, 34.1, 27.9, 14.0, 14.0.

HRMS (*m*/*z*): 374.1480 (calcd for $C_{19}H_{22}N_2O_6$, 374.1478).



Compound 1-98p

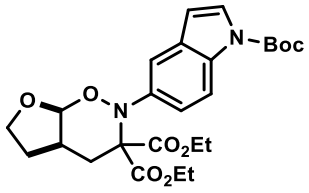
The title compound was prepared according to the general cycloaddition procedure B at rt for 2 h to afford a yellow syrup (30 mg, 28%).

R_f = 0.34 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 8.01 – 8.04 (m, 1 H), 7.55 – 7.60 (m, 1 H), 7.19 – 7.23 (m, 1 H), 6.75 – 6.79 (m, 1 H), 5.58 (d, *J* = 4.7 Hz, 1 H), 4.22 – 4.32 (m, 2 H), 4.19 (q, *J* = 7.0 Hz, 1 H), 4.10 – 4.17 (m, 1 H), 3.93 (q, *J* = 8.0 Hz, 1 H), 2.68 – 2.77 (m, 2 H), 2.53 – 2.60 (m, 1 H), 1.98 – 2.10 (m, 2 H), 1.22 – 1.27 (m, 3 H), 1.13 – 1.17 (m, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 168.9, 168.7, 159.3, 145.6, 137.5, 116.7, 109.8, 104.1, 69.9, 69.1, 62.0, 61.6, 36.1, 31.8, 27.6, 13.8, 13.7.

HRMS (*m*/*z*): 350.1470 (calcd for $C_{17}H_{22}N_2O_6$, 350.1478).



Compound 1-98q

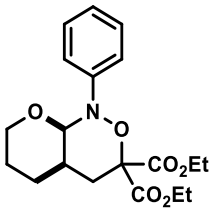
The title compound was prepared according to the general cycloaddition procedure B, employing MgI_2 (10 mol %) at rt for 4 h to afford a pale yellow oil (28 mg, 19%).

R_f = 0.29 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (d, *J* = 8.6 Hz, 1 H), 7.52 (d, *J* = 3.5 Hz, 1 H), 7.50 (d, *J* = 2.3 Hz, 1 H), 7.26 (dd, *J* = 9.0, 2.3 Hz, 1 H), 6.47 (d, *J* = 3.5 Hz, 1 H), 5.60 (d, *J* = 5.5 Hz, 1 H), 3.94 – 4.28 (m, 6 H), 2.64 – 2.77 (m, 2 H), 2.51 – 2.62 (m, 1 H), 2.02 – 2.13 (m, 1 H), 1.92 – 2.02 (m, 1 H), 1.65 (s, 9 H), 1.12 (t, *J* = 7.0 Hz, 3 H), 1.04 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 169.0, 168.9, 142.9, 130.1, 126.1, 118.0, 114.1, 112.9, 107.5, 104.5, 83.4, 74.4, 68.8, 62.0, 61.6, 35.3, 32.6, 29.0, 28.2, 13.8, 13.7.

HRMS (*m*/*z*): 488.2153 (calcd for $C_{25}H_{32}N_2O_8$, 488.2159).



Compound 1-108aa

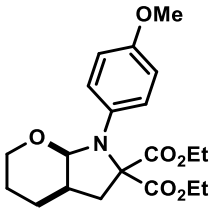
The title compound was prepared according to the general cycloaddition procedure A for 4 h to afford a pale yellow solid (50 mg, 45%).

R_f = 0.25 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.22 – 7.31 (m, 4 H), 7.00 (t, *J* = 7.0 Hz, 1 H), 4.88 (d, *J* = 2.9 Hz, 1 H), 4.26 – 4.33 (m, 2 H), 4.14 – 4.26 (m, 2 H), 4.04 – 4.10 (m, 1 H), 3.50 (td, *J* = 11.7, 1.8 Hz, 1 H), 2.42 – 2.49 (m, 1 H), 2.22 – 2.35 (m, 2 H), 1.87 – 1.95 (m, 1 H), 1.76 – 1.86 (m, 2 H), 1.31 (t, *J* = 7.0 Hz, 3 H), 1.16 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 168.0, 166.9, 146.6, 128.5, 122.9, 117.4, 84.4, 67.9, 62.1, 61.8, 29.9, 28.5, 27.5, 20.1, 14.1, 14.0.

HRMS (*m*/*z*): 363.1688 (calcd for $C_{19}H_{25}NO_6$, 363.1682).



Compound 1-110an

The title compound was prepared according to the general cycloaddition procedure B to afford a pale brown solid (40 mg, 35%).

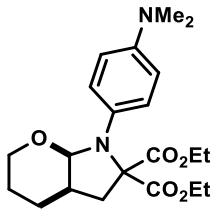
R_f = 0.26 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 6.90 – 6.94 (m, 2 H), 6.72 – 6.77 (m, 2 H), 5.03 (d, *J* = 3.5 Hz, 1 H), 4.15 – 4.25 (m, 4 H), 3.90 – 3.96 (m, 1 H), 3.73 (s, 3 H), 3.44 (td, *J* = 11.3,

2.1 Hz, 1 H), 2.84 (t, *J* = 12.3 Hz, 1 H), 2.43 (dd, *J* = 12.0, 6.8 Hz, 1 H), 2.33 – 2.40 (m, 1 H), 1.85 – 1.94 (m, 1 H), 1.69 – 1.80 (m, 2 H), 1.38 – 1.44 (m, 1 H), 1.22 (t, *J* = 7.0 Hz, 3 H), 1.16 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 171.1, 153.3, 137.8, 118.0, 113.8, 90.0, 74.0, 63.9, 61.7, 61.7, 55.5, 38.2, 35.1, 23.7, 20.7, 14.0, 13.9.

HRMS (*m*/*z*): 377.1837 (calcd for $C_{20}H_{27}NO_6$, 377.1838).



Compound 1-110ao

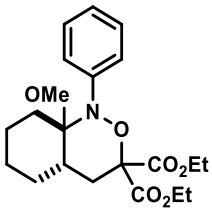
The title compound was prepared according to the general cycloaddition procedure B for 1 h, followed by 1 h at rt to afford a yellow oil (22 mg, 19%).

R_f = 0.43 (50% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 6.92 – 6.96 (m, 2 H), 6.65 – 6.68 (m, 2 H), 5.01 (d, *J* = 4.1 Hz, 1 H), 4.15 – 4.21 (m, 4 H), 3.92 (d, *J* = 11.2 Hz, 1 H), 3.42 (td, *J* = 11.0, 2.1 Hz, 1 H), 2.82 (s, 6 H), 2.39 – 2.44 (m, 1 H), 2.33 – 2.39 (m, 1 H), 1.83 – 1.93 (m, 1 H), 1.68 – 1.80 (m, 2 H), 1.37 – 1.43 (m, 1 H), 1.24 – 1.30 (m, 1 H), 1.21 (t, *J* = 7.3 Hz, 3 H), 1.15 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 171.4, 170.4, 145.5, 135.5, 118.9, 114.3, 90.2, 74.1, 63.8, 61.6, 61.5, 41.8, 38.1, 35.2, 23.8, 20.8, 14.0, 13.9.

HRMS (*m*/*z*): 390.2167 (calcd for $C_{21}H_{30}N_2O_5$, 390.2155).



Compound 1-108ga

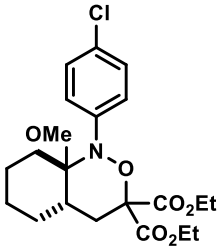
The title compound was prepared according to the general cycloaddition procedure A for 15 min to afford a pale yellow oil (85 mg, 73%).

R_f = 0.59 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.18 - 7.24 (m, 4 H), 6.98 - 7.01 (m, 1 H), 4.11 - 4.22 (m, 4 H), 3.13 (s, 3 H), 2.60 (t, *J* = 12.6 Hz, 1 H), 2.14 (dd, *J* = 12.6, 3.8 Hz, 1 H), 1.95 - 2.00 (m, 1 H), 1.66 - 1.75 (m, 2 H), 1.60 - 1.65 (m, 1 H), 1.43 - 1.48 (m, 2 H), 1.21 - 1.35 (m, 3 H), 1.12 - 1.18 (m, 6 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 168.8, 167.9, 148.8, 127.6, 123.3, 120.5, 101.4, 76.3, 62.1, 61.0, 48.1, 40.6, 33.8, 29.3, 27.6, 25.5, 22.5, 13.9, 13.7.

HRMS (*m*/*z*): 391.1987 (calcd for $C_{21}H_{29}NO_6$, 391.1995).



Compound 1-108gc

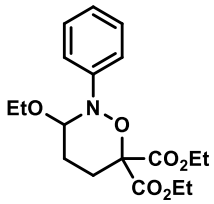
The title compound was prepared according to the general cycloaddition procedure A to afford a pale yellow oil (90 mg, 70%).

R_f = 0.65 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.16 (s, 4 H), 4.11 - 4.23 (m, 4 H), 3.10 (s, 3 H), 2.58 (t, *J* = 12.6 Hz, 1 H), 2.12 (dd, *J* = 12.6, 3.8 Hz), 1.93 – 1.99 (m, 1 H), 1.60 - 1.75 (m, 3 H), 1.42 - 1.52 (m, 3 H), 1.26 - 1.36 (m, 1 H), 1.19 - 1.26 (m, 1 H), 1.14 - 1.19 (m, 6 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 168.6, 167.8, 147.5, 127.6, 122.0, 101.6, 76.4, 62.2, 61.2, 48.0, 40.6, 33.7, 29.3, 27.6, 25.5, 22.5, 14.0, 13.7.

HRMS (*m*/*z*): 425.1607 (calcd for $C_{21}H_{28}ClNO_6$, 425.1605).



Compound 1-108fa

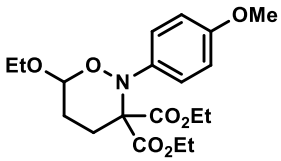
The title compound was prepared according to the general cycloaddition procedure A to afford a yellow oil (29 mg, 21%).

R_f = 0.40 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.16 – 7.24 (m, 4 H), 6.99 – 7.03 (m, 1 H), 5.03 (dd, *J* = 7.9, 3.8 Hz, 1 H), 4.19 – 4.25 (m, 2 H), 4.11 – 4.19 (m, 2 H), 3.94 (dq, *J* = 9.9, 7.1 Hz, 1 H), 3.61 (dq, *J* = 9.9, 7.1 Hz, 1 H), 2.58 (dt, 13.5, 4.7 Hz, 1 H), 2.44 (ddd, 13.4, 12.2, 4.4 Hz, 1 H), 1.97 (dq, *J* = 13.4, 4.2 Hz, 1 H), 1.76 – 1.84 (m, 1 H), 1.22 (t, *J* = 7.0 Hz, 3 H), 1.18 (t, *J* = 7.0 Hz, 3 H), 1.13 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 168.4, 168.1, 148.3, 127.7, 123.3, 119.5, 102.5, 74.8, 64.7, 61.9, 61.6, 30.8, 27.0, 15.1, 13.8, 13.7.

HRMS (*m*/*z*): 351.1679 (calcd for $C_{18}H_{25}NO_6$, 351.1682).



Compound 1-109fn

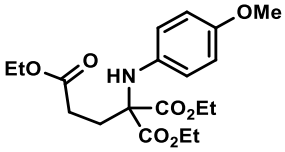
The title compound was prepared according to the general cycloaddition procedure B to afford a yellow oil (43 mg, 38%).

$\mathbf{R_f}$ = 0.36 (30% EtOAc/hexanes)

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.19 – 7.23 (m, 2 H), 6.75 – 6.79 (m, 2 H), 5.00 (dd, *J* = 8.2, 3.5 Hz, 1 H), 4.06 – 4.23 (m, 4 H), 3.83 – 3.90 (m, 1 H), 3.77 (s, 3 H), 3.53 – 3.60 (m, 1 H), 2.57 (dt, *J* = 13.5, 4.7 Hz, 1 H), 2.44 (td, *J* = 12.6, 4.7 Hz, 1 H), 1.95 (dq, *J* = 13.4, 4.2 Hz, 1 H), 1.73 – 1.83 (m, 1 H), 1.17 – 1.22 (m, 6 H), 1.13 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 168.3, 168.1, 156.4, 141.3, 122.7, 112.8, 102.3, 75.2, 64.6, 61.8, 61.5, 55.4, 27.1, 37.7, 15.1, 13.9, 13.8.

HRMS (*m*/*z*): 381.1778 (calcd for $C_{19}H_{27}NO_7$, 381.1788).



Compound 1-111fn

To a stirred solution of MgI_2 (47 mg, 0.17 mmol) in 6 mL CH_2Cl_2 at rt was added **1-109fn** (130 mg, 0.34 mmol). The RM was stirred for about 30 min at rt (complete consumption of starting material by TLC) then the RM was layered directly onto a silica gel column and purified by flash chromatography (0-25% EtOAc/hexanes) to afford a yellow oil (50 mg, 38%).

$\mathbf{R_f}$ = 0.43 (30% EtOAc/hexanes).

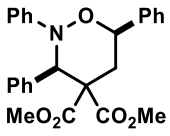
^{1}H NMR (400 MHz, $CDCl_3$) δ 6.70 - 6.75 (m, 2 H), 6.58 - 6.64 (m, 2 H), 4.81 (s, 1 H), 4.16 - 4.26 (m, 4 H), 4.04 (q, *J* = 7.2 Hz, 2 H), 3.73 (s, 3 H), 2.61 - 2.68 (m, 2 H), 2.22 - 2.29 (m, 2 H), 1.19 (t, *J* = 7.0 Hz, 9 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 196.3, 172.7, 169.6, 153.2, 137.6, 116.9, 114.6, 68.1, 62.4, 60.5, 55.6, 28.7, 27.4, 14.1, 13.9.

HRMS (*m*/*z*): 381.1789 (calcd for $C_{19}H_{27}NO_7$, 381.1788).

1.4.3 Cascade Reaction of Donor-Acceptor Cyclopropanes: Mechanistic Studies in Cycloadditions with Nitrosoarenes and *cis*-Diazenes

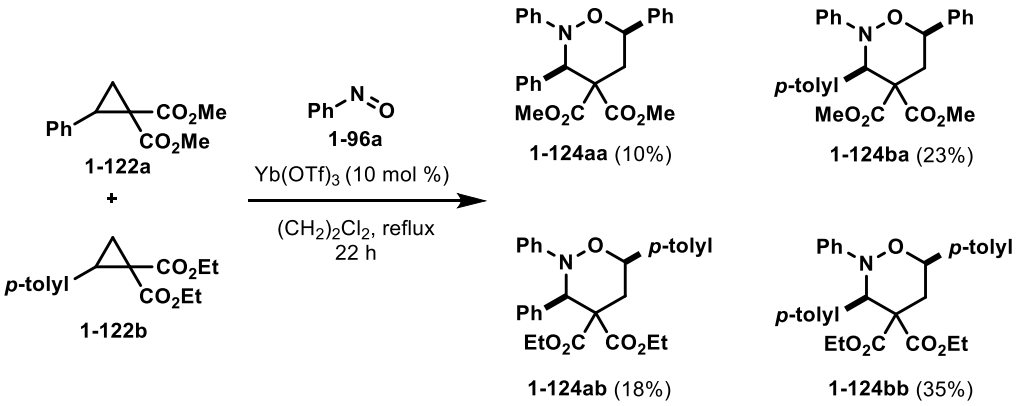
Majority of the experimental work done by Tristan Chidley (M.Sc. 2015) and only representative examples are shown in here.[88]



Compound 1-124aa

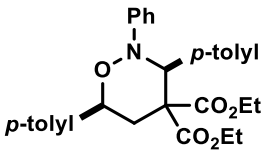
To a solution of cyclopropane **1-122a** (100 mg, 0.43 mmol) and nitrosobenzene (**1-96a**, 21 mg, 0.20 mmol) in $(CH_2)_2Cl_2$ (3 mL) at rt was added $Yb(OTf)_3 \cdot H_2O$ (12 mg, 0.02 mmol) and stirred for about 15 min. The RM was then heated to reflux until compete consumption of nitrosobenzene (3 h, as indicated by TLC). Then the RM was cooled to rt and directly layered onto a silica gel column and purified by flash chromatography (0-10% EtOAc/hexanes) to afford the title compound as a yellow oil, which was recrystallized with CH_2Cl_2/hexanes to give a white solid (75 mg, 87%). The characterization data is in agreement with literature values.[89]

Crossover Experiment 1



To a solution of cyclopropanes **1-122a** (0.43 mmol, 1.0 equiv), **1-122b** (0.43 mmol, 1.0 equiv) and nitrosobenzene (**1-96a**, 0.43 mmol, 1.0 equiv) in $(CH_2)_2Cl_2$ (3 mL) was added $Yb(OTf)_3 \cdot H_2O$ (0.02 mmol, 0.1 equiv) and stirred for 15 min. The mixture was then refluxed for about 22 h. After compete consumption of nitrosobenzene (as indicated by TLC) the RM was directly layered onto a silica gel column and isolated all 4 compounds in pure form by flash chromatography (0-10% EtOAc/hexanes).

These 4 isolated compounds are identical with the standards independently synthesized from literature methods.[90]



Compound 1-124bb

The title compound was isolated in crossover experiment 1 as yellow oil, which was recrystallized with CH_2Cl_2/hexanes to give a white solid (73 mg, 35%).

R_f = 0.58 (25% EtOAc/hexanes).

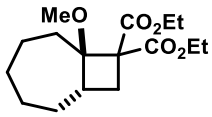
^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 - 7.49 (m, app dd, *J* = 8.2, 6.6 Hz, 4 H), 7.27 (app d, *J* = 8.2 Hz, 2 H), 7.07 - 7.17 (m, 4 H), 6.98 (d, *J* = 8.2 Hz, 2 H), 6.80 (app tt, *J* = 7.0, 1.6 Hz, 1 H), 5.76 (s, 1 H), 4.99 (dd, *J* = 12.1, 2.3 Hz, 1 H), 4.38 (q, *J* = 7.0 Hz, 2 H), 3.84 – 4.02 (app dddd, *J* = 7.0, 7.0, 7.0, 10.5 Hz, 2 H), 2.87 (app dd, *J* = 14.5, 12.5 Hz, 1 H), 2.75 (app dd, *J* = 14.5, 2.3 Hz, 1 H), 2.41 (s, 3 H), 2.22 (s, 3 H), 1.35 (t, *J* = 7.0 Hz, 3 H), 1.06 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 169.7, 168.0, 148.7, 138.1, 137.5, 136.6, 131.9, 130.4, 129.2, 128.6, 128.5, 126.5, 121.3, 115.7, 78.7, 65.4, 62.2, 61.7, 59.4, 31.6, 21.2, 21.0, 14.2, 13.7.

HRMS (*m/z*): 487.2348 (Calcd for $C_{30}H_{33}NO_5$, 487.2359).

1.4.4 Cycloadditions of Donor-Acceptor Cyclobutanes and *cis*-Diazenes

Known AACDs **1-53a** – **1-53f** were prepared according to literature procedures.[38]



Compound 1-67l

Following a reported procedure,[38] to a stirring solution of $Yb(OTf)_3 \cdot H_2O$ (415 mg, 0.05 equiv) in CH_2Cl_2 (25 mL) at rt was slowly added, a cold solution (maintained at –78 °C) of 1-methoxycyclohept-1-ene[91] (2.0 g, 15.85 mmol, 1.2 equiv), and diethyl 2-methylenemalonate (2.3 g, 13.36 mmol, 1.0 equiv) in CH_2Cl_2 (25 mL). After addition, the RM was stirred until appeared complete by TLC (~30 min). Pyridine (1 mL) was added and the reaction was filtered through a bilayer pad of silica gel (2 cm) and Celite® (1 cm) open to the atmosphere. The filtrate was concentrated *in vacuo* and the residue was purified by silica gel flash chromatography (0-5% EtOAc/hexanes, buffered with 1% Et_3N) to afford the title compound as a colorless oil (1.60 g, 40%).

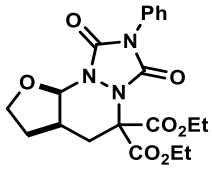
R_f = 0.41 (20% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.21 (dq, *J* = 14.3, 7.2 Hz, 4 H), 3.27 (s, 3 H), 2.63 - 2.75 (m, 1 H), 2.43 - 2.55 (m, 2 H), 2.00 (dt, *J* = 13.9, 7.1 Hz, 1 H), 1.75 - 1.85 (m, 1 H), 1.63 - 1.74 (m, 2 H), 1.54 - 1.63 (m, 1 H), 1.34 - 1.52 (m, 2 H), 1.25 - 1.32 (m, 6 H), 1.08 - 1.25 (m, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 169.6, 87.0, 61.4, 60.8, 60.3, 50.8, 43.0, 31.7, 28.5, 27.9, 26.1, 24.3, 23.3, 14.1, 14.0.

HRMS (*m*/*z*): 298.1792 (calcd for $C_{16}H_{26}O_5$, 298.1780).

The [4+2] cycloadditions of AACDs with *cis*–diazene (PTAD) were performed by Tristan Chidley (M.Sc. 2015) and only a representative example is shown in here.[88]



Compound 1-136b

To a solution of cyclobutane **1-67b** (141 mg, 0.58 mmol, 2.0 equiv) and PTAD (**1-30a**,50 mg, 0.29 mmol, 1.0 equiv) in $(CH_2)_2Cl_2$ (3 mL) at rt was added a solution of $GaCl_3$ (2.6 mg, 0.015 mmol, 0.05 equiv) in $(CH_2)_2Cl_2$ (0.5 mL) and stirred for about 30 min. Then the RM directly loaded onto a SiO_2 column and was purified by flash chromatography (30-50% EtOAc/hexanes) to afford the title compound as a white solid. (111 mg, 92%).

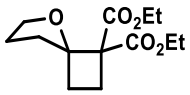
$\mathbf{R}_f$ = 0.50 (50% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) 7.45 - 7.53 (m, 4 H), 7.38 (app t, *J* = 7.0 Hz, 1 H), 5.78 (d, *J* = 4.3 Hz, 1 H), 4.29 - 4.37 (m, 4 H), 4.18 - 4.23 (m, 2 H), 4.08 (td, *J* = 9.4, 2.0 Hz, 1 H), 2.64 (dd, *J* = 13.3, 5.9 Hz, 1 H), 2.40 - 2.48 (m, 1 H), 2.28 - 2.36 (m, 1 H), 2.24 (dd, *J* = 13.3, 12.1 Hz, 1 H), 1.90 (ddd, *J* = 6.6, 6.6, 2.0 Hz, 1 H), 1.34 (t, *J* = 7.0 Hz, 3 H), 1.32 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) 166.2, 165.8, 153.7, 151.0, 131.0, 129.1, 128.3, 125.7, 77.6, 70.4, 65.0, 63.2, 63.0, 26.5, 25.6, 15.0, 14.1, 13.8.

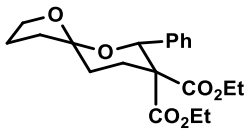
HRMS (*m*/*z*): 417.1530 (Calcd for $C_{20}H_{23}N_3O_7$, 417.1536).

1.4.5 Spiroketals from AACDs



Compound 1-143a

To a stirring solution of $Zn(OTf)_2$ (216 mg, 0.05 equiv) in CH_2Cl_2 (10 mL) at -78 °C was simultaneously added (over 1 h), a rt solution of 2-methylenetetrahydrofuran (1.0 g, 11.89 mmol, 1.0 equiv) in CH_2Cl_2 (3 mL) and diethyl 2-methylenemalonate (3.1 g, 17.83 mmol, 1.5 equiv) in CH_2Cl_2 (3 mL). After addition, the RM was stirred for about 15 min, and pyridine (0.3 mL) was added. Stirring was continued for 5 more min, then RM was filtered through a bilayer pad of silica gel (2 cm) and Celite® (1 cm) open to the atmosphere and the filtrate was concentrated *in vacuo*. After two unsuccessful attempts to purify the residue by flash column chromatography on silica gel (0-1% EtOAc/hexanes, buffered with 2% Et_3N), the partially purified compound carried forward to next step without characterization.



Compound 1-145a

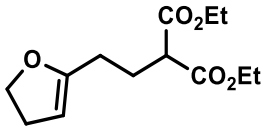
To a solution of $Yb(OTf)_3 \cdot H_2O$ (29 mg, 0.04 mmol, 0.1 equiv) in CH_2Cl_2 (1 mL) at 0 °C was added benzaldehyde (145 mg, 0.57 mmol, 1.0 equiv) followed by cyclobutane **1-143a** (50 mg, 0.47 mmol, 1.2 equiv). After 15 min the RM passed through a plug of silica gel (2 cm), washed with CH_2Cl_2 (5 mL), and the solvent concentrated *in vacuo* to obtain the title compound as a colorless oil in a reasonably pure form (77 mg, 45%).

$\mathbf{R}_f$ = 0.24 (20% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.43 (d, *J* = 7.0 Hz, 2 H), 7.19-7.25 (m, 3 H), 5.50 (s, 1 H), 4.14 (q, *J* = 7.4 Hz, 2 H), 4.01 (dq, *J* = 10.9, 7.1 Hz, 1 H), 3.91 (td, *J* = 8.2, 5.9 Hz, 1 H), 3.79-3.85 (m, 2 H), 2.39-2.45 (m, 2 H), 2.30-2.36 (m, 1 H), 2.09-2.16 (m, 1 H), 1.98-2.06 (m, 1 H), 1.82-1.90 (m, 1 H), 1.71-1.80 (m, 2 H), 1.16 (t, *J* = 7.3 Hz, 3 H), 0.93 (t, *J* = 7.3 Hz, 3 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 170.9, 169.1, 139.9, 127.6 (2 C), 127.1, 127.0 (2 C), 106.2, 73.4, 67.4, 61.1, 60.4, 58.2, 37.4, 29.1 (2 C), 23.5, 13.9, 13.5.

HRMS (*m*/*z*): 385.1612 (calcd for $C_{20}H_{26}O_6$ + Na, 385.1627).



Compound 1-149a

The title compound was isolated as a byproduct in [2+2] cycloaddition reaction.

R_f = 0.43 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.18 (app qd, *J* = 7.0, 1.6 Hz, 6 H), 4.07 (t, *J* = 6.8 Hz, 1 H), 3.40 (t, *J* = 7.6 Hz, 1 H), 2.63 (app t, *J* = 7.6 Hz, 2 H), 2.45 (td, *J* = 7.5, 1.4 Hz, 2 H), 2.93 (quin, *J* = 7.1 Hz, 2 H), 1.25 (t, *J* = 7.0 Hz, 6 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 169.3, 157.1, 90.3, 70.5, 61.0, 52.3, 28.8, 24.8, 24.8, 14.0.

HRMS (*m*/*z*): 256.1310 (calcd for $C_{13}H_{20}O_5$, 256.1311).

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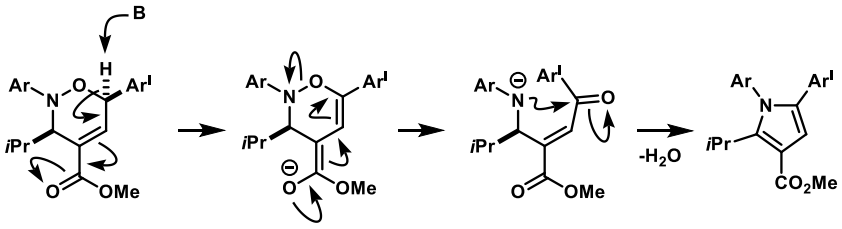

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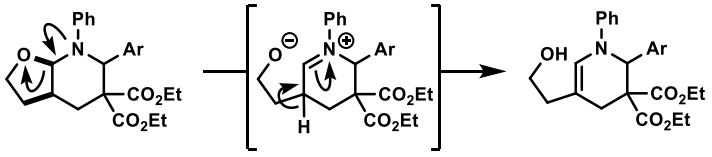

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Chapter 2. Studies Towards the Synthesis of Streptorubin B

This chapter describes synthetic efforts towards the prodigiosin alkaloid streptorubin B using our group developed [3+2] cycloaddition of DA cyclopropanes and nitriles. An overview of this methodology along with relevant background information as well as reported studies directed towards the synthesis of streptorubin B and related prodigiosins has been discussed.

2.1 Introduction

The prodigiosin family of alkaloids have been of interest to both chemists and biologists for their unique molecular architecture and range of biological properties.[1] Even though, prodigiosins share a common tripyrrole skeleton, they are diverse in molecular connectivity (Figure 2-1).[2] Some of them have unique pyrrolophane core structure (such as **2-1**) and some are distinctive macrocycles (such as **2-2**). They display a characteristic deep-red color which has been misinterpreted in certain religious or symbolic contexts as the miraculous appearance of blood in certain foods.[2b]

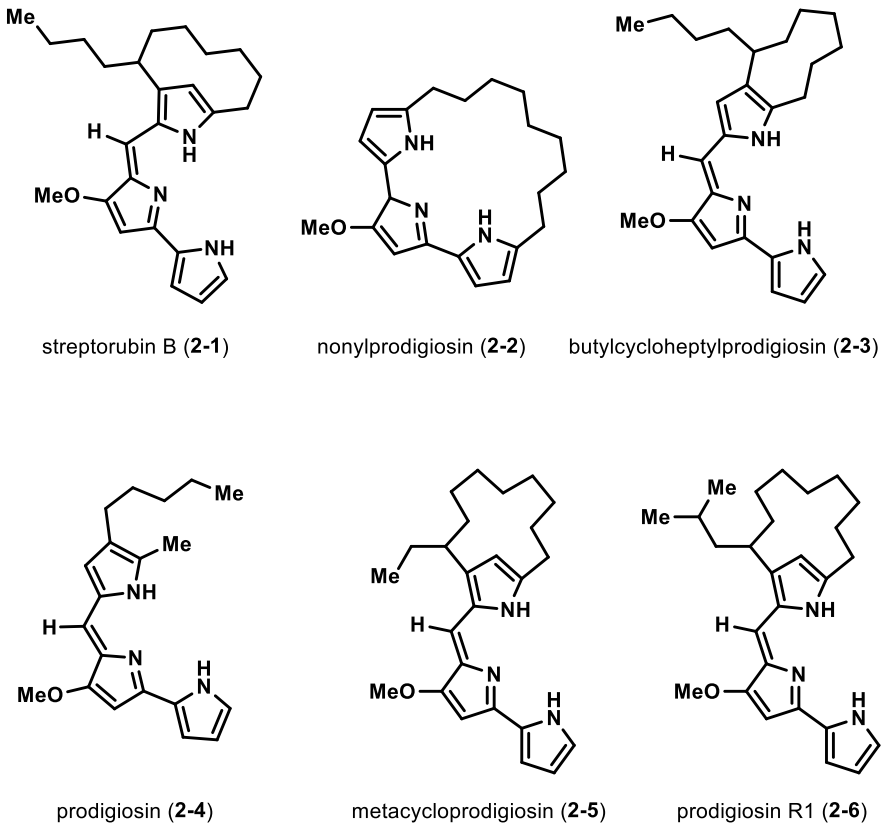


Figure 2-1. Representative members of prodigiosin family of alkaloids.

2.1.1 Biological Activity of Prodigiosins

The natural prodigiosins have impressive array of biological activities,[3] and have inspired many medicinal chemists to synthesize hundreds of structural congeners for their potential as active ingredients in immunosuppressant and anti-cancer therapeutics.[4] As a result of these studies, Pharmacia-Upjohn discovered a synthetic congener PNU156804 (**2-7**, Figure 2-2), which had impressive immunosuppressive properties, and was selected as a drug candidate for further studies.[5] Gemin X (which was later acquired by Cephalon) discovered Obatoclax (**2-8**, Figure 2-2) for the treatment of various types of cancers, which is currently in Phase II clinical trials for the treatment of leukemia, lymphoma, myelofibrosis, and mastocytosis.[6]

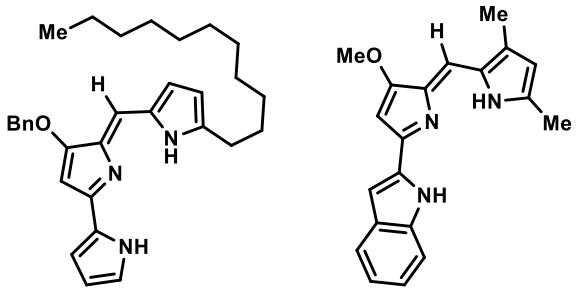


Figure 2-2. Structures of PNU156804 (**2-7**) and Obatoclax (**2-8**).

2.1.2 Streptorubin B

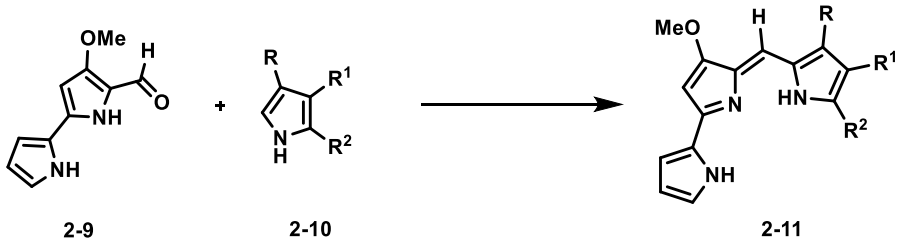
Streptorubin B (**2-1**) was first isolated in 1964 by Thirumalachar and co-workers from *Streptomyces caespitosus* bacteria, found in soil samples in Pimpri, India.[7] In 1975, Gerber and co-workers reported isolation of a red pigment from *Streptomyces* sp. Y-42 and *Streptomyces abikoensis*, which was structurally assigned as butylcycloheptylprodigiosin (**2-3**).[8] Due to the structural similarities between **2-1** and **2-3**, which differ only in connectivity of the pyrrole ring, there was confusion regarding the

structures of these compounds. Later in 1978, Gerber expressed the need to revise the structure of **2-3** to **2-1** without elaborating the reasons behind this revision.[9] A few years later, in 1985, Floss and co-workers assigned the structure of **2-3** to a pink pigment isolated from a strain of *Streptomyces coelicolor*.[10] In 1991, Weyland and co-workers reported the isolation of a red pigment from an actinomycete strain B 4358, which was assigned as **2-1** based on 2D NMR data.[11] Weyland also stated that the assignment of **2-3** assigned by Gerber and Floss should be revised to **2-1**. In 2005, Fürstner reported the synthesis of **2-3**,[12] followed by Reeves in 2007,[13] who stated **2-3** is in fact the natural product isolated by Gerber and Floss, against Weyland claims. Futhermore, in 2008, Challis and co-workers isolated **2-1** from *Streptomyces coelicolor*, the organism from which Floss isolated red pigment, and they found no evidence for the production of **2-3**.[14] The debate was continued until 2013, when Thomson and co-workers conducted mass spectral analysis and proposed biosynthesis hypotheses to eliminate butylcycloheptylprodigiosin (**2-3**) as a known natural product.[15] The compound Floss isolated from *Streptomyces coelicolor* and Gerber from *Streptomyces* sp. Y-42 and *Streptomyces abikoensis* was in fact streptorubin B (**2-1**).

From a synthetic chemist point of view, streptorubin B (**2-1**) is very interesting target for its unique 10-membered 2,4-pyrrolophane structure with possible atropisomerism[16] and its potent cytotoxicity against tumor cells,[30] it has been shown to selectively kill 100% breast cancer cells at 1 µM doses.[17]

2.1.3 Biosynthesis of Streptorubin B and Related Prodigiosins

It was widely accepted that a key step in the biosynthesis of the prodigiosins is the non-enzymatic condensation of 4-methoxy-2,2'-bipyrrole-5-carboxaldehyde (**2-9**) with a substituted pyrrole moiety **2-10** (Scheme 2-1).[2]



Scheme 2-1. Biosynthesis of the prodigiosins from condensation of aldehyde **2-9** with pyrrole **2-10**.

Biosynthetic studies including ^{13}C labelled feeding studies established that each pyrrole was derived in a series of enzymatic reactions from different amino acids and alkyl chains formed from several acetyl units.[18]

From a structural standpoint, streptorubin B (**2-1**) and streptorubin A (**2-5**, widely known as metacycloprodigiosin) are very similar (Figure 2-3). It was understood that these highly strained pyrrolophane natural products were formed by oxidative ring closure mediated by Rieske oxygenase-like enzymes from a common intermediate, undecylprodigiosin (**2-12**).[19] This biosynthesis proposal was supported by the fact that undecylprodigiosin (**2-12**) has been isolated from the same strains of bacteria as metacycloprodigiosin (**2-5**) and streptorubin B (**2-1**).[8a, 9]

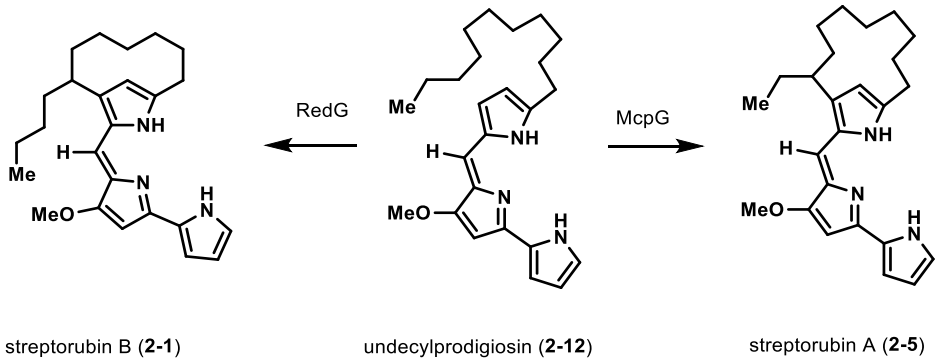
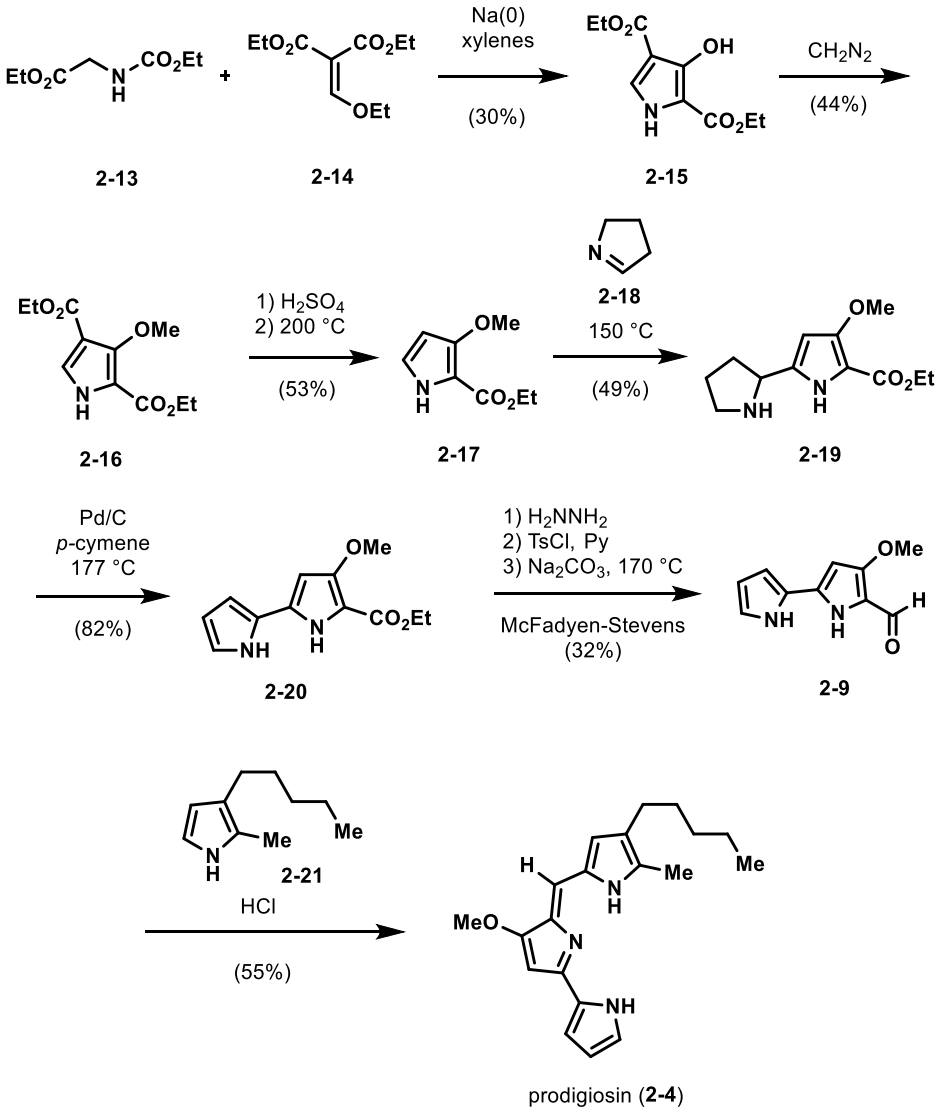


Figure 2-3. Biosynthesis of streptorubin B (**2-1**) and streptorubin A (**2-5**) from undecylprodigiosin (**2-12**) catalyzed by enzymes RedG and McpG respectively.

2.1.4 Published Studies Towards the Streptorubin B and Related Prodigiosins

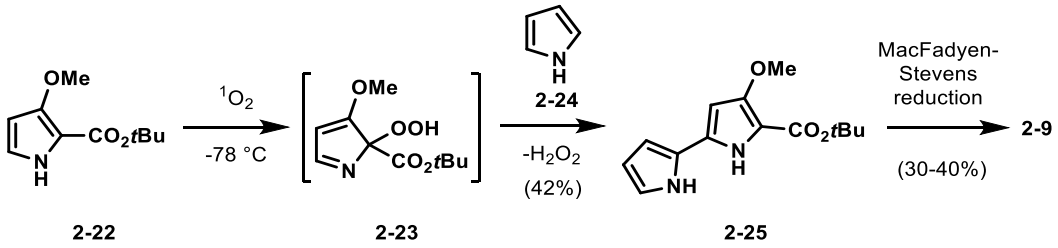
There have been many synthetic studies reported towards aldehyde **2-9**. The first successful synthesis of aldehyde **2-9** was reported by Rapoport and co-workers in 1962.[20] Rapoport's synthesis of aldehyde **2-9** was straightforward, consisting of seven linear steps (Scheme 2-2). The synthesis began with the condensation of ethyl *N*-(ethoxycarbonyl)glycinate (**2-13**) with diethyl ethoxymethylenemalonate (**2-14**) followed by conversion of the resulting alcohol **2-15** to methyl ether **2-16** with diazomethane. Selective dealkoxy-carbonylation with H_2SO_4 and heat followed by condensation with 1-pyrroline (**2-18**) led to pyrrolidinylpyrrole **2-19** which was dehydrogenated to 2,2'-bipyrrole **2-20**. Bipyrrole ester **2-20** was then converted to the corresponding aldehyde **2-9** under McFadyen-Stevens conditions. Acid catalyzed condensation of this aldehyde with 2-methyl-3-pentylpyrrole (**2-21**, which was made in five steps from 3-octanone) resulted in synthetic prodigiosin (**2-4**).



Scheme 2-2. Rapoport's synthesis of prodigiosin (**2-4**).

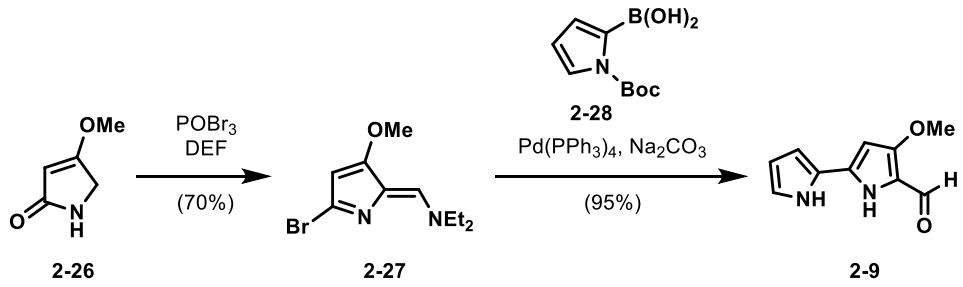
In 2004, Wasserman and co-workers reported a short synthesis of aldehyde **2-9**. The report described the synthesis of the *tert*-butyl analogue **2-25** (Scheme 2-3) of Rapoport's intermediate **2-20** *via* addition of singlet oxygen to certain pyrrole compounds (Scheme 2-3).[21] The transient imino hydroperoxide intermediate **2-23** has been shown to react with a number of nucleophiles, such as pyrrole to give 2,2'-bipyrrole **2-25**. Subsequent McFadyen-Stevens reduction produced aldehyde **2-9** (see Scheme 2-2).

Although this route allows for the structural modifications on the pyrrole, it is limited by the low yields of both the singlet oxygen reaction as well as the McFadyen-Stevens reduction.



Scheme 2-3. Wasserman's singlet oxygen methodology for the synthesis of aldehyde **2-9**.

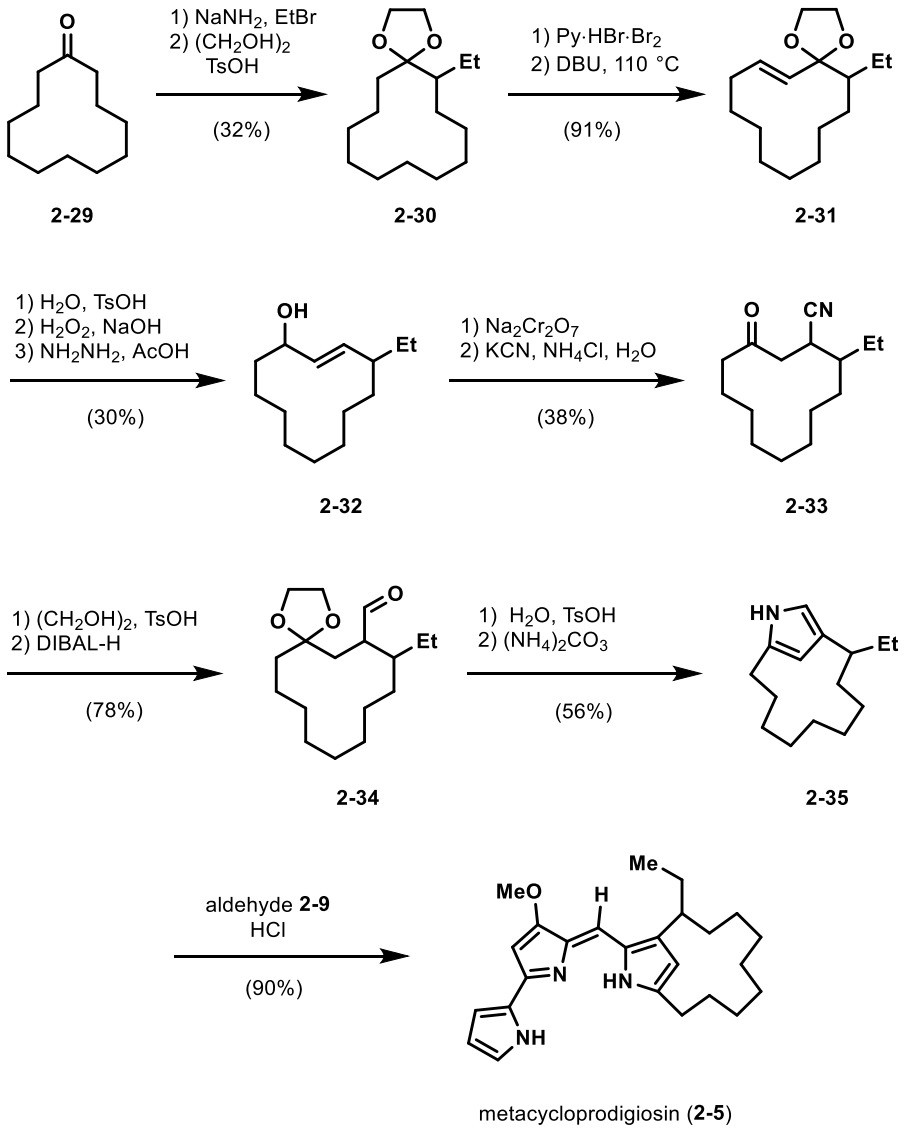
In 2006, Lavallèe and Tripathy reported the shortest synthesis of aldehyde **2-9** to date.[22] Commercially available 4-methoxy-3-pyrolin-2-one (**2-26**) was treated with the Vislmeier–Haack reagent derived from diethylformamide[23] to produce bromopyrrole enamine **2-27** in 70% yield. Suzuki cross-coupling reaction of **2-27** with *N*-Boc-2-pyrroleboronic acid (**2-28**) followed by aq work-up led to the aldehyde **2-9** in 95% yield (Scheme 2-4). Furthermore, the authors applied this methodology towards the efficient synthesis of Obatoclax (**2-8**).[24]



Scheme 2-4. Lavallèe and Tripathy's synthesis of aldehyde **2-9**.

The first total synthesis of metacycloprodigiosin (**2-5**) was reported by Wassermann and co-workers in 1969, following its isolation and structural

determination.[25] As described in Scheme 2-5, the synthesis began with enolate ethylation of **2-29** followed by protection of the carbonyl as spiroketal **2-30** in a 32% yield. Regioselective bromination followed by E2 elimination with DBU establishes enone **2-31** in a 91% yield. Deprotection of the carbonyl, epoxidation, followed by acidic hydrazine-promoted rearrangement of α,β-epoxyketone to allylic alchol **2-32** was achieved in 30% yield. Oxidation of alcohol **2-32** followed by 1,4-addition of cyanide to the resulting enone was accomplished in 91% yield. Protection of the ketone followed by DIBAL-H reduction of nitrile **2-33** led to aldehyde **2-34**. Deprotection of the ketone followed by Paal-Knorr cyclization with ammonium carbonate completed the synthesis of pyrrole **2-35** in 3.5% overall yield over 13 linear steps. This pyrrole moiety was then condensed with the known aldehyde **2-9** to complete the synthesis of metacycloprodigiosin (**2-5**).

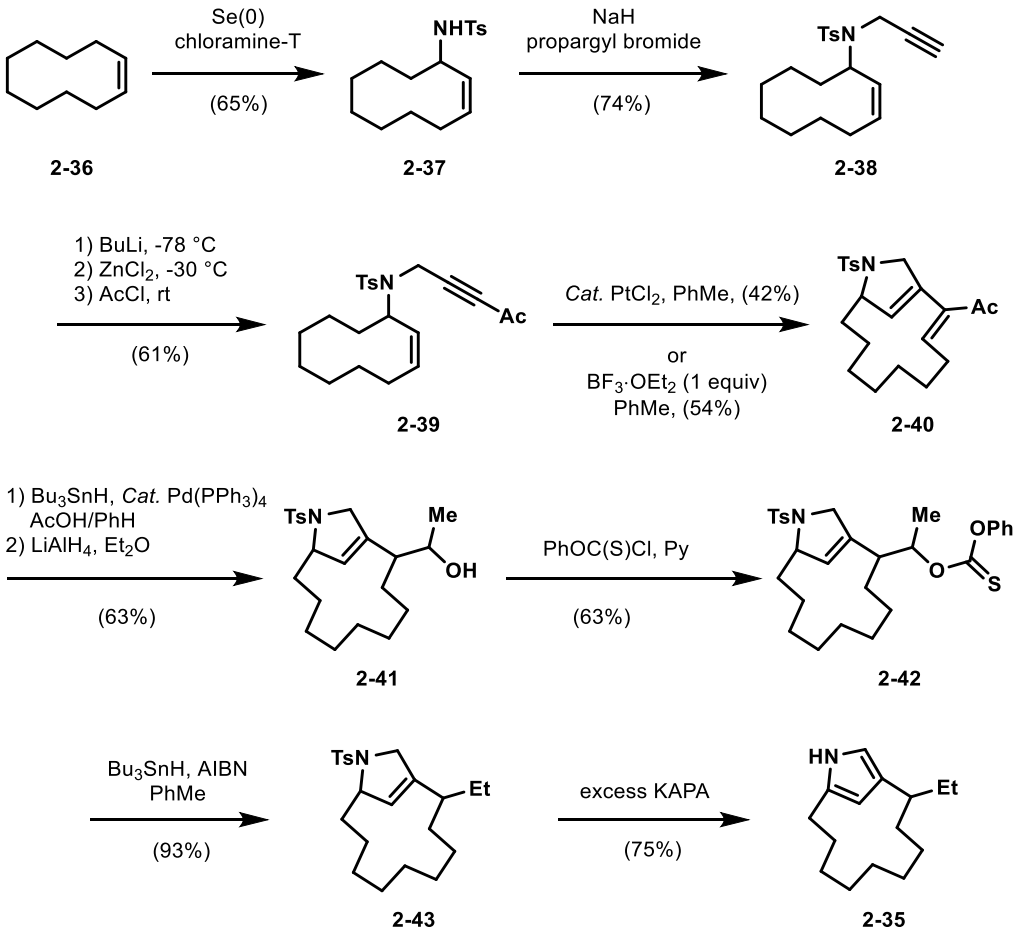


Scheme 2-5. Wasserman's total synthesis of metacycloprodigiosin (**2-5**).

A few years later, in 1998, Fürstner and co-workers reported an efficient synthesis of the pyrrolophane core (**2-35**) of metacycloprodigiosin (**2-5**) *via* enyne metathesis.[26]

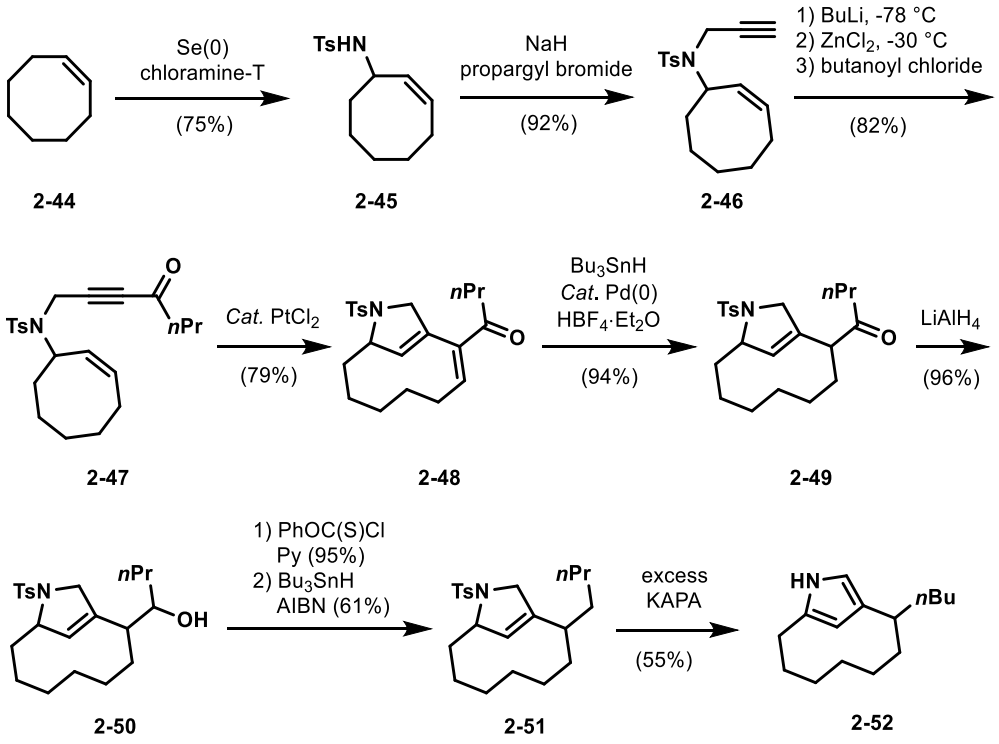
As depicted in Scheme 2-6, the synthesis began with an ene-type reaction on the cyclodecene (**2-36**) with an *in situ* generated diiminoselenium reagent.[27] Alkylation of allyl amine **2-37** with propargyl bromide, and a subsequent acylation of the resulting terminal alkyne **2-38** with acetyl chloride established the enyne **2-39** required for the

metathesis reaction. The enyne metathesis reaction[28] on **2-39** was initiated with either $BF_3{\cdot}OEt_2$ or $PtCl_2$ to afford ring-expanded product **2-40** in moderate yield. The enone of bicycle **2-40** was reduced to 2° alcohol **2-41**, which was thionylated with *O*-Phenyl chlorothionoformate followed by Barton-McCombie dehydroxylation to give **2-43**. Compound **2-43** was then converted into pyrrolophane **2-35** by a one pot detosylation and aromatization with potassium 3-aminopropylamide (KAPA).[29] Thus, the formal synthesis of metacycloprodigiosin **2-5** was achieved in 5% overall yield from commercially available cyclodecene.



Scheme 2-6. Fürstner's synthesis of Wasserman's pyrrole **2-35** *via* enyne metathesis.

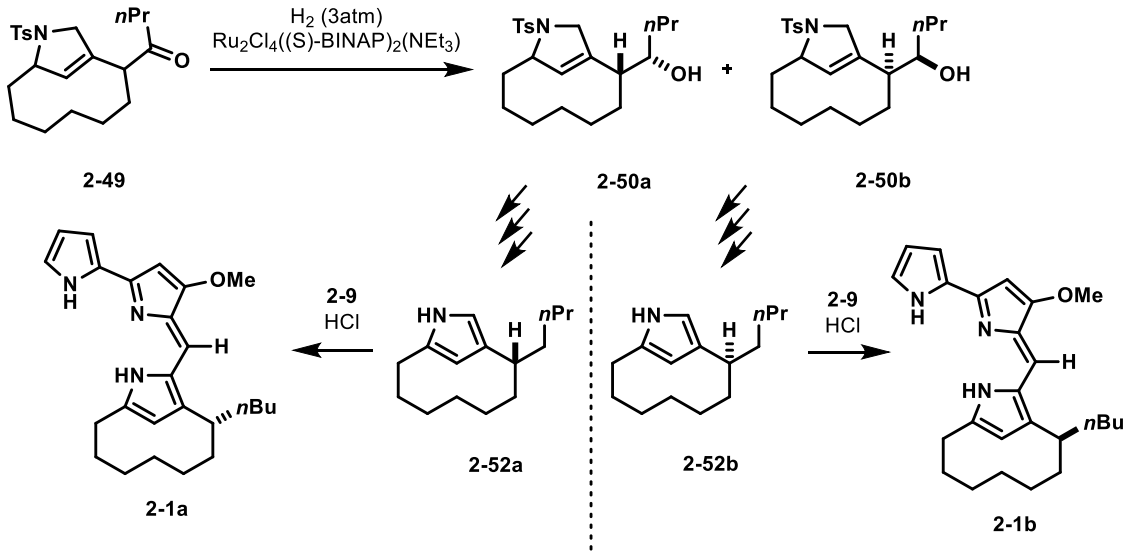
The first synthesis of the pyrrolophane core (**2-52**) of streptorubin B (**2-1)** was accomplished by the Fürstner group (Scheme 2-7).[26] The required precursor **2-47** for the enyne metathesis reaction was prepared from cyclooctene by a series of transformations similar to those discussed earlier (*vide supra*). The $PtCl_2$-catalyzed enyne metathesis reaction on **2-47** resulted in ring expanded product **2-48** in 94% yield, which was then converted into pyrrolophane **2-52** through previously described transformations. Thus, the first synthesis of pyrrolophane core (**2-52**) of streptorubin B (**2-1**) was achieved in about 16% overall yield in nine steps from cyclooctene.



Scheme 2-7. Fürstner's first synthesis of pyrrolophane core (**2-52**) of streptorubin B (**2-1**).

In an effort to synthesize a library of prodigiosin derivatives for drug discovery, Murthy and co-workers completed the first total synthesis of streptorubin B along with

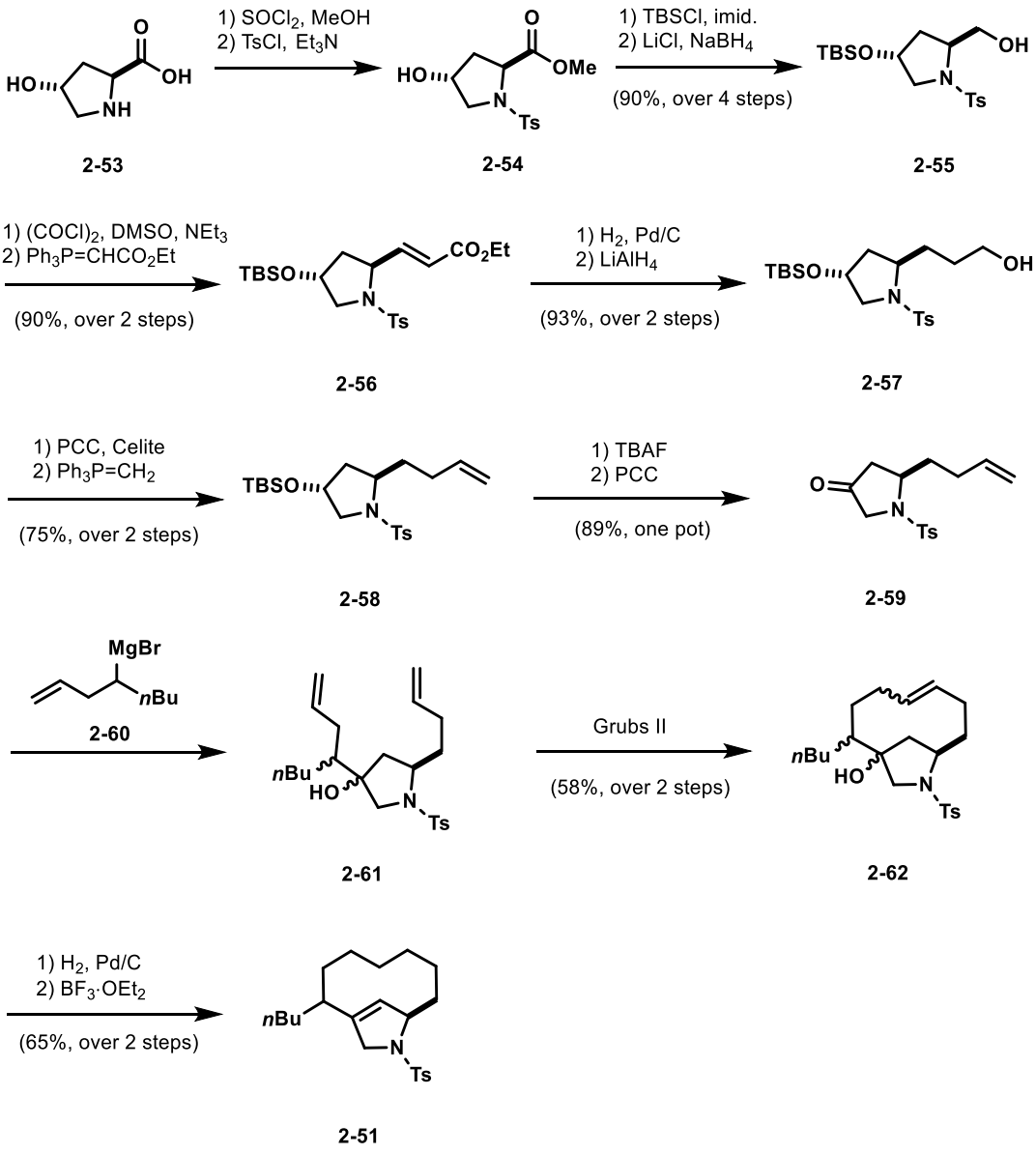
several structural congeners using Fürstner's route.[30] They used chiral catalyst $Ru_2Cl_4((S)\text{-BINAP})_2(NEt_3)$ to reduce the ketone **2-49** to a pair of alcohols **2-50a** and **2-50b**, which were separated and carried on independently according to Fürstner's route to pyrrolophanes **2-52a** and **2-52b** (Scheme 2-8). These pyrrolophanes were then condensed independently with the known aldehyde **2-9** to access both enantiomers of streptorubin B.



Scheme 2-8. Murthy's asymmetric syntheses of both enantiomers of streptorubin B.

In 2005, Chang and co-workers reported a synthesis of intermediate **2-51** using ring closing metathesis (RCM).[31] The synthesis began with the commericially available *trans*-4-hydroxy-L-proline (**2-53**). Esterificaton of the acid and tosylation of the amine followed by silylation of the 2° alcohol and reduction of the ester resuted in prolinol **2-55** in 90% yield over four steps. Swern oxidation, Wittig reaction on the resulting aldehyde, followed by two reductions gave 1° alcohol **2-57**. Oxidation of this alcohol by PCC, followed by Wittig reaction installed the alkene required for the RCM reaction. Deprotection of the alcohol followed by PCC oxidation gave ketone **2-59**. Grignard addition into this ketone followed by RCM with Grubbs II catalyst resulted in **2-62** as a

mixture of geometrical isomers and diastereomers. This mixture was then converted to Fürstner's intermediate **2-51** by hydrogenation of the alkene followed by dehydration of the 3° alcohol.

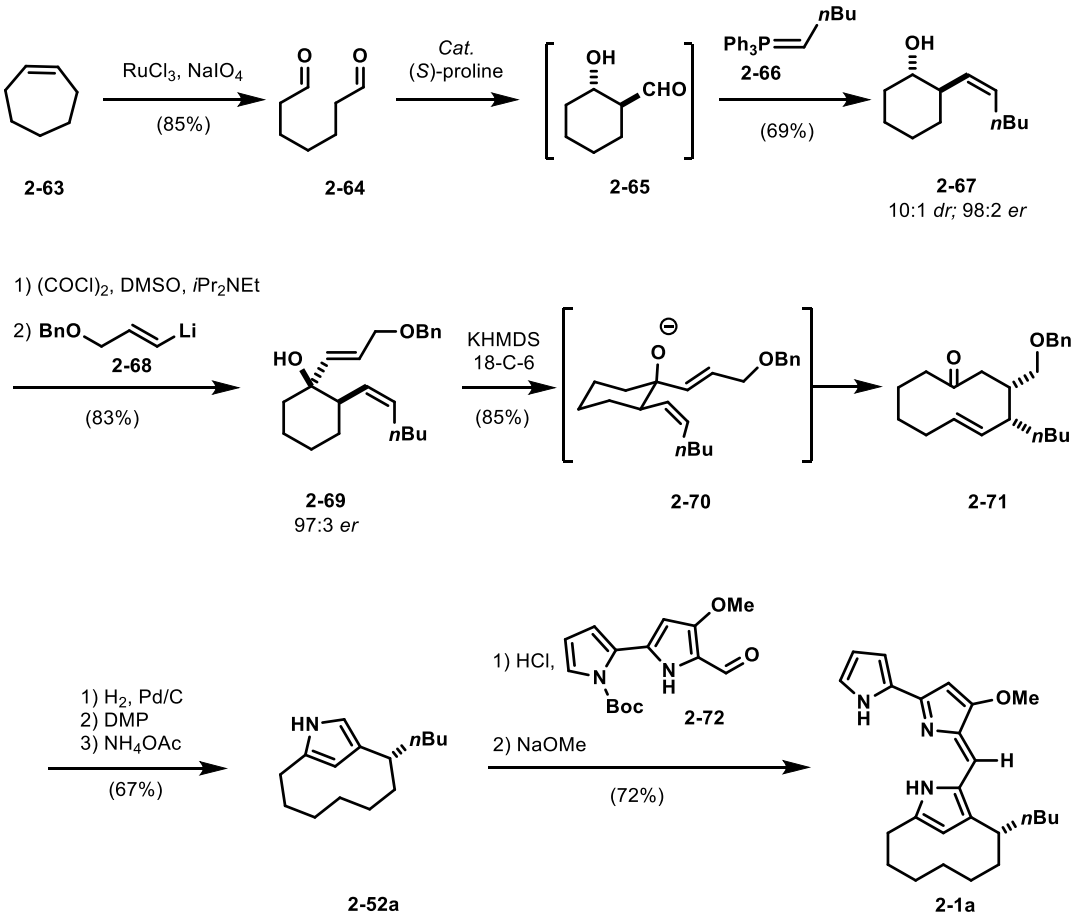


Scheme 2-9. Chang's synthesis of Fürstner's intermediate **2-51** of streptorubin B.

Even though the total synthesis of the streptorubin B has been achieved, no comparison was made between synthetic and natural samples of streptorubin B to

establish the absolute and relative configuration. It was not until 2010 when the Thompson group established the correct absolute and relative stereochemistry of streptorubin B through an enantioselective total synthesis and comparisons of circular dichroism (CD) spectra.[32]

As described in Scheme 2-10, the synthesis began with the oxidative cleavage of cycloheptene (**2-63**) to afford the dialdehyde necessary for an asymmetric intramolecular aldol reaction.[33] An (*S*)-proline catalyzed aldol followed by Witting reaction with ylide **2-66** gave the homoallylic alcohol **2-67** with high diastereocontrol. Oxidation of alcohol **2-67** followed by addition of vinyl anion **2-68** installed the functional handles required for an anionic Cope rearrangement. Upon exposure of alcohol **2-69** to KHMDS and 18-crown-6 produced the desired 10-membered ring in 85% yield with excellent stereochemical transfer. This cyclic ketone was then efficiently converted into pyrrole **2-52a** following reduction of the alkene with concomitant cleavage of the benzyl ether, Dess-Martin oxidation of the resulting alcohol, and Paal-Knorr pyrrole synthesis. Pyrrole **2-52a** was converted into streptorubin B (**2-1**) through an acid-promoted condensation with aldehyde **2-72**, followed by deprotection of Boc group *via* basic methanolysis. Interestingly, the isolated product was a 10:1 mixture of two compounds of which the major compound is not the streptorubin B (possibly atropisomer of streptorubin B). However, over time (10 days), the mixture completely transformed into the natural product, making this route the shortest to date, in nine linear steps with 20% overall yield from cycloheptene (**2-63**).

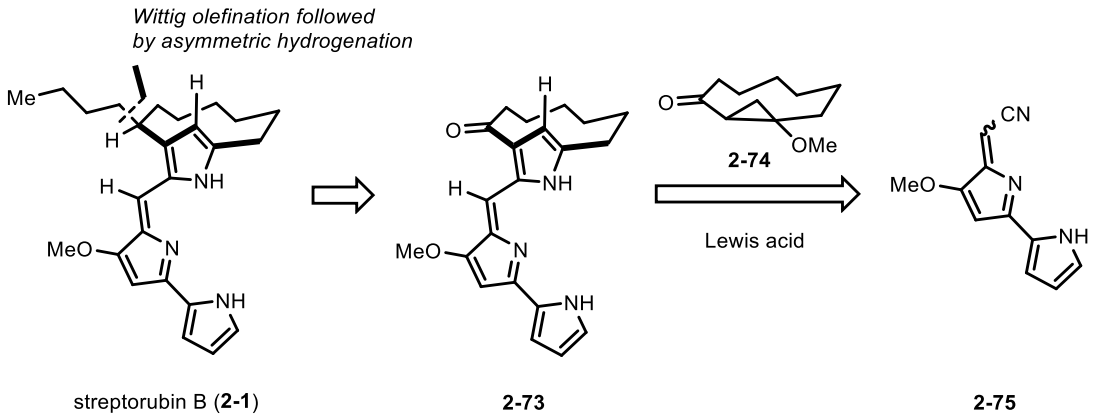


Scheme 2-10. Thompson's enantioselective total synthesis of streptorubin B (**2-1**).

In summary, the synthesis of streptorubin B (**2-1**) was achieved and its absolute and relative stereochemistry was firmly established with X-ray crystallography. The above discussed syntheses (and a few unsuccessful studies)[34] are efficient in their own way, but they are linear and rather lengthy. Thus, a convergent approach to streptorubin B, which would also allow the expedited synthesis of structural congeners is warranted.

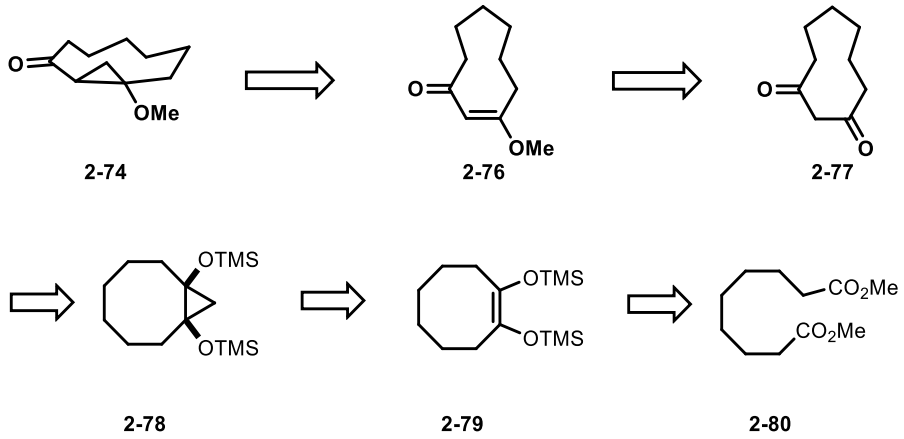
2.2 Project Plans and Goals

Our goal for this project was to achieve the total synthesis of streptorubin B in a modular approach, which would allow for late stage functionalization. As shown in Scheme 2-11, the butyl side chain of the streptorubin B could be attained *via* a Wittig reaction followed by an asymmetric hydrogenation of compound **2-73**.[35] We envisioned the pyrrolophane core structure can be prepared *via* our group developed [3+2] cycloaddition between DA cyclopropanes and nitriles (see Section 2.3). Therefore, compound **2-73** can come from a Lewis acid catalyzed [3+2] cycloaddition of bicyclic DA cyclopropane **2-74** and functionalized nitrile **2-75**.



Scheme 2-11. Retrosynthesis of streptorubin B (**2-1**).

The bicyclic DA cyclopropane **2-74** can be accessed from a known cyclononane-1,3-dione (**2-77**)[36] *via* enolate *O*-alkylation followed by cyclopropanation (Scheme 2-12). The cyclononane-1,3-dione (**2-77**) could be prepared from commercially available dimethyl octanedioate (**2-80**) using a known 3-step procedure[36] *via* acyloin condensation of **2-80**, followed by Simmons-Smith cyclopropanation and subsequent oxidative ring-expansion.



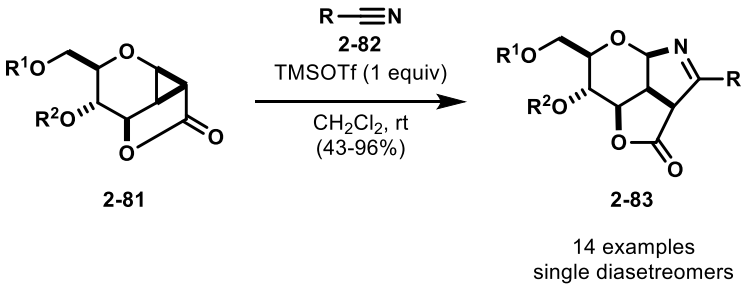
Scheme 2-12. Retrosynthesis of bicyclic DA cyclopropane **2-74**.

One of the major advantages of this synthesis would be the ease of late stage functionalization. Also, this strategy, if ideally executed, could be a short synthesis of streptorubin B in five linear steps from a known 1,3-dione **2-77**.

2.3 Cycloaddition of DA Cyclopropanes and Nitriles

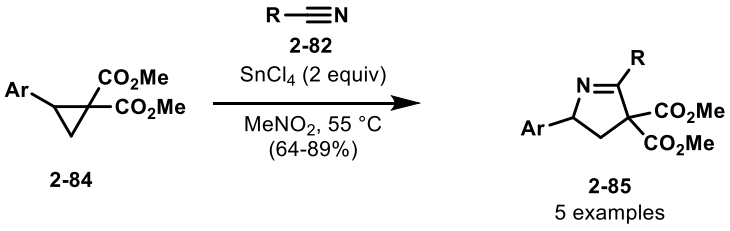
2.3.1 The [3+2] Cycloaddition of DA Cyclopropanes and Nitriles

The first example of [3+2] cycloaddition between DA cyclopropanes and nitriles was reported by Pagenkopf and Yu in 2003.[37] The report disclosed a novel TMSOTf-promoted [3+2] cycloaddition of carbohydrate-derived DA cyclopropanes **2-81** with a wide range of nitriles **2-82** to produce 1-pyrrolines (**2-83**) in good to excellent yields (Scheme 2-13).



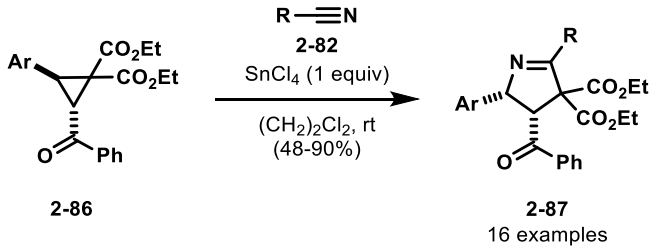
Scheme 2-13. TMSOTf-promoted [3+2] cycloaddition of DA cyclopropanes and nitriles.

A few years later, in 2010, Trushkov and co-workers extended this methodology to aryl-activated DA cyclopropanes.[38] In this report, only alkyl nitriles were examined in cycloadditions with DA cyclopropanes under excess-stoichiometric $SnCl_4$ conditions. The cycloaddition afforded 1-pyrrolines in good yields (Scheme 2-14).



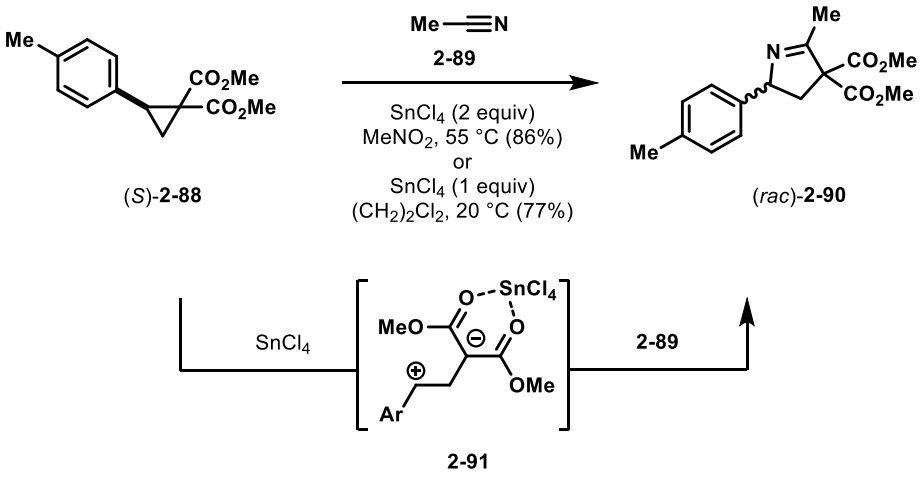
Scheme 2-14. $SnCl_4$-promoted [3+2] cycloaddition of DA cyclopropanes and nitriles.

In 2011, Srinivasan and co-workers further extended Trushkov's methodology to a highly activated DA cyclopropane **2-86** under stoichiometric $SnCl_4$ conditions (Scheme 2-15).[39] Both alkyl and aryl nitriles were reported to undergo efficient cyclizations with DA cyclopropane **2-68** affording 1-pyrrolines in good yields.



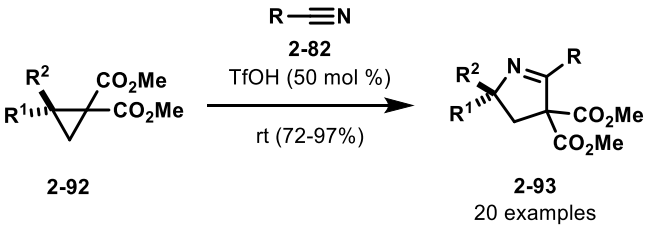
Scheme 2-15. $SnCl_4$-promoted [3+2] cycloaddition of highly activated DA cyclopropane **2-86** with nitriles.

In an attempt to prepare enantiopure 1-pyrrolines *via* [3+2] cycloaddition of DA cyclopropanes and nitriles, Trushkov and co-workers subjected an enantiopure DA cyclopropane (*S*)-**2-88** to previously reported cycloaddition conditions (see Scheme 2-14). The reaction with acetonitrile (**2-89**) resulted in racemic 1-pyrroline **2-90** suggesting that the reaction is going through an achiral zwitterionic intermediate **2-91** (Scheme 2-16). Changing the solvent or temp did not help improve the stereoselectivity.



Scheme 2-16. $SnCl_4$-promoted [3+2] cycloaddition of DA cyclopropane (*S*)-**2-88** and acetonitrile (**2-89**).

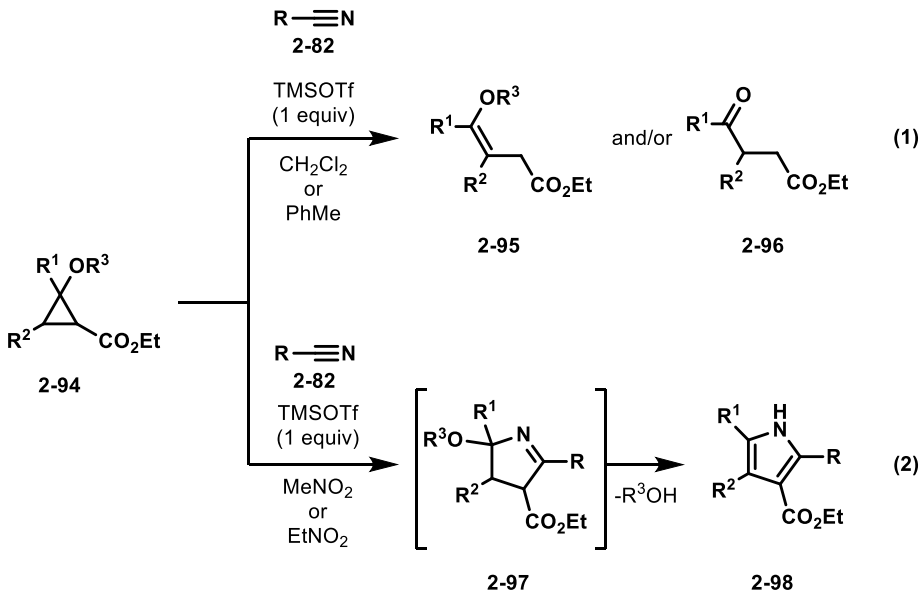
Recently, Wang and co-workers reported a TfOH-promoted [3+2] cycloaddition of DA cyclopropanes with nitriles.[40] The cycloaddition reported to have a broad substrate scope including aryl, allyl, or alkyl activated DA cyclopropanes with a wide range of nitriles (Scheme 2-17).



Scheme 2-17. TfOH-promoted [3+2] cycloaddition of DA cyclopropanes with nitriles

2.3.2 Pyrroles from DA Cyclopropanes and Nitriles

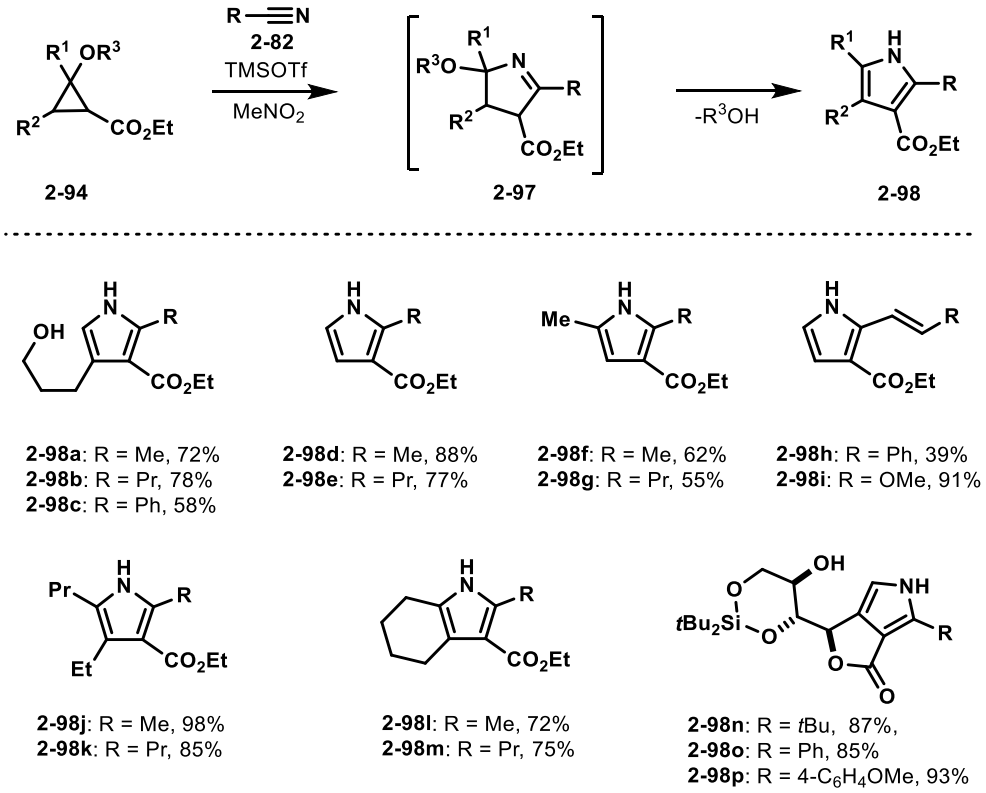
During the efforts to expand TMSOTf-promoted [3+2] cycloaddition of DA cyclopropanes and nitriles (see Scheme 2-13), Pagenkopf and Yu made an interesting observation. When the reaction was conducted in either toluene or dichloromethane, only rearranged products **2-95** and/or **2-96** were formed (eq 1, Scheme 2-18), but when highly polar solvents, such as nitromethane or nitroethane were used, the reaction underwent a tandem [3+2] cycloaddition, elimination, and tautomerization sequence to produce pyrroles **2-98** (eq 2, Scheme 2-18).[41]



Scheme 2-18. The effect of solvent in reaction of DA cyclopropanes with nitriles.

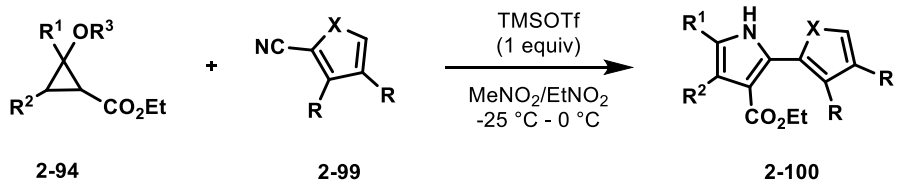
Gratifyingly, this cascade reaction has a broad substrate scope (Table 2-1).[42] A wide range of DA cyclopropanes, irrespective of the substitution around the ring, were found to undergo efficient cyclizations with a variety of nitriles in good to excellent yields (**2-98a**-**2-98m**). Interestingly, substrates with silyl protecting groups, were also tolerated by the reaction conditions to afford pyrroles (**2-98n**-**2-98p**).

Table 2-1. Pyrroles from DA cyclopropanes and nitriles.

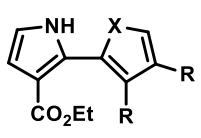


A year later, in 2004, Pagenkopf and co-workers applied this methodology towards the synthesis of unsymmetrical 2,2'-bipyrroles and 2,2'-thienylpyrroles.[43] A series of DA cyclopropanes were reported to undergo cycloadditions with 2-cyanopyrroles and 2-cyanothiophenes, to afford 2,2'-bipyrroles and 2,2'-thienylpyrroles, respectively (Table 2-2).

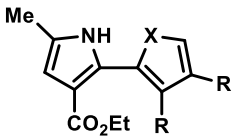
Table 2-2. Synthesis of 2,2'-bipyrroles and 2,2'-thienylpyrroles from cycloadditions of DA cyclopropanes and nitriles.



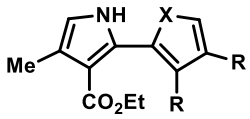
2-94 **2-99** **2-100**



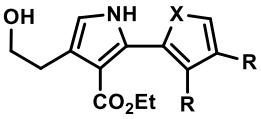
2-100a: R = H, X = NH, 67%
2-100b: R = Et, X = NH, 72%
2-100c: R = H, X = S, 61%



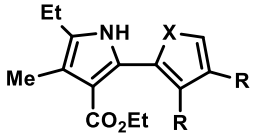
2-100d: R = H, X = NH, 81%
2-100e: R = Et, X = NH, 78%
2-100f: R = H, X = S, 52%



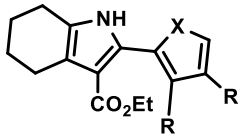
2-100g: R = H, X = NH, 45%
2-100h: R = Et, X = NH, 48%
2-100i: R = H, X = S, 75%



2-100j: R = H, X = NH, 49%
2-100k: R = Et, X = NH, 46%
2-100l: R = H, X = S, 34%

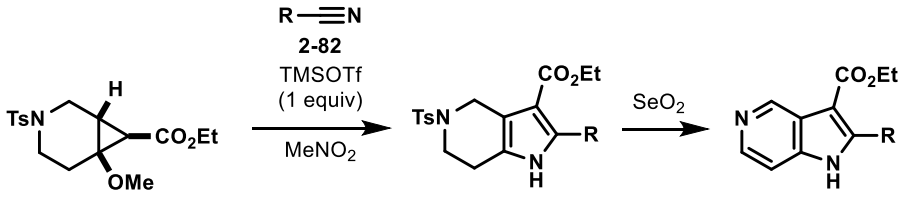


2-100m: R = H, X = NH, 85%
2-100n: R = Et, X = NH, 82%
2-100o: R = H, X = S, 52%



2-100p: R = H, X = NH, 61%
2-100q: R = Et, X = NH, 52%
2-100r: R = H, X = S, 67%

In 2010, Moustafa and Pagenkopf further developed this methodology towards the synthesis of 5-azaindoles *via* oxidation of the cycloadducts obtained through cycloadditions between functionalized DA cyclopropane **2-101** and nitriles (Scheme 2-19).[44]

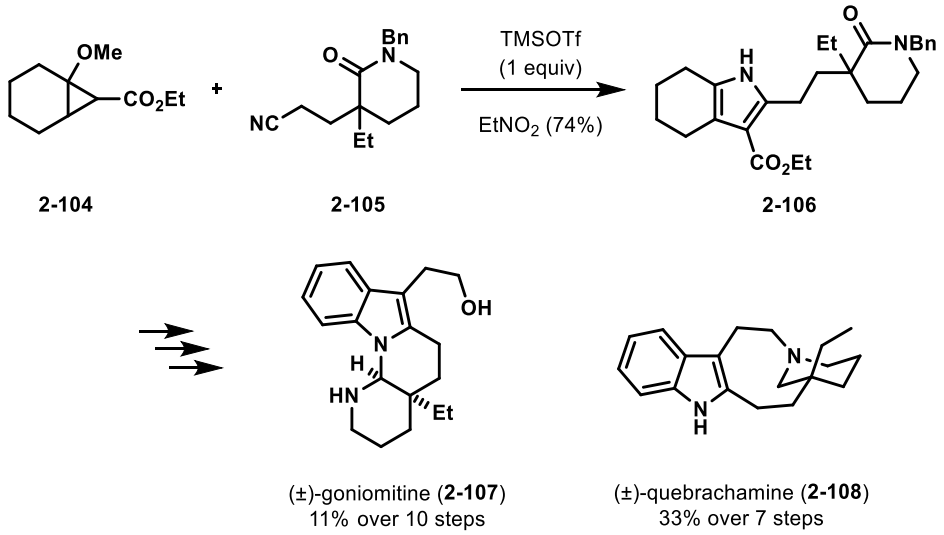


2-101 **2-102** **2-103**
6 examples
(42-87%) 2 steps

Scheme 2-19. Synthesis of 5-azaindoles from DA cyclopropane **2-101** and nitriles.

2.3.3 Application in Total Synthesis

Pagenkopf and co-workers demonstrated the utility of [3+2] cycloaddition of DA cyclopropanes and nitriles in their total syntheses of (±)-goniomitine (**2-107**)[45] and (±)-quebrachamine (**2-108**, Scheme 2-20).[46] As shown in Scheme 2-20 the [3+2] cycloaddition of DA cyclopropane **2-104** with functionalized nitrile **2-105** (which was prepared from commercially available δ-valerolactam in 48% yield over 5 steps) afforded the pyrrole **2-106** in 74% yield. This pyrrole **2-106** was then converted into (±)-goniomitine (**2-107**) in 11% yield over 10 steps. The pyrrole **2-106** was also transformed into (±)-quebrachamine (**2-108**) in 33% yield over 7 steps. Thus the syntheses of aspidosperma alkaloids (±)-goniomitine (**2-107**) and (±)-quebrachamine (**2-108**) were efficiently achieved *via* a [3+2] cycloaddition of DA cyclopropane **2-104** and nitrile **2-105**.



Scheme 2-20. Total synthesis of (±)-goniomitine (**2-107**) and (±)-quebrachamine (**2-108**) *via* [3+2] cycloaddition of DA cyclopropane **2-104** and nitrile **2-105**.

In summary, cycloadditions of DA cyclopropanes with nitriles have been revealed to be an efficient method to prepare 1-pyrrolines. The diversity oriented synthesis of pyrroles *via* [3+2] cycloaddition, dehydration and tautomerization sequence, proved to be an excellent method with a broad substrate scope. The efficiency and practicality of this method has been shown in synthesis of 2,2'-bipyrroles, 2,2'-thienylpyrroles and 5-azaindoles. Finally, this methodology has been showcased in the total synthesis of aspidosperma alkaloids (±)-goniomitine and (±)-quebrachamine.

2.4 General Introduction to Medium-sized Rings

Molecules with medium-sized rings (MRs, 8-11 atoms)[47] are present in a large number of biologically active natural products and are an important class of synthetic targets in drug discovery (Figure 2-4).[48]

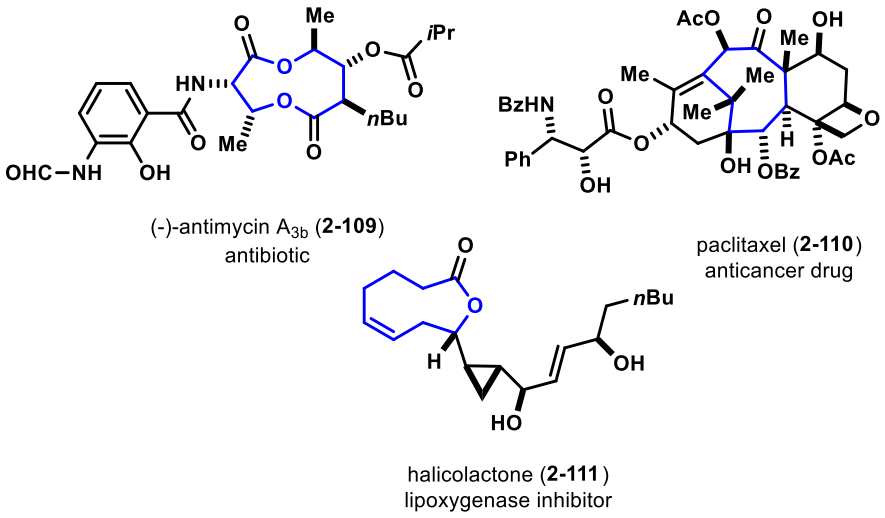


Figure 2-4. Representative examples of medium-sized rings in biologically important molecules.

In contrast to larger rings (>11 atoms), the MRs have inherent strain associated with them.[49] While Baeyer strain is predominant in small rings, transannular and Pitzer strains are severe in MRs compared to both smaller and larger rings.[50] As shown in Figure 2-5, the measured experimental strain energies for MRs are quite high compared to other cycloalkanes (exempting cyclopropane and cyclobutane).[51]

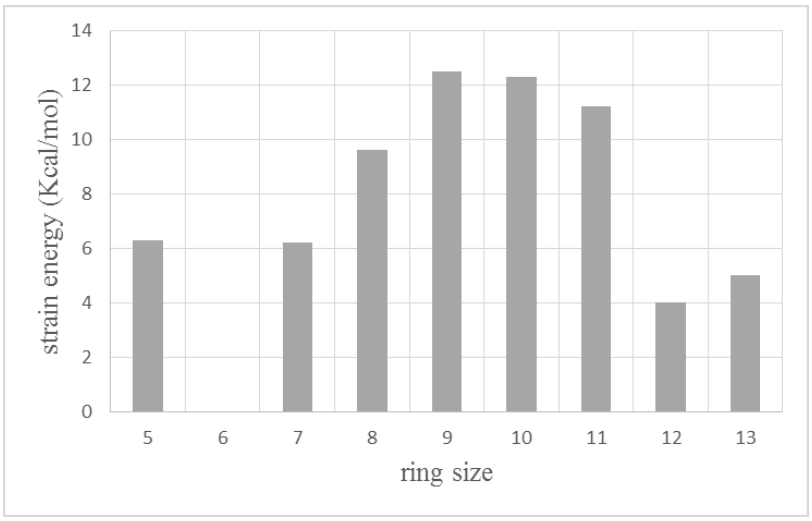
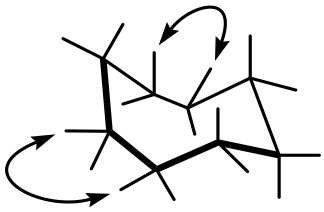


Figure 2-5. Relative strain energies of cycloalkanes.

(Energies are referenced to the chair-confirmation of cyclohexane at 0 Kcal/mol)

The conformational properties of cyclooctane have been extensively studied, and it was revealed that the conformational preference for "boat-chair" at rt is the result of avoidance of unfavorable transannular interactions at the expense of Pitzer strain (Figure 2-6).[52]



2-112

Figure 2-6. Boat-chair conformation of cyclooctane (**2-112**, eclipsed bonds shown).

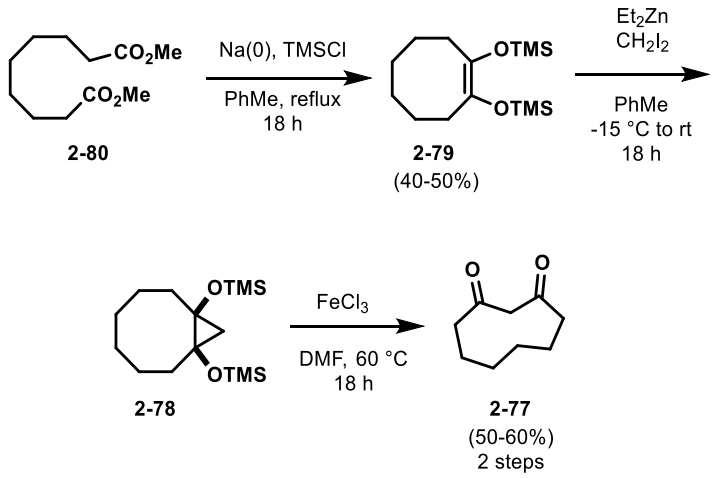
Because of these unique structural features, any synthesis of MRs must overcome both enthalpic (increasing strain in the transition state) and entropic (probability of the

chain ends meeting) energy barriers. Thus the synthesis of MRs is relatively difficult compared to smaller or larger rings.[53]

2.5 Results and Discussion

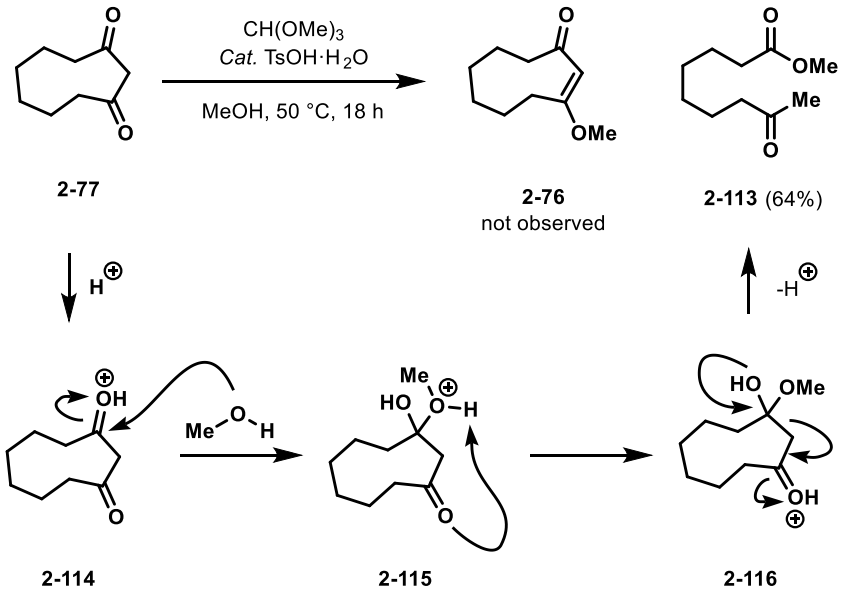
2.5.1 Attempted Synthesis DA Cyclopropane 2-74

In order to attempt the proposed synthesis (see Scheme 2-11), we set out to synthesize cyclononane-1,3-dione (**2-77**). Following a reported synthesis,[36] 1,3-dione **2-77** was prepared in ~25% yield over three steps from commercially available dimethyl octanedioate (**2-80**, Scheme 2-21). Acyloin condensation of **2-80** followed by trapping the intermediate with TMSCl afforded cyclooctene **2-79** in moderate yields. Furukawa modified Simmons-Smith cyclopropanation[54] of **2-79** followed by oxidative ring expansion with $FeCl_3$ afforded the cyclononane-1,3-dione (**2-77**).



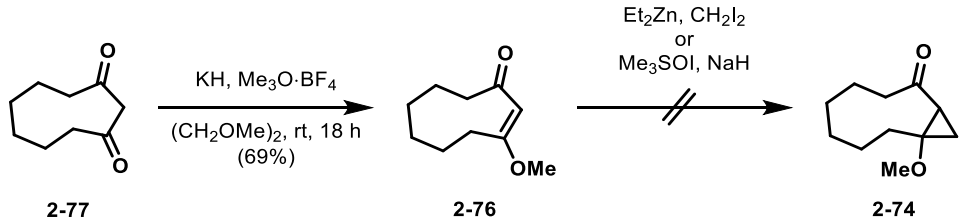
Scheme 2-21. Synthesis of cyclononane-1,3-dione (**2-77**).

Having 1,3-dione **2-77** at hand, *O*-methylation was attempted under TsOH catalyzed conditions. Disappointingly, **2-77** underwent a retro-Claisen reaction instead of *O*-methylation (Scheme 2-22). This could be due to the severe strain associated with the 9-membered ring (see Section 2.4).



Scheme 2-22. Retro-Claisen condensation of 1,3-dione **2-77**.

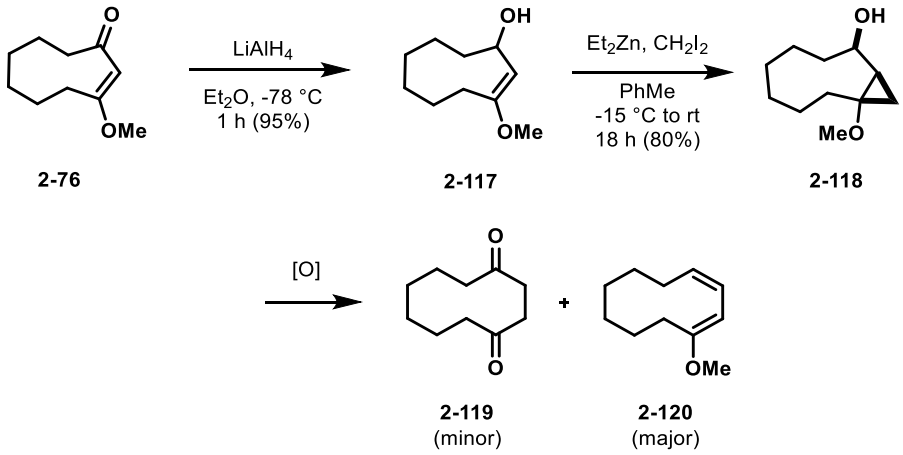
We then examined base-mediated *O*-methylation with a variety of bases and methylating agents and were pleased to find KH and methyl Meerwein salt in DME afforded the vinylogous ester **2-76** in a 69% yield (Scheme 2-23). After unsuccessful attempts at cyclopropanation of vinylogous ester **2-76**, we decided to reduce the ketone to an alcohol prior to cyclopropanation.



Scheme 2-23. *O*-Methylation of cyclononane-1,3-dione (**2-77**)

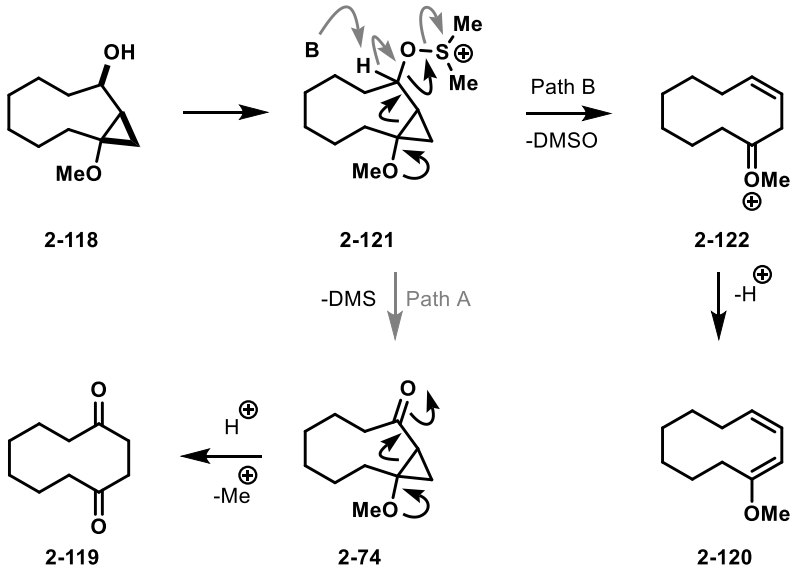
According to the revised plan (Scheme 2-24), the ketone of **2-76** was reduced to allylic alcohol **2-117** with $LiAlH_4$ in excellent yield. Furukawa modified Simmons-Smith cyclopropanation of allylic alcohol resulted in bicyclic cyclopropyl alcohol **2-118** in an

80% yield. Disappointingly, the 2° alcohol could not be oxidized back to the ketone despite extensive efforts, as only ring expansion products **2-119** and **2-120** were observed (Scheme 2-24).



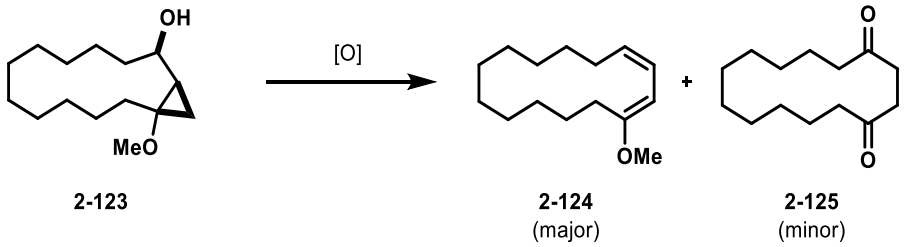
Scheme 2-24. Synthesis of bicyclic cyclopropane **2-118**.

A plausible mechanism for this ring expansion is shown in Scheme 2-25. Typical activation of cyclopropyl alcohol **2-118** (with DMSO shown in this case) results in **2-121**. Instead of undergoing deprotonation with base to yield ketone **2-74** (Path A), the more favorable pathway is ring expansion[55] to give **2-122** which eventually deprotonates to diene **2-120**. Any formation of desired ketone **2-74** quickly undergoes ring expansion to yield 1,4-diketone **2-119**.



Scheme 2-25. Proposed mechanism for the formation of ring expansion products **2-119** and **2-120**.

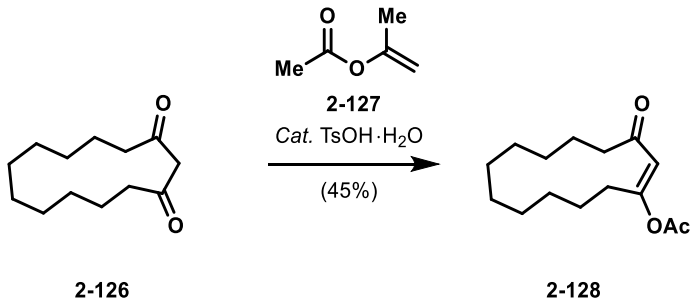
In order to investigate if this ring expansion is solely due to severe ring strain associated with medium sized ring, we wanted to examine a macrocycle. Thus, 13-membered cyclopropyl alcohol **2-123** was prepared using similar steps discussed above.[56] Unfortunately, this compound also resulted in ring expansion products as discussed above (Scheme 2-26).



Scheme 2-26. Attempted oxidation of cyclopropyl alcohol **2-123**.

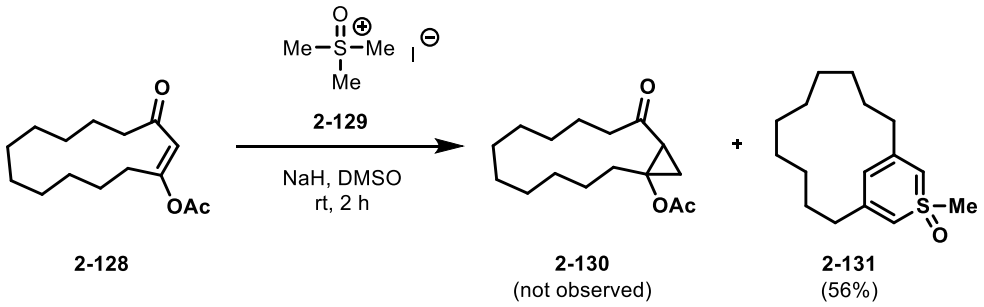
We then wanted to replace the methoxy functionality with acetoxy, hoping it would reduce the electron-density on oxygen, impeding the cyclopropane ring from

expanding (see Scheme 2-25). Thus, the cyclotridecane-1,3-dione (**2-126**) was converted into vinylogous anhydride **2-128** using isopropenyl acetate (**2-127**, Scheme 2-27).



Scheme 2-27. Acetylation of cyclotridecane-1,3-dione (**2-126**).

As **2-128** is less electron rich compared to its methoxy analogue, we attempted a Corey-Chaykovsky cyclopropanation, and were surprised to isolate thiabenzene l-oxide **2-131**.[57]



Scheme 2-28. Formation of thiabenzene 1-oxide **2-131**.

Thiabenzene 1-oxides are known in the literature since the 1960s for their appreciable aromatic conjugation,[58] and have been used in synthesis of coordination complexes.[59]

The structure of the thiabenzene **2-131** was assigned based on single crystal X-ray diffraction and the ORTEP structure is depicted in Figure 2-7.[60]

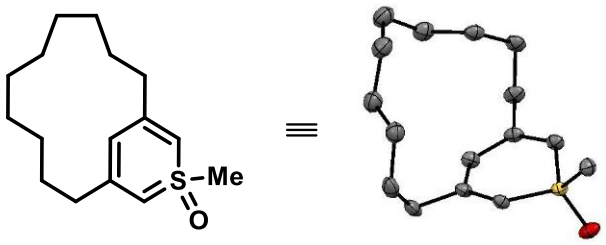
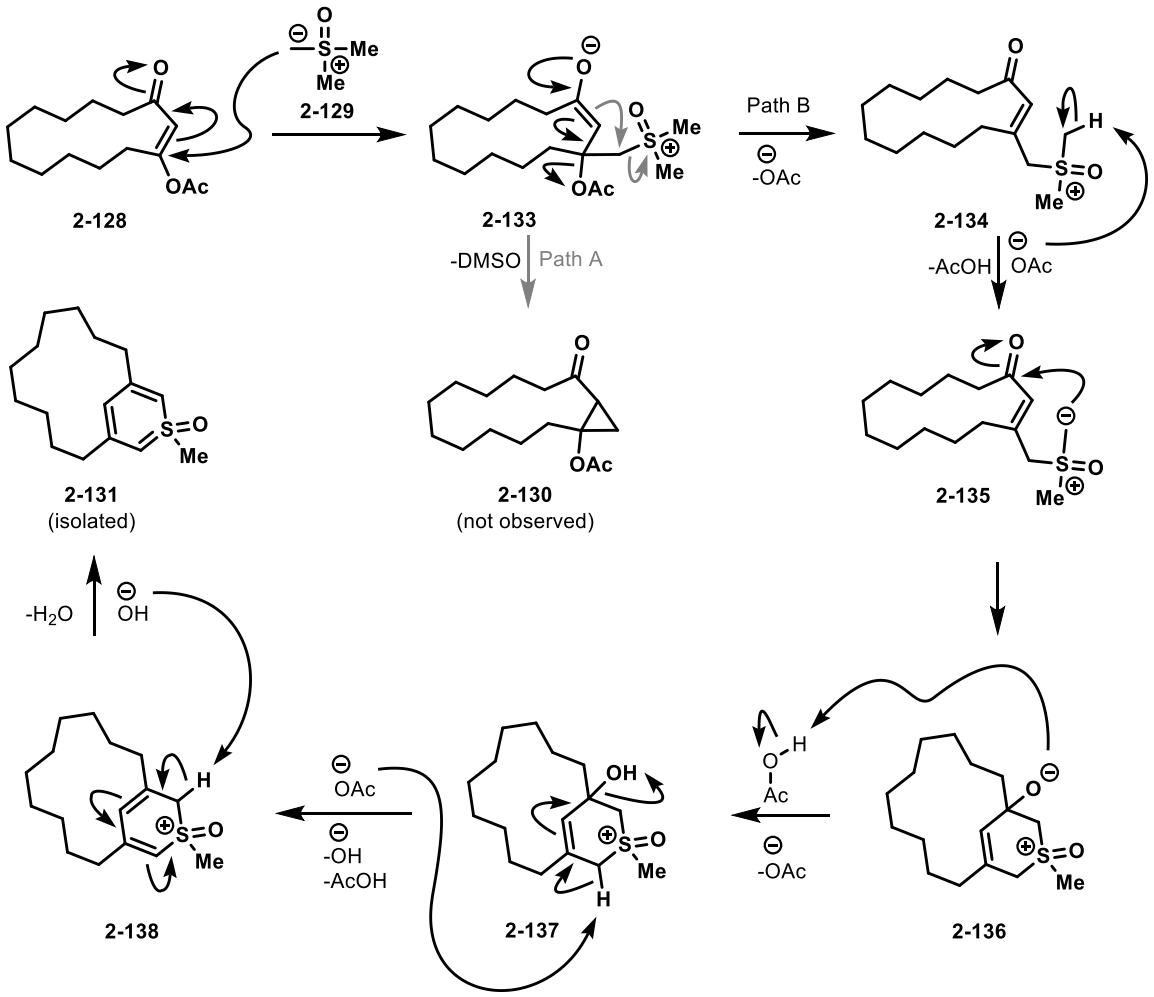


Figure 2-7. ORTEP structure of thiabenzene 1-oxide **2-131**.

A plausible mechanism accounting the formation of **2-131** is depicted in Scheme 2-29. Nucleophilic attack of the *in situ* generated ylide **2-132** on **2-128** results in intermediate **2-133**. Which instead of undergoing a ring closure to give cyclopropane **2-130** (Path A) eliminates acetate to give enone **2-134**. Deprotonation of the methyl of the sulfoxide followed by 1,2-addition on the carbonyl **2-135** results in intermediate **2-136**. Protonation of the alkoxide, followed by dehydration and aromatization results in thiabenzene 1-oxide **2-131**.

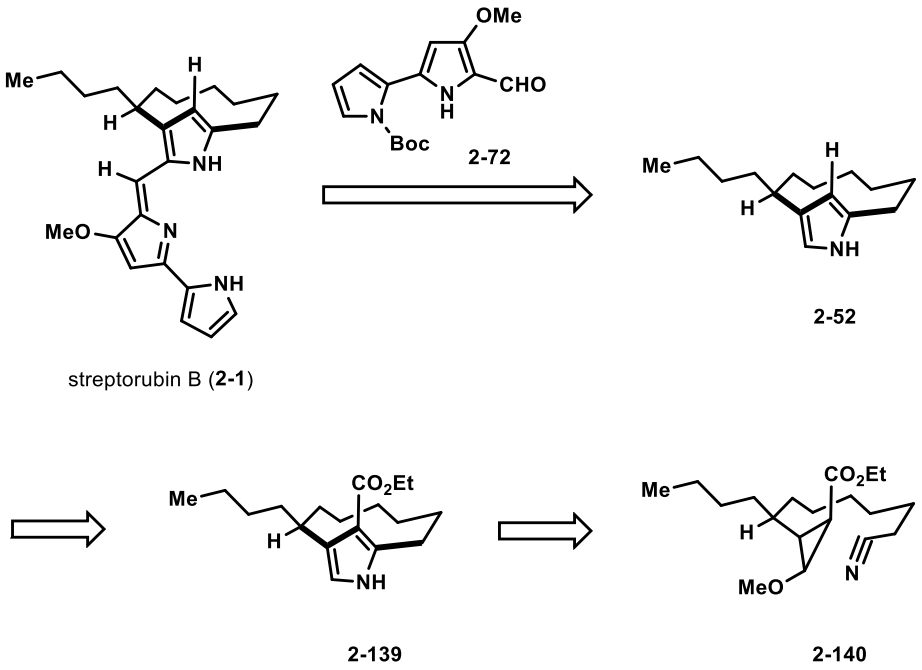


Scheme 2-29. Proposed mechanism for the formation of thiabenzene 1-oxide **2-131**.

After numerous unsuccessful attempts to oxidize the cyclopropyl alcohols **2-118** and **2-123** to bicyclic DA cyclopropanes to test our methodology, this route was terminated.

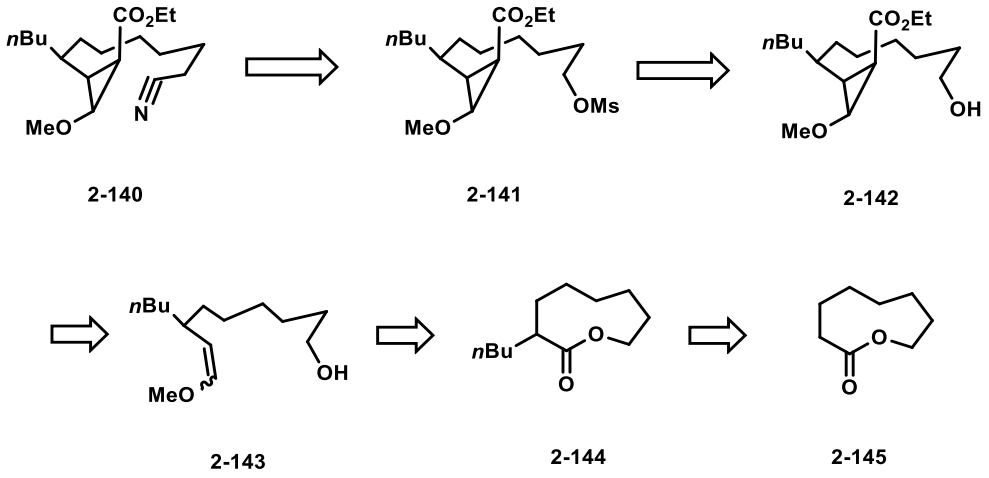
2.5.2 Progress Towards the Formal Synthesis

As our initial strategy did not allow us to try our anticipated [3+2] cycloaddition, we revised our strategy to make streptorubin B (**2-1**) *via* an intramolecular DA cyclopropane/nitrile cycloaddition (Scheme 2-30).



Scheme 2-30. Retrosynthesis of streptorubin B (**2-1**) *via* an intramolecular DA cyclopropane/nitrile cycloaddition.

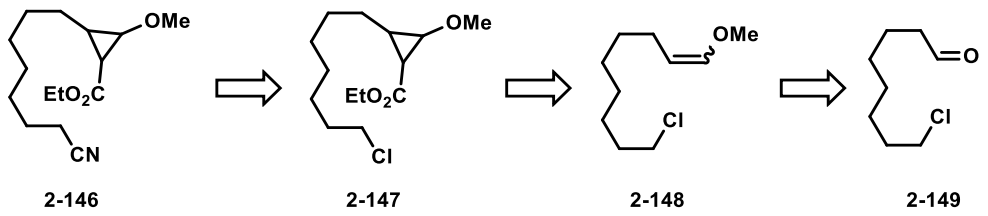
As shown in Scheme 2-30, the target can be achieved from a condensation reaction of pyrrolophane **2-52** with known aldehyde **2-72**. This has been well established by the Thompson group in their enantioselective synthesis (see Scheme 2-10). Thus, we chose pyrrolophane **2-52** as a target for our synthesis. Our idea was to proceed through an intramolecular cycloaddition of DA cyclopropane/nitrile **2-140**. Dealkoxy-carbonylation of the ester in **2-139** would result in target molecule **2-52**. Intermediate **2-140** is proposed to be made from known oxonan-2-one **2-145** (Scheme 2-31).



Scheme 2-31. Retrosynthesis of intermediate **2-140**.

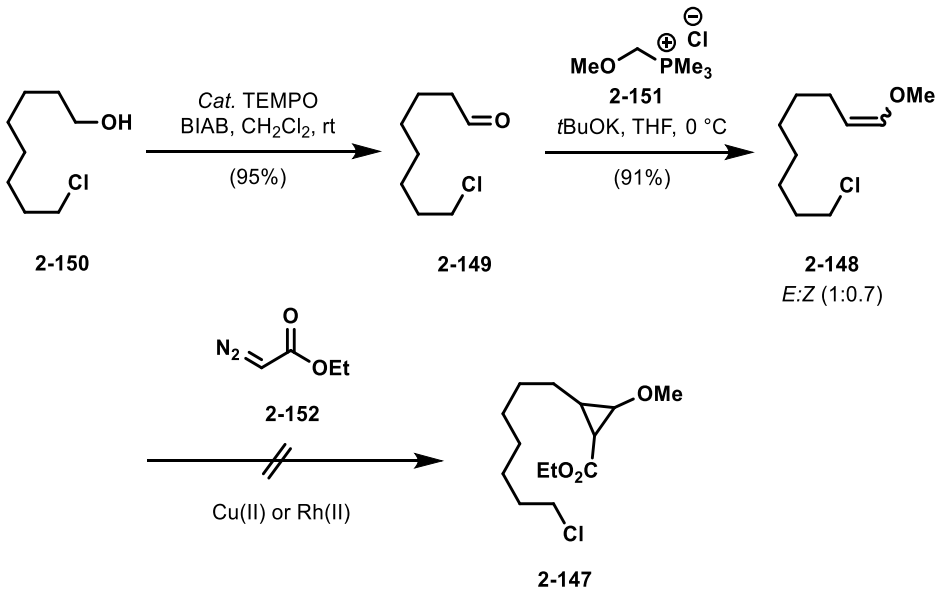
As shown in Scheme 2-31, we anticipated that the nitrile functionality could come from an S_N2 displacement of mesylated alcohol **2-141**. The DA cyclopropane could come from cyclopropanation of enol ether **2-143** with ethyl diazoacetate. Enol ether **2-143** could be made from a reductive ring opening of lactone **2-144** followed by a Wittig reaction of the resulting aldehyde. Ultimately, lactone **2-144** could be generated from a base mediated butylation of known oxonan-2-one **2-145**.

As an intramolecular variant of [3+2] cycloaddition between DA cyclopropanes and nitriles is unknown, we thought it would be practical to perform a model study prior to our intended late stage [3+2] cycloaddition. Thus, we targeted model compound **2-146**, which can be prepared from known aldehyde **2-149** *via* a Wittig reaction, cyclopropanation, followed by cyanation of alkyl chloride (**2-147**, Scheme 2-34).



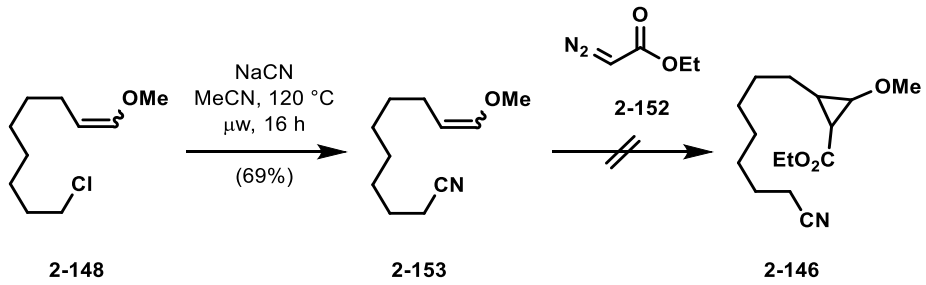
Scheme 2-32. Retrosynthesis for the model compound **2-146**.

The forward synthesis began with the oxidation of commercially available alcohol **2-150** to give aldehyde **2-149** (Scheme 2-33). Wittig reaction of the aldehyde **2-149** with the ylide *in situ* generated from **2-151** gave the enol ether **2-148** as a 1:0.7 mixture of *E* and *Z* isomers in 91% yield. Surprisingly, cyclopropanation of enol ether **2-148** with ethyl diazoacetate (**2-152**) was unsuccessful under either Cu(II) or Rh(II) catalysis.



Scheme 2-33. Attempted synthesis of cyclopropane **2-147**.

We then converted the alkyl chloride **2-148** to nitrile **2-153** and subjected it to cyclopropanation conditions. Disappointingly the cyclopropanation was unsuccessful despite a variety of conditions employed.



Scheme 2-34. Attempted synthesis of model system **2-146**.

We hypothesized having an alkyl chloride or nitrile functionality in the molecule might be causing the problem in cyclopropanation, and thus we decided to pursue the originally proposed strategy towards streptorubin B (see Scheme 2-30 and Scheme 2-31). But, unfortunately, due to time constraints this project was suspended.

2.6 Conclusions and Outlook

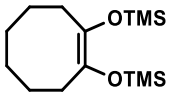
Unfortunately, we never got to try our anticipated [3+2] cycloaddition of DA cyclopropane and nitrile towards the synthesis of streptorubin B. Herein we described the two different strategies investigated towards the synthesis of streptorubin B. Although the synthesis was not complete, the described synthesis of bicyclic cyclopropyl alcohols, **2-118** and **2-123**, could potentially be of use for future studies. The proposed formal synthesis seems much simpler, but many challenging synthetic steps need to be overcome. The intramolecular cycloaddition of DA cyclopropanes/nitriles, if ideally executed, could be an efficient way to make pyrrole macrocycles.

2.7 Experimental

2.7.1 General Considerations

Same as in section 1.4.1.

2.7.2 Experimental Procedures and Characterization Data



Compound 2-79

Following literature protocol,[61] a three neck round bottom flask (RBF) containing a magnetic stir bar was fitted with a Liebig condenser and a pressurized addition funnel. The system was flame dried under vacuum and purged with argon twice. Toluene (600 mL) was charged into the flask through the third neck of the flask followed by pentane washed sodium (24.00 g, 1043.93 mmol, 4.8 equiv) in pieces. The solution was refluxed for about 1 h to produce a sodium dispersion. The addition funnel was charged with toluene (200 mL), dimethyl suberate (50.00 g, 217.10 mmol, 1 equiv), and chlorotrimethylsilane (152 mL, 1197.64 mmol, 5.5 equiv). The solution in the addition funnel was mixed *via* argon ebullition and added dropwise over 3 h to the refluxing RM, with stirring. The RM turned purple upon addition. After addition, stirring and reflux were continued for 16 h. After being cooled to rt, the mixture was vacuum filtered through a plug of glass wool and then vacuum filtered through a pad of Celite® (3 cm) on a glass frit to remove residual sodium particles (about 200 mL of hexane/s were used for washings). The resulting light yellow filtrate was distilled to yield the title compound as a colorless oil (31.65 g, 0.11 mol, 51%): bp 92-97 °C/1 mbar.

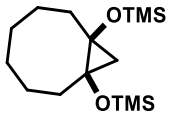
R_f = 0.29 (10% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 2.14 - 2.19 (m, 4 H), 1.56 - 1.62 (m, 4 H), 1.49 - 1.54 (m,

4 H), 0.18 (s, 18 H).

^{13}C NMR (151 MHz, $CDCl_3$) δ 133.1, 31.2, 28.8, 26.4, 1.1.

^{1}H and ^{13}C NMR spectra were in agreement with previously reported data.[61]



Compound 2-78

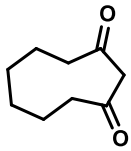
Following literature protocol,[36b] to a degassed solution of **2-79** (63.30 g, 0.221 mol, 1.0 equiv) and CH_2I_2 (159.75 g, 0.596 mol, 2.7 equiv) in toluene (750 mL) at -15 °C, was slowly added (over a period of 1 h) a solution of Et_2Zn (79.12 g, 0.64 mol, 2.9 equiv)[62] in toluene (250 mL). After addition, the RM was stirred for 1 h, then warmed up to rt, and stirred for about 16 h. The RM was then cooled to -15 °C and carefully was added a satd. NH_4Cl aq solution (300 mL). Salts filtered by passing through a pad of Celite® (5 cm) and washing with ether (200 mL). Layers separated, and aq layer extracted with ether (2 x 300 mL). Combined organic extractions were dried over anhyd. $MgSO_4$, filtered, and concentrated *in vacuo*. The resulting pale yellow oil was distilled to yield the title compound as a colorless oil (54.00 g, 0.18 mol, 81%): bp 110-115 °C/1 mbar.

R_f = 0.59 (10% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 2.13 (dt, *J* = 14.8, 3.7 Hz, 2 H), 1.72 – 1.80 (m, 2 H), 1.57 – 1.65 (m, 2 H), 1.27 – 1.35 (m, 4 H), 1.09 (ddd, *J* = 15.1, 13.1, 3.5 Hz, 2 H), 0.76 (d, *J* = 6.5 Hz, 1 H), 0.38 (d, *J* = 6.5 Hz, 1 H), 0.16 (s, 18 H).

^{13}C NMR (151 MHz, $CDCl_3$) δ 59.9, 34.9, 26.3, 25.5, 24.7, 1.4.

^{1}H NMR spectrum was in agreement with previously reported data.[36b]



Compound 2-77

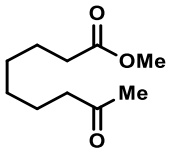
Following literature protocol,[63] to a degassed solution of **2-78** (54.00 g, 0.180 mol, 1.0 equiv) in DMF (540 mL) at rt, was added anhyd. $FeCl_3$ (64.11 g, 0.395 mol, 2.2 equiv) in 10 equal portions. After addition, the RM was heated to 60 °C and maintained for 18 h. RM then cooled down to rt and transferred into a vigorously stirring aq solution of 1 N HCl (500 mL) and stirred for 3 h. RM then extracted with $CHCl_3$ (2 x 500 mL, 2 x 250 mL), dried over anhyd. $MgSO_4$, and concentrated *in vacuo*. The crude compound was then purified on silica gel flash chromatography (15% EtOAc/hexanes) to afford the title compound as a pale brown syrup (19.10 g, 0.12 mol, 69%).

$\mathbf{R_f}$ = 0.28 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 3.68 (s, 2 H), 2.52 – 2.56 (m, 4 H), 1.77 – 1.84 (m, 4 H), 1.43 – 1.49 (m, 4 H).

^{13}C NMR (151 MHz, $CDCl_3$) δ 204.9, 61.3, 42.4, 25.1, 23.5.

^{1}H NMR spectrum was in agreement with previously reported data.[63]



Compound 2-113

To a solution of **2-77** (260 mg, 1.69 mmol, 1 equiv) and $CH(OMe)_3$ (197 mg, 1.86 mmol, 1.1 equiv) in MeOH (1 mL) at rt, was added $TsOH{\cdot}H_2O$ (3 mg, 0.02 mmol, 0.01 equiv).

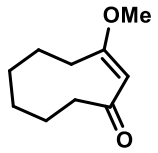
RM was then heated to 50 °C and maintained for 5 h. Cooled down to rt, concentrated *in vacuo,* and the residue was diluted in CH_2Cl_2 (2 mL) and passed through a plug of silica gel and concentrated *in vacuo*. The crude compound purified on silica gel flash chromatography (15% EtOAc/hexanes) to afford the title compound as a color less oil (200 mg, 1.07 mmol, 64%).

R_f = 0.24 (20% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 3.66 (s, 3 H), 2.42 (t, *J* = 7.3 Hz, 2 H), 2.30 (t, *J* = 7.6 Hz, 2 H), 2.13 (s, 3 H), 1.54 – 1.66 (m, 4 H), 1.27 – 1.36 (m, 4 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 208.5, 173.7, 51.0, 43.2, 33.6, 29.5, 28.5, 28.4, 24.4, 23.2.

^{1}H NMR spectrum was in agreement with previously reported data.[64]



Compound 2-76

To a suspension of KH [(30% in mineral oil) 5.20 g, 38.91 mmol, 2 equiv] in a RBF at 0 °C was slowly added DME (90 mL). To this dark brown RM, was slowly added a solution of **2-77** (3.00 g, 19.45 mmol, 1.0 equiv) in DME (10 mL) (syringe pump addition, 0.5 mL/min). After addition, the RM stirred at the same temp for about 10 min, then warmed up to rt and stirred for 1 h.[65] RM then cooled down to 0 °C, at which time a fine powder of $Me_3O{\cdot}BF_4$ (5.75 g, 38.90 mmol, 2.0 equiv) was added in 2 equal portions with a 5 min interval. After addition, RM was stirred at the same temp for 1 h, and at rt for 14 h. Cooled down to 0 °C and carefully was added H_2O (30 mL). Warmed up to rt,

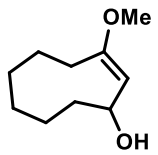
stirred for 15 min, DME removed *in vacuo,* and aq layer extracted into EtOAc (50 mL, 2 x 25 mL). Combined organic extractions were dried over anhyd. $MgSO_4$ and concentrated *in vacuo*. The crude compound was purified on silica gel flash chromatography (0-20% EtOAc/hexanes) to afford the title compound as a pale brown oil, which turned into a cake upon cooling in the freezer at around -5 °C (2.27 g, 13.49 mmol, 69%).

R_f = 0.29 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 5.48 (s, 1 H), 3.61 (s, 3 H), 2.72 (dt, *J* = 9.1, 3.1 Hz, 4 H), 1.75 – 1.84 (m, 2 H), 1.55 – 1.68 (m, 4 H), 1.44 – 1.52 (m, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 203.7, 172.8, 107.3, 55.4, 40.6, 31.2, 29.1, 28.7, 26.7, 25.0.

HRMS (*m/z*): 168.1147 (Calcd for $C_{10}H_{16}O_2$, 168.1150).



Compound 2-117

Following literature protocol,[66] to a suspension of $LiAlH_4$ (1.96 g, 51.65 mmol, 1.1 equiv) in Et_2O (100 mL) at -78 °C was added a solution of **2-76** (7.90 g, 46.96 mmol, 1.0 equiv) in Et_2O (50 mL) over a period of 1 h. After addition, RM stirred at the same temp for 1 h and carefully was added H_2O (3 mL) followed by 10% aq NaOH (2 mL) and finally with more H_2O (10 mL). RM then warmed up to rt and stirred until the RM turned into a white slurry. Salts filtered by passing through a pad of Celite® (3 cm) washing with Et_2O (20 mL). Et_2O dried over anhyd. $MgSO_4$ and concentrated *in vacuo* to afford the title compound as a pale yellow syrup (7.50 g, 44.05 mmol, 94%) which was

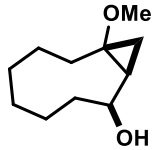
reasonably pure and forwarded to next step without further purification.

R_f = 0.32 (50% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 4.61 (td, *J* = 9.0, 4.4 Hz, 1 H), 4.39 (d, *J* = 8.8 Hz, 1 H), 3.52 (s, 3 H), 2.23 – 2.30 (m, 1 H), 2.12 – 2.18 (m, 1 H), 1.79 – 1.87 (m, 1 H), 1.67 – 1.77 (m, 2 H), 1.49 – 1.57 (m, 3 H), 1.41 – 1.49 (m, 3 H), 1.32 – 1.41 (m, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 158.3, 101.0, 70.0, 54.4, 37.7, 32.1, 27.2, 27.0, 24.8, 23.5.

HRMS (*m/z*): 170.1308 (Calcd for $C_{10}H_{18}O_2$, 170.1307).



Compound 2-118

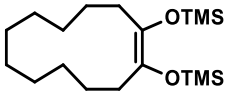
Following literature protocol,[67] to a degassed solution of **2-117** (7.50 g, 44.05 mol, 1.0 equiv) and CH_2I_2 (35.40 g, 132.16 mol, 3.0 equiv) in toluene (130 mL) at -15 °C, was slowly added (over a period of 1 h) a solution of Et_2Zn (16.32 g, 132.16 mol, 3.0 equiv) in toluene (120 mL). After addition, the RM was stirred for 1 h, then warmed up to rt, and stirred for about 18 h. The RM was then cooled to -15 °C and carefully added a half satd. NH_4Cl aq solution (250 mL). RM warmed up to rt, and stirred for 15 min. Salts filtered by passing through a pad of Celite® (5 cm) washing with ether (200 mL). Layers separated, and aq layer extracted with ether (2 x 300 mL). Combined organic extractions were dried over anhyd. $MgSO_4$ and concentrated *in vacuo*. The residue was purified on silica gel flash chromatography (0-20% EtOAc/hexanes, buffered with 1% Et_3N) to afford the title compound as a pale yellow syrup (6.50 g, 35.27 mmol, 80%).

R_f = 0.19 (50% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 3.41 (td, *J* = 10.3, 4.1 Hz, 1 H), 3.23 (s, 3 H), 2.56 (ddd, *J* = 15.8, 7.0, 1.2 Hz, 1 H), 1.79 – 1.87 (m, 2 H), 1.65 – 1.77 (m, 2 H), 1.48 – 1.65 (m, 4 H), 1.33 – 1.41 (m, 1 H), 1.19 – 1.28 (m, 1 H), 1.17 (td, *J* = 10.1, 6.8 Hz, 1 H), 0.93 (ddd, *J* = 15.8, 10.6, 2.4 Hz, 1 H), 0.88 (dd, *J* = 10.0, 5.3 Hz, 1 H), 0.16 (dd, *J* = 7.0, 5.3 Hz, 1 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 72.8, 64.7, 52.8, 37.2, 34.4, 29.6, 27.8, 26.4, 21.6, 20.1, 13.9.

HRMS (*m/z*): 184.1461 (Calcd for $C_{11}H_{20}O_2$, 184.1463).



Compound 2-154

Following literature protocol,[36b] a three neck round bottom flask containing a magnetic stir bar was fitted with a Liebig condenser and a pressurized addition funnel. The system was flame dried under vacuum and purged with argon twice. Xylenes (900 mL) was charged into the flask through the third neck of the flask followed by pentane washed sodium (24.00 g, 1043.93 mmol, 5.4 equiv) in pieces. The solution was heated to 100 °C and maintained for about 1 h to produce a sodium dispersion. The pressurized addition funnel was charged with xylenes (300 mL), dimethyl dodecanedioate[68] (50.00 g, 193.53 mmol, 1 equiv), and chlorotrimethylsilane (115.64 g, 1064.41 mmol, 5.5 equiv). The solution in the addition funnel was mixed *via* argon ebullition and then added dropwise over 6 h to the RM, with stirring. The RM turned pale brown upon addition. After addition, RM heated to reflux and maintained for 4 h before being cooled to rt. The

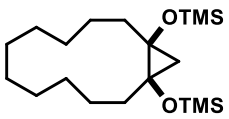
mixture was vacuum filtered through a plug of glass wool and then vacuum filtered through a pad of Celite® (3 cm) on a glass frit to remove residual sodium particles (about 200 mL of hexane/s were used for washings). The resulting brownish yellow filtrate was distilled to yield the title compound as a colorless oil (23.50 g, 68.67 mmol, 35%): bp 125-135 °C/1.5 mbar.

R_f = 0.29 (10% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 2.09 - 2.12 (t, *J* = 7.0 Hz, 4 H), 1.52 - 1.57 (m, 4 H), 1.35 - 1.38 (m, 8 H), 1.26 - 1.32 (m, 4 H), 0.18 (s, 18 H).

HRMS (*m/z*): 342.2416 (Calcd for $C_{18}H_{38}O_2Si_2$, 342.2410).

^{1}H spectrum was in agreement with previously reported data.[36b]



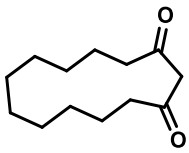
Compound 2-155

Following literature protocol,[36b] to a degassed solution of **2-154** (30.00 g, 0.088 mol, 1.0 equiv) and CH_2I_2 (63.39 g, 0.268 mol, 2.7 equiv) in toluene (260 mL) at -15 °C, was slowly added (over a period of 1 h) a solution of Et_2Zn (31.40 g, 0.254 mol, 2.9 equiv) in toluene (160 mL). After addition, the RM was stirred for 1 h, then warmed up to rt, and stirred for about 12 h. The RM was then cooled to -15 °C and carefully was added a satd. aq solution of NH_4Cl (300 mL). RM warmed up to rt and stirred for 30 min. Salts filtered by passing through a pad of Celite® (5 cm) washing with ether (200 mL). Layers separated, and aq layer extracted with ether (2 x 300 mL). Combined organic extractions were dried over anhyd. $MgSO_4$ and concentrated *in vacuo* to afford the title compound as a pale yellow oil in reasonable purity (31.00 g, 0.087 mol, 98% crude yield). The crude

compound was directly forwarded to next step without further purification.

^{1}H NMR (600 MHz, $CDCl_3$) δ 1.77 – 1.87 (m, 4 H), 1.20 – 1.64 (m, 16 H), 0.81 (d, *J* = 6.5 Hz, 1 H), 0.44 (d, *J* = 6.5 Hz, 1 H). 0.17 (s, 18 H).

^{1}H spectrum was in agreement with previously reported data.[36b]



Compound 2-126

Following literature protocol,[36b] to a degassed solution of **2-155** (31.00 g, 0.087 mol, 1.0 equiv) in DMF (300 mL) at rt, was added anhyd. $FeCl_3$ (31.01 g, 0.191 mol, 2.2 equiv) in 10 equal portions. After addition, RM heated to 60 °C and maintained for 14 h. RM then cooled down to rt and transferred into a vigorously stirring aq solution of 1 N HCl (300 mL) and stirred for 3 h. RM then extracted with $CHCl_3$ (2 x 200 mL, 2 x 100 mL). Combined organic extractions were dried over $MgSO_4$, concentrated *in vacuo* and the residue purified on silica gel flash chromatography (15% EtOAc/hexanes) to afford the title compound as a pale brown syrup (0.3:1 mixture of keto, enol tautomers, 16.60 g, 0.079 mol, 90%).

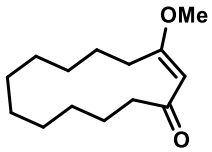
R_f = 0.45 (20% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$)

Signals correspond to keto-tautomer: δ 3.60 (s, 2 H), 2.59 - 2.63 (m, 4 H), 1.66 (dt, *J* = 11.9, 6.1 Hz, 4 H), 1.36 (quin, *J* = 6.6 Hz, 8 H), 1.01 – 110 (m, 4 H).

Signals correspond to enol-tautomer: δ 5.70 (s, 1 H), 2.26 – 2.31 (m, 4 H), 1.69 – 1.74 (m, 4 H), 1.20 – 1.32 (m, 12 H).

^{1}H NMR spectrum was in agreement with previously reported data.[63]



Compound 2-156

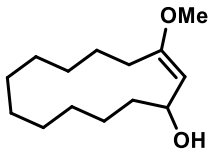
To a solution of **2-126** (3.10 g, 14.74 mmol, 1.0 equiv) and $CH(OMe)_3$ (1.72 g, 16.22 mmol, 1.1 equiv) in MeOH (15 mL) at 0 °C, was added $TsOH \cdot H_2O$ (28 mg, 0.15 mmol, 0.01 equiv). RM was stirred at the same temp for 1 h, and warmed up to rt. After the RM was stirred for 18 h, was carefully added a 15% aq solution of NaOH (0.2 mL), and passed through a pad of Celite® washing with Et_2O (10 mL). Solvents dried over anhyd. $MgSO_4$, concentrated *in vacuo,* and the residue was purified on silica gel flash chromatography (5% EtOAc/hexanes) to afford the title compound as a bright greenish yellow oil (1.65 g, 7.35 mmol, 50%).

R_f = 0.50 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 5.53 (s, 1 H), 3.65 (s, 3 H), 2.88 – 2.94 (m, 2 H), 2.35 – 2.40 (m, 2 H), 1.71 – 1.79 (m, 2 H), 1.55 – 1.63 (m, 2 H), 1.36 – 1.45 (m, 2 H), 1.16 – 1.32 (m, 10 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 201.8, 175.1, 100.9, 55.2, 45.5, 29.0, 28.0, 27.1, 26.5, 25.7, 25.5, 24.7, 24.6, 23.7.

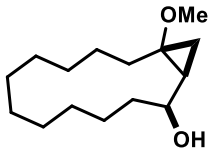
HRMS (*m/z*): 224.1778 (Calcd for $C_{14}H_{24}O_2$, 224.1776).



Compound 2-157

To a suspension of $LiAlH_4$ (127 mg, 3.35 mmol, 1.0 equiv) in Et_2O (9 mL) at -78 °C was added a solution of **2-156** (750 mg, 3.34 mmol, 1.0 equiv) in Et_2O (4 mL) over a period of 30 min. After addition, RM stirred at the same temp for 1.5 h and carefully was added H_2O (0.5 mL), followed by 10% aq solution of NaOH (0.5 mL), and finally an additional H_2O (1 mL). RM then warmed up to rt and stirred until the RM turned into a white slurry. Salts filtered by passing through a pad of Celite® (2 cm) washing with Et_2O (10 mL). Et_2O dried over anhyd. $MgSO_4$ and concentrated *in vacuo* to afford the title compound as a pale yellow syrup which was carried forward to next step without further purification.[69]

$\mathbf{R_f}$ = 0.31 (30% EtOAc/hexanes).



Compound 2-123

To a degassed solution of **2-157** (1.00 g, 4.42 mmol, 1.0 equiv) and CH_2I_2 (3.20 g, 11.93 mmol, 2.7 equiv) in toluene (10 mL) at -15 °C, was slowly added (over a period of 1 h) a solution of Et_2Zn (1.47 g, 11.93 mmol, 2.7 equiv) in toluene (10 mL). After addition, stirred the cloudy RM for 30 min, then warmed up to rt, and stirred for about 18 h. The RM was then cooled to -15 °C and carefully was added a half satd. aq solution of NH_4Cl (20 mL), warmed up to rt, and stirred for 5 min. Salts filtered by passing through a pad of

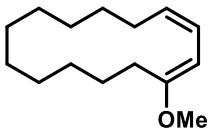
Celite® (3 cm) washing with ether (20 mL). Layers separated, and aq layer extracted with ether (2 x 15 mL). Combined organic extractions were dried over anhyd. $MgSO_4$ and concentrated *in vacuo*. The residue was purified on silica gel flash chromatography (0-20% EtOAc/hexanes, buffered with 1% Et_3N) to afford the title compound as an off white paste (350 mg, 1.46 mmol, 33% from crude **2-124**).

R_f = 0.43 (50% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 3.22 (s, 3 H), 3.14 (td, *J* = 9.7, 1.8 Hz, 1 H), 2.30 (ddd, *J* = 15.0, 11.5, 5.5 Hz, 1 H), 1.77 – 1.85 (m, 1 H), 1.58 – 1.65 (m, 2 H), 1.38 – 1.57 (m, 6 H), 1.27 – 1.38 (m, 8 H), 1.17 – 1.27 (m, 3 H), 1.00 – 1.06 (m, 1 H), 0.90 (dd, *J* = 10.3, 5.6 Hz, 1 H), 0.33 (dd, *J* = 7.0, 5.3 Hz, 1 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 72.2, 65.8, 53.0, 36.1, 33.1, 29.6, 27.0, 25.5, 25.5, 25.2, 25.0, 24.4, 24.4, 23.5, 15.4.

HRMS (*m/z*): 240.2082 (Calcd for $C_{15}H_{28}O_2$, 240.2089).



Compound 2-124

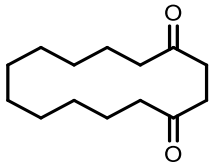
Following literature protocol,[70] to a solution of $(COCl)_2$ (158 mg, 1.25 mmol, 1.5 equiv) in CH_2Cl_2 (4 mL) at -78 °C was added dropwise, a solution of DMSO (162 mg, 2.07 mmol, 2.5 equiv) in CH_2Cl_2 (1 mL). The RM was stirred for 10 min, then a solution of **2-123** (200 mg, 0.83 mmol, 1.0 equiv) in CH_2Cl_2 (1 mL) was added dropwise (syringe pump addition, 0.05 mL/min). After addition, the RM was stirred for 30 min, then Et_3N (420 mg, 4.15 mmol, 5.0 equiv) was slowly added. Stirring continued for an additional 15 min, warmed up to rt, and H_2O (10 mL) was added. Layers separated, aq layer extracted

with CH_2Cl_2 (2 x 10 mL), combined organic extractions were dried over anhyd. $MgSO_4$, and concentrated *in vacuo*. The residue was purified on silica gel flash chromatography (0-15% EtOAc/hexanes, buffered with 1% Et_3N) to afford the title compound as a pale yellow oil (52 mg, 0.23 mmol, 28%).

R_f = 0.78 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 6.17 (app ddt, *J* = 15.1, 10.6, 1.3 Hz, 1 H), 5.33 (d, *J* = 10.6 Hz, 1 H), 5.28 (dt, *J* = 15.0, 7.2 Hz, 1 H), 3.55 (s, 3 H), 2.31 – 2.35 (m, 2 H), 2.16 (app dq, *J* =7.1, 1.2 Hz, 2 H), 1.54 - 1.60 (m, 2 H), 1.43 – 1.49 (m, 2 H), 1.34 – 1.39 (m, 2 H), 1.18 – 1.31 (m, 10 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 157.8, 127.7, 126.3, 99.9, 54.2, 30.3, 27.4, 27.2, 26.5, 26.2, 26.0, 25.6, 25.1, 23.7, 23.1.



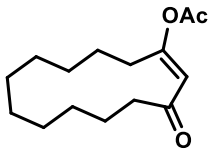
Compound 2-125

The title compound was isolated along with **2-124** as an off white paste (25 mg, 0.11 mmol, 13%).

R_f = 0.42 (30% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 2.71 (s, 4 H), 2.48 (t, *J* = 6.3 Hz, 4 H), 1.66 (quin, *J* = 6.3 Hz, 4 H), 1.31 - 1.22 (m, 8 H), 1.18 - 1.12 (m, 4 H).

^{1}H NMR spectrum was in agreement with previously reported data.[71]



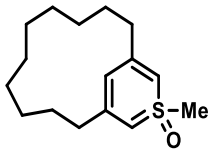
Compound 2-128

Following literature protocol,[72] to a mixture of **2-126** (470 mg, 2.24 mmol, 1 equiv) and isopropenyl acetate (**2-127**, 1.57 g, 15.64 mmol, 7 equiv) at rt was added a few crystals of $TsOH \cdot H_2O$. RM was then heated to reflux and maintained for 2 h. Cooled to rt, diluted with CH_2Cl_2 (15 mL), and washed with ice cold Satd. aq solution of $NaHCO_3$. Combined organic extractions were dried over anhyd. $MgSO_4$, and concentrated *in vacuo*. The resulting purple syrup was purified on silica gel flash chromatography (10% EtOAc/hexanes) to afford the title compound as a yellow syrup (254 mg, 1.07 mmol, 45%).

R_f = 0.69 (20% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 6.09 (s, 1 H), 2.34 (s, br, 4 H), 2.26 (s, br, 3 H), 1.67 (s, br, 4 H), 1.34 (s, br, 12 H).

HRMS (*m/z*): 252.1721 (Calcd for $C_{15}H_{24}O_3$, 252.1725).



Compound 2-131

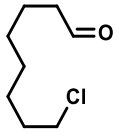
To a slurry of Me_3SOI (156 mg, 0.71 mmol, 1.2 equiv) in DMSO (1 mL) at rt was added NaH (60% w/w in mineral oil, 35 mg, 0.88 mmol, 1.5 equiv). Stirred the RM for 1 h, then a solution of **2-128** (140 mg, 0.59 mmol, 1 equiv) in DMSO (1 mL) was added dropwise.

The RM was stirred for an additional 18 h, then H_2O (10 mL) was slowly added. RM extracted into EtOAc (2 x 15 mL), dried over anhyd. $MgSO_4$, and concentrated *in vacuo*. The resulting yellow oil was purified on silica gel flash chromatography (50% EtOAc/hexanes) to afford the title compound as an off white fluffy material (99 mg, 0.37 mmol, 56%).

R_f = 0.22 (30% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) δ 5.63 (s, 1 H), 5.29 (s, 2 H), 3.45 (s, 3 H), 2.45 (t, *J* = 6.5 Hz, 4 H), 1.61 - 1.71 (m, 4 H), 1.12 - 1.30 (m, 10 H), 1.05 - 1.12 (m, 2 H).

^{13}C NMR (101 MHz, $CDCl_3$) δ 147.6, 104.9, 83.4, 50.6, 36.7, 27.4, 26.8, 26.2, 25.3.



Compound 2-149

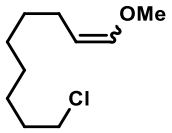
Following literature protocol,[73] to a mixture of **2-150** (11.00 g, 66.80 mmol, 1 equiv) and TEMPO (1.05 g, 6.72 mmol, 0.1 equiv) in CH_2Cl_2 (110 mL) at rt was added BIAB (25.00 g, 77.62 mmol, 1.2 equiv). Stirred the RM at rt until **2-150** was completely consumed (by TLC). The RM was washed with satd. aq solution of $Na_2S_2O_3$ (100 mL), layers separated, and aq layer again extracted with CH_2Cl_2 (2 x 100 mL). Combined organic extractions were washed with satd. aq $NaHCO_3$ (100 mL), dried over MgSO4, and concentrated *in vacuo*. The residue was then purified on silica gel flash chromatography (0-5% EtOAc/hexanes) to afford the title compound as a yellow oil (10.32 g, 63.45 mmol, 95%).

R_f = 0.42 (20% EtOAc/hexanes).

^{1}H NMR (400 MHz, $CDCl_3$) δ 9.77 (t, *J* = 1.8 Hz, 1 H), 3.53 (t, *J* = 6.6 Hz, 2 H), 2.43 (td, *J* = 7.3, 1.8 Hz, 2 H), 1.73 – 1.81 (m, 2 H), 1.59 – 1.68 (m, 2 H), 1.40 – 1.49 (m, 2

H), 1.32 – 1.37 (m, 4 H).

^{1}H NMR spectrum was in agreement with previously reported data.[73]



Compound 2-148

Following literature protocol,[74] to a suspension of the salt **2-151** (6.32 g, 18.44 mmol, 1.2 equiv) in THF (45 mL) at -78 °C was added a solution of *t*BuOK (2.25 g, 20.05 mmol, 1.3 equiv) in THF (10 mL). RM was then slowly warmed up to rt, stirred for 1 h, and cooled back to -78 °C. To this cold RM was slowly added, a solution of **2-149** (2.50 g, 15.37 mmol, 1.0 equiv) in THF (10 mL). After addition, RM slowly warmed up to rt, and stirred for 14 h before concentrating *in vacuo.* The residue was dissolved in Et_2O (50 mL) and washed with H_2O (50 mL). The aq layer was extracted with Et_2O (2 x 50 mL), combined organic extractions were dried over $MgSO_4$, and concentrated *in vacuo.* The crude compound was then purified on silica gel flash chromatography (0-10% EtOAc/hexanes) to afford the title compound as an inseparable mixture of *E* and *Z* isomers (1.0:0.7; 2.67 g, 14.00 mmol, 91%).

R_f = 0.56 (15% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$)

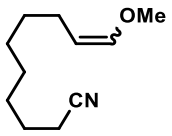
Signals correspond to *E*-isomer: δ 6.26 (d, *J* = 12.3 Hz, 1 H), 4.70 (dt, *J* = 12.6, 7.2 Hz, 1 H), 3.51 (td, *J* = 6.8, 1.8, Hz, 2 H), 3.48 (s, 3 H), 1.90 (q, *J* = 6.8 Hz, 2 H), 1.72 – 1.78 (m, 2 H), 1.37 – 1.45 (m, 2 H), 1.27 – 1.35 (m, 6 H).

Signals correspond to *Z*-isomer: δ 5.84 – 5.86 (m, 1 H), 4.29 – 4.33 (m, 1 H), 3.56 (s, 3 H), 3.51 (td, *J* = 6.8, 1.8 Hz, 2 H), 2.01 – 2.07 (m, 2 H), 1.72 – 1.78 (m, 2 H), 1.37 – 1.45

(m, 2 H), 1.27 – 1.35 (m, 6 H).

^{13}C NMR (151 MHz, $CDCl_3$) δ 147.0, 146.0, 106.8, 102.9, 55.8, 45.0, 32.6, 30.6, 29.0, 28.7, 27.6, 26.8.

HRMS (*m/z*): 181.1467 (Calcd for $C_{10}H_{19}ClO$, 181.1467).



Compound 2-153

Following literature protocol,[75] to a mixture of **2-148** (1.18 g, 6.19 mmol, 1 equiv) in MeCN (11 mL) at rt, was added NaCN (0.76 g, 15.47 mmol, 2.5 equiv). The RM was then heated to 120 °C in a microwave reactor for 16 h. Cooled to rt, filtered through a plug of cotton, washed with CH_2Cl_2 (10 mL), and concentrated *in vacuo*. The resulting residue dissolved in CH_2Cl_2 (25 mL), washed with H_2O (25 mL), and aq layer extracted with CH_2Cl_2 (2 x 25 mL). Combined organic extractions were dried over $MgSO_4$, and concentrated *in vacuo*. The crude compound was then purified on silica gel flash chromatography (0-15% EtOAc/hexanes) to afford the title compound as a pale yellow oil (0.77 g, 4.25 mmol, 69%).

R_f = 0.42 (20% EtOAc/hexanes).

^{1}H NMR (600 MHz, $CDCl_3$) *E*:*Z* ; 1.0:0.7.

Signals correspond to *E*-isomer: δ 6.27 (d, *J* =12.3 Hz, 1 H), 4.71 (dt, *J* = 12.6, 7.5 Hz, 1 H), 3.50 (s, 3 H), 2.33 (td, *J* = 7.3, 2.9 Hz, 2 H), 1.91 (q, *J* = 6.5 Hz, 2 H), 1.65 (quin, *J* = 7.3 Hz, 2 H), 1.41 – 1.49 (m, 2 H), 1.26 – 1.38 (m, 6 H).

Signals correspond to *Z*-isomer: δ 5.87 (app d, *J* = 6.5 Hz, 1 H), 4.32 (q, *J* = 6.8 Hz, 1 H),

3.57 (s, 3 H), 2.33 (td, *J* = 7.3, 2.9 Hz, 2 H), 2.02 – 2.07 (m, 2 H), 1.65 (quin, *J* = 7.3 Hz, 2 H), 1.41 – 1.49 (m, 2 H), 1.26 – 1.38 (m, 6 H).

HRMS (*m/z*): 181.1467 (Calcd for $C_{11}H_{19}NO$, 181.1467).

2.8 Notes and References

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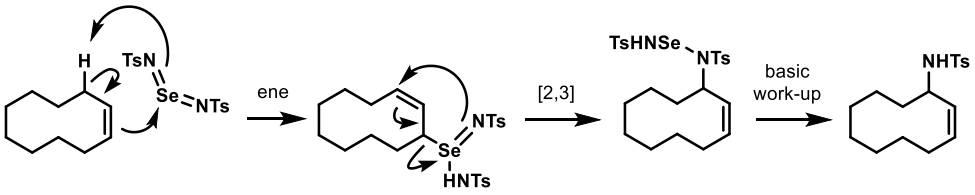

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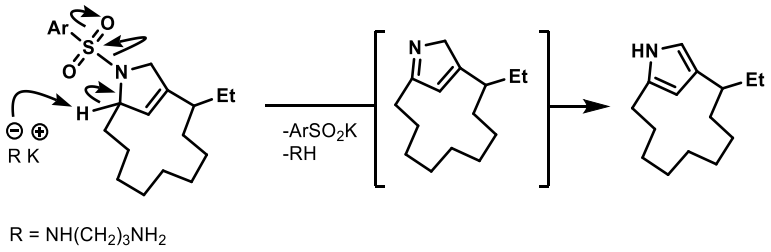

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"Synthesis and reactivity of alkoxy-activated cyclobutane-1,1-dicarboxylates."

Vemula, N.; Pagenkopf, B. L. *Org. Chem. Front.* **2016**, Advance Article. DOI: 10.1039/C6QO00244G.

"The [4+2] cycloaddition of donor–acceptor cyclobutanes and nitrosoarenes"

Vemula, N.; Stevens, A. C.; Schon, T. B.; Pagenkopf, B. L. *Chem. Commun*. **2014**, *50*, 1668.

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Appendix IB. John Wiley and Sons:

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Licensed Content Publication: European Journal of Organic Chemistry

Licensed Content Title: *"Synthesis of Tetrahydro-1,2-oxazines and Pyrrolidines via Cycloadditions of Donor–Acceptor Cyclobutanes and Nitrosoarenes"*

Licensed Content Author: Naresh Vemula, Brian L. Pagenkopf

Licensed Content Date: Jun 22, 2015

Appendix IC. American Chemical Society:

Title: *"Cascade Reaction of Donor-Acceptor Cyclopropanes: Mechanistic Studies on Cycloadditions with Nitrosoarenes and cis-Diazenes"*

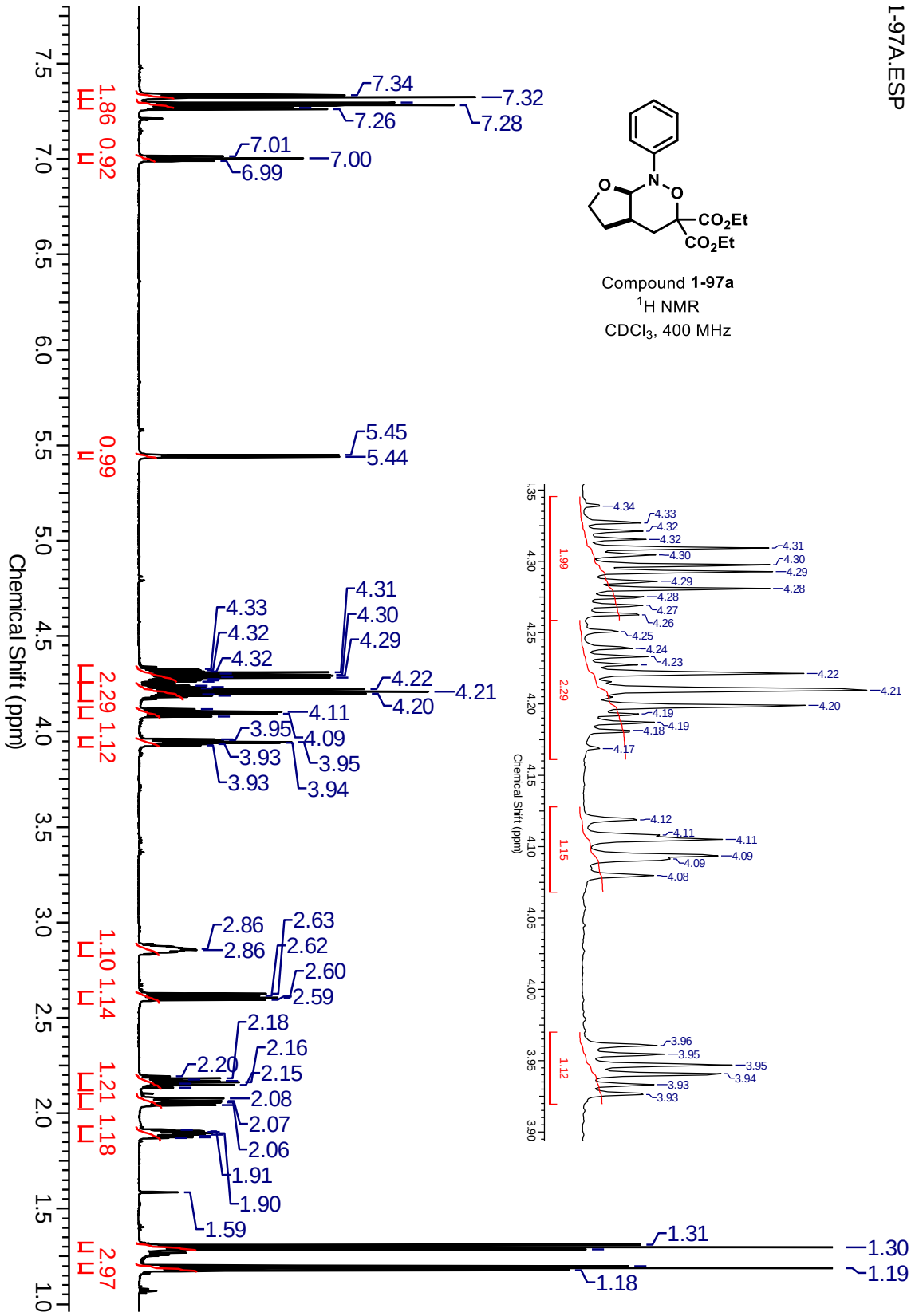
Author: Tristan Chidley, Naresh Vemula, Cheryl A. Carson, Michael A. Kerr, Brian L. Pagenkopf.

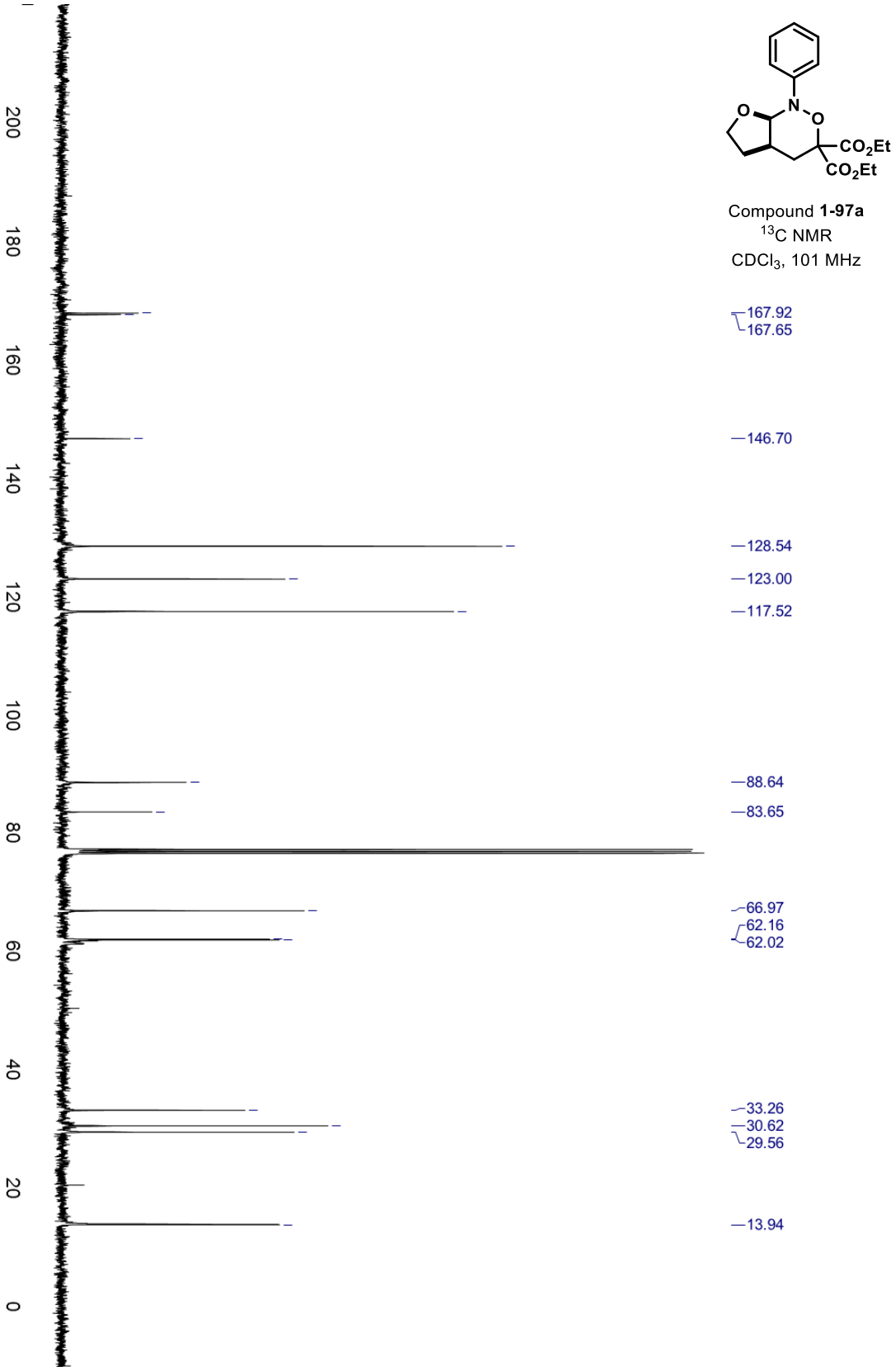
Publication: Organic Letters

Publisher: American Chemical Society

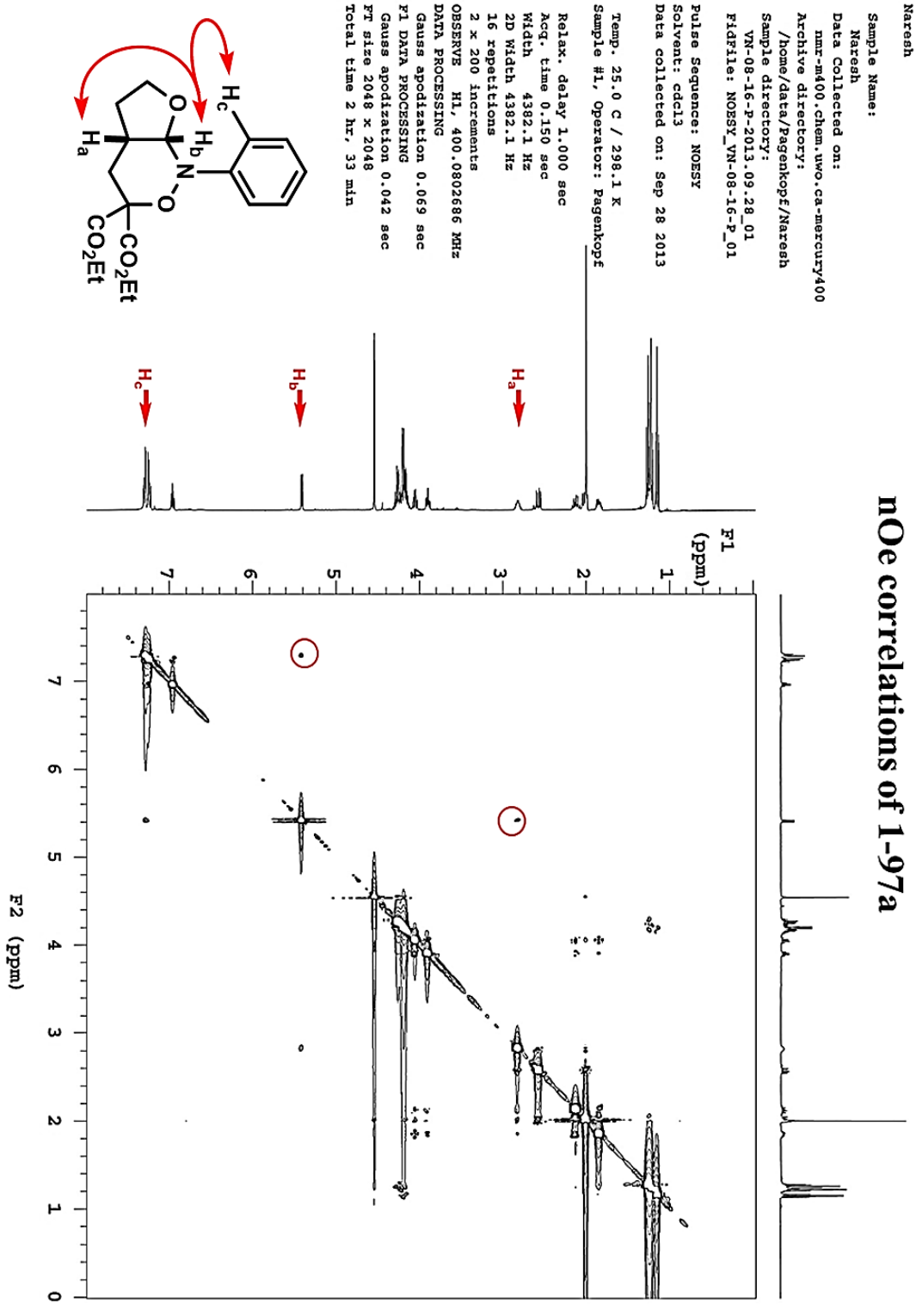
Date: Jun 1, 2016

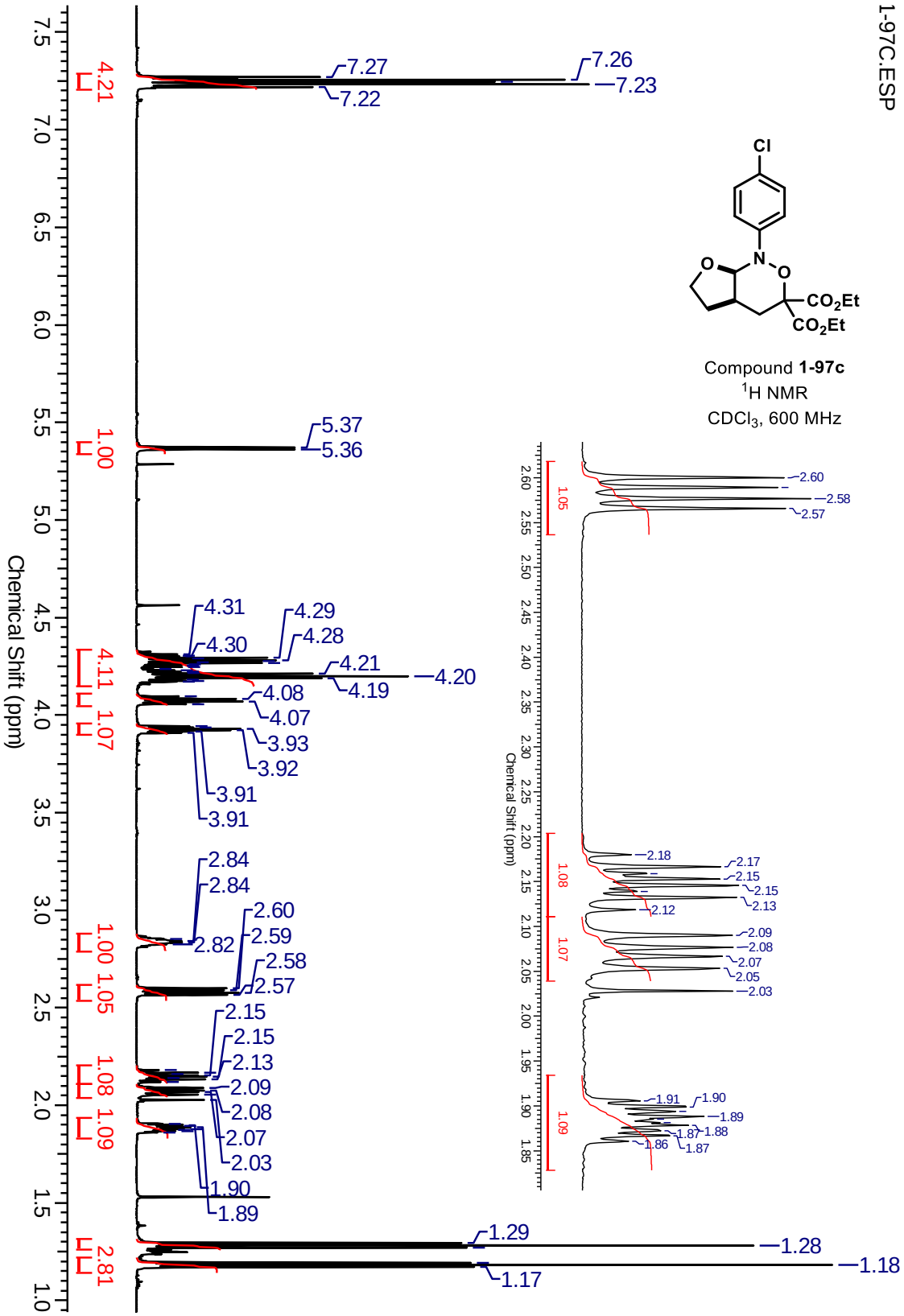
Appendix II. NMR Spectral Data of New Compounds for Chapter 1

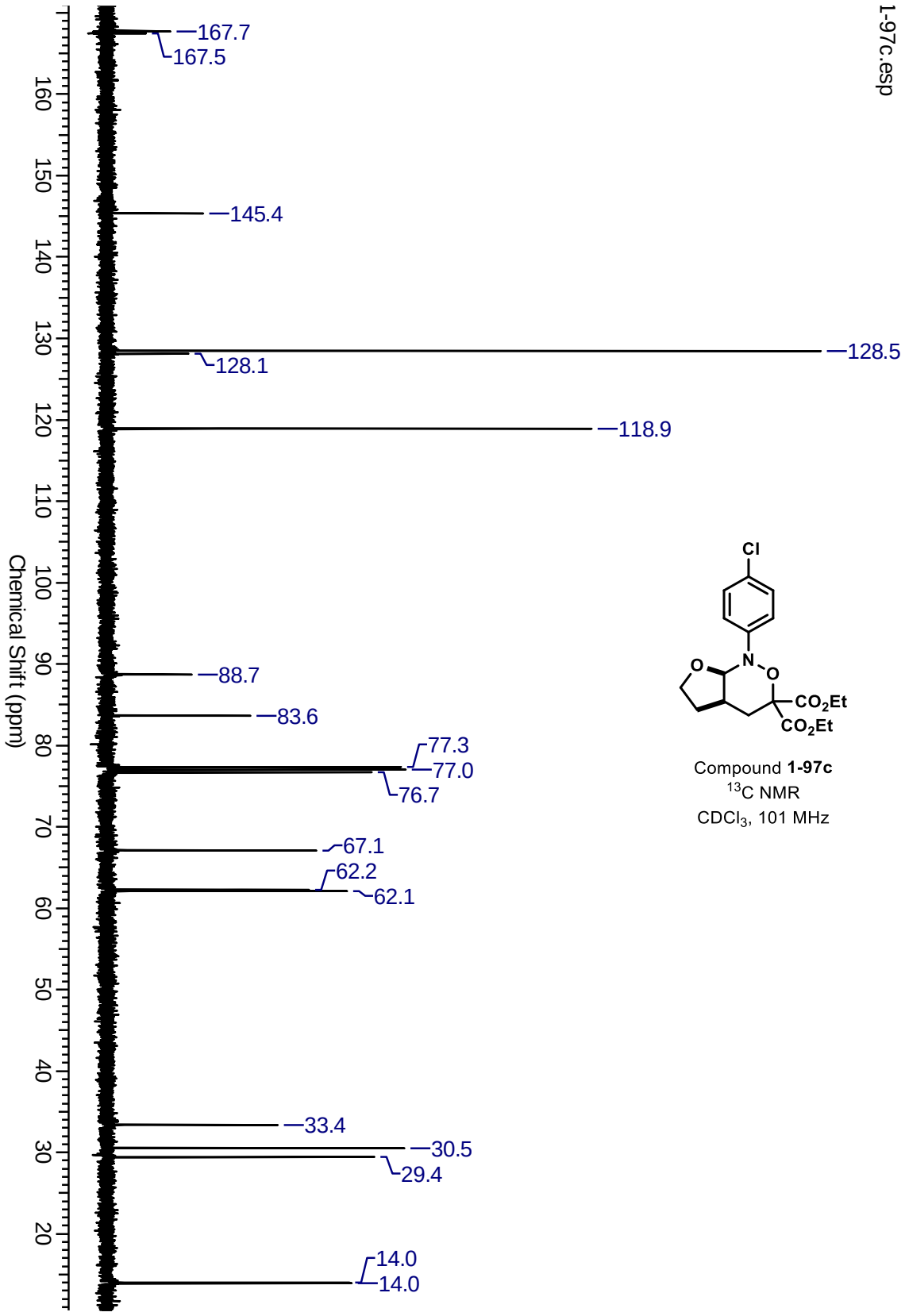




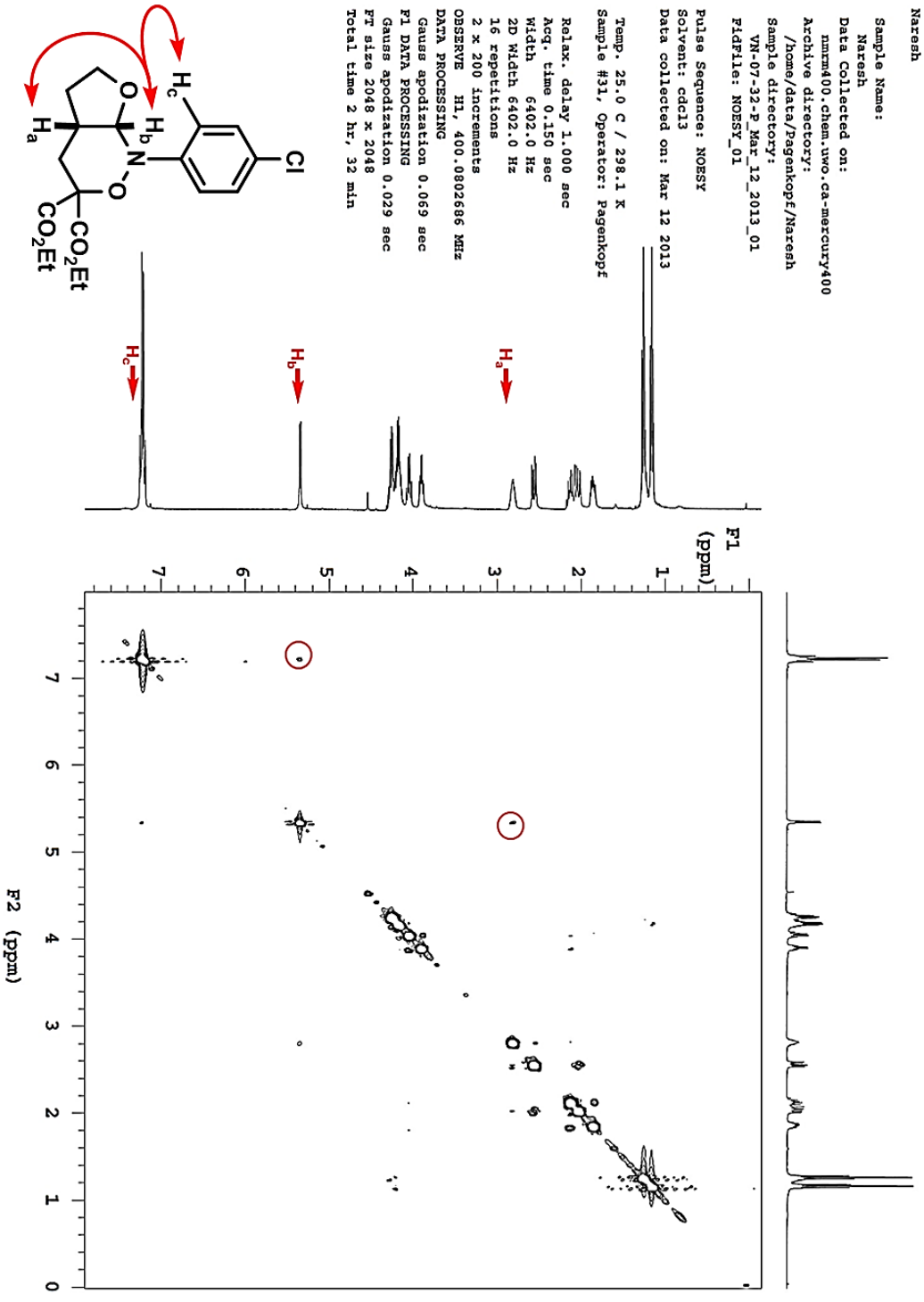
nOe correlations of 1-97a

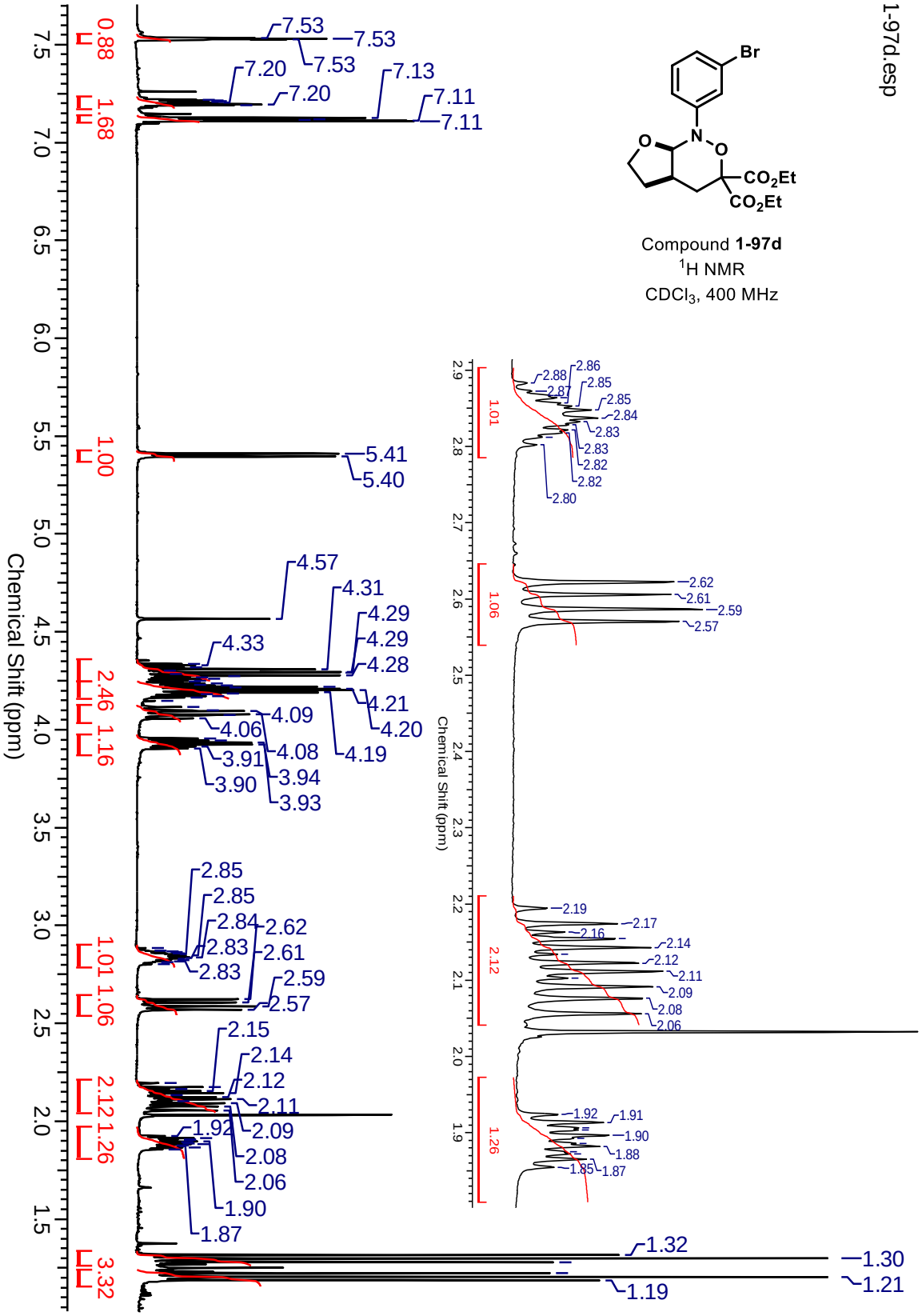


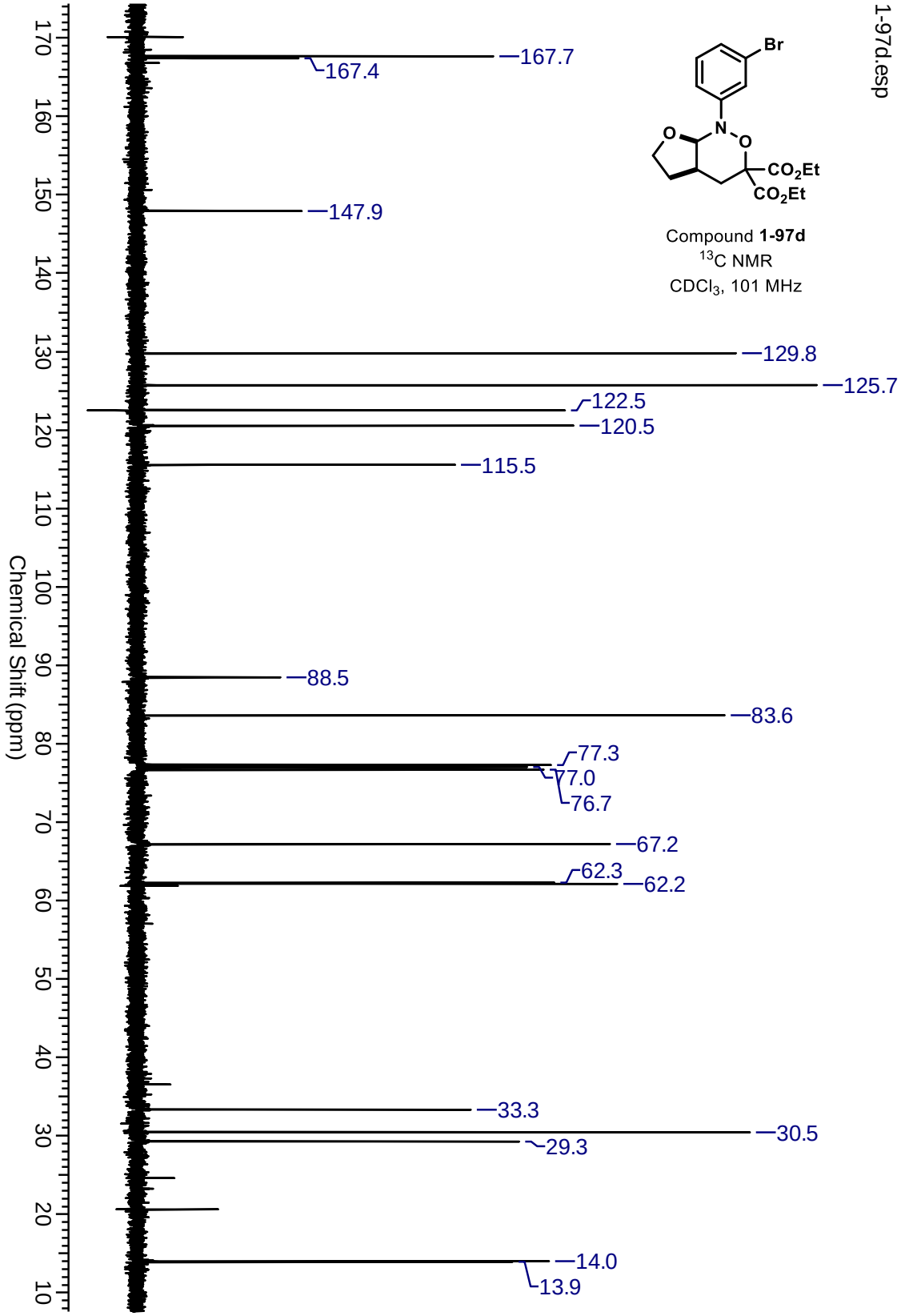


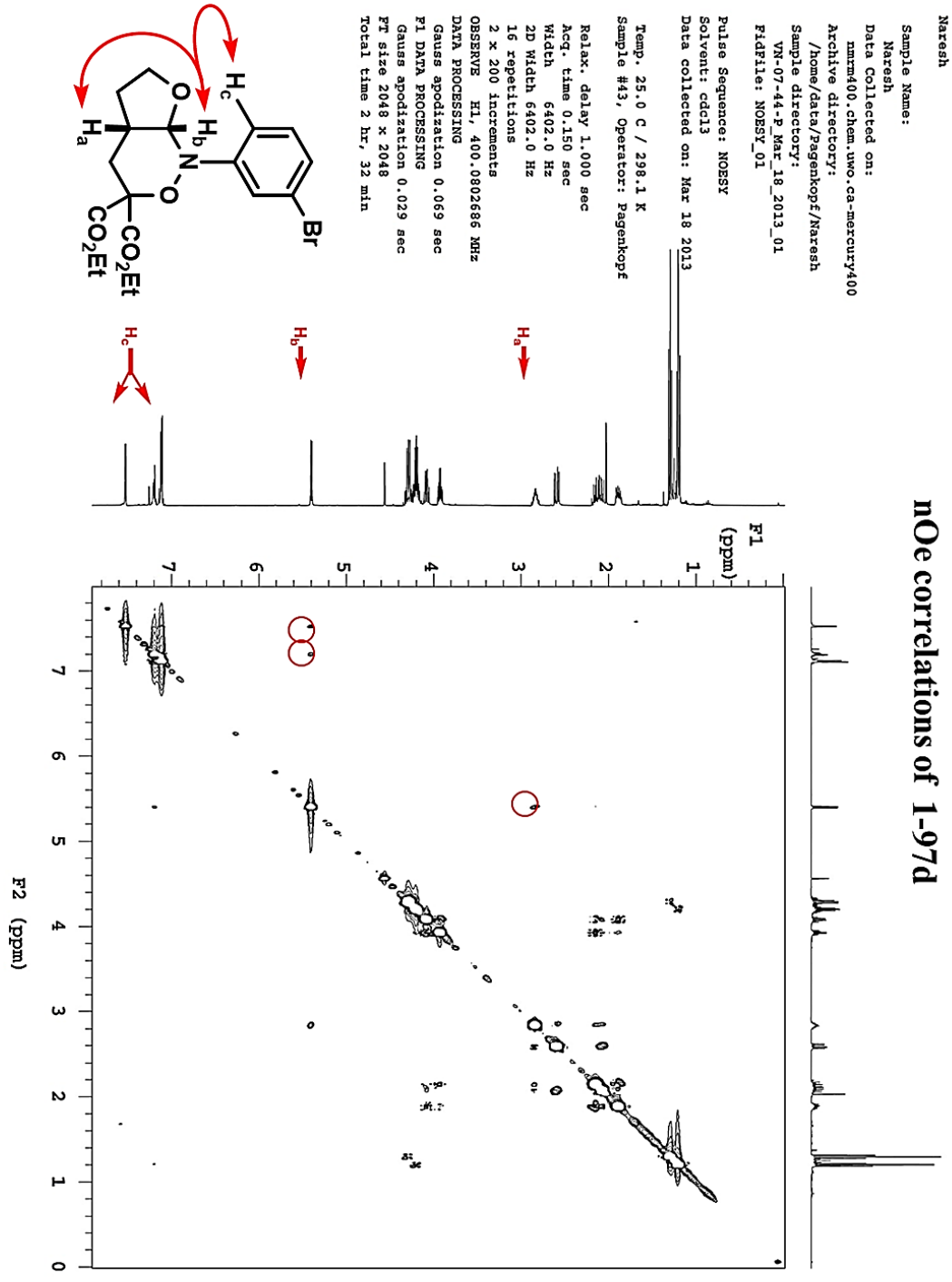


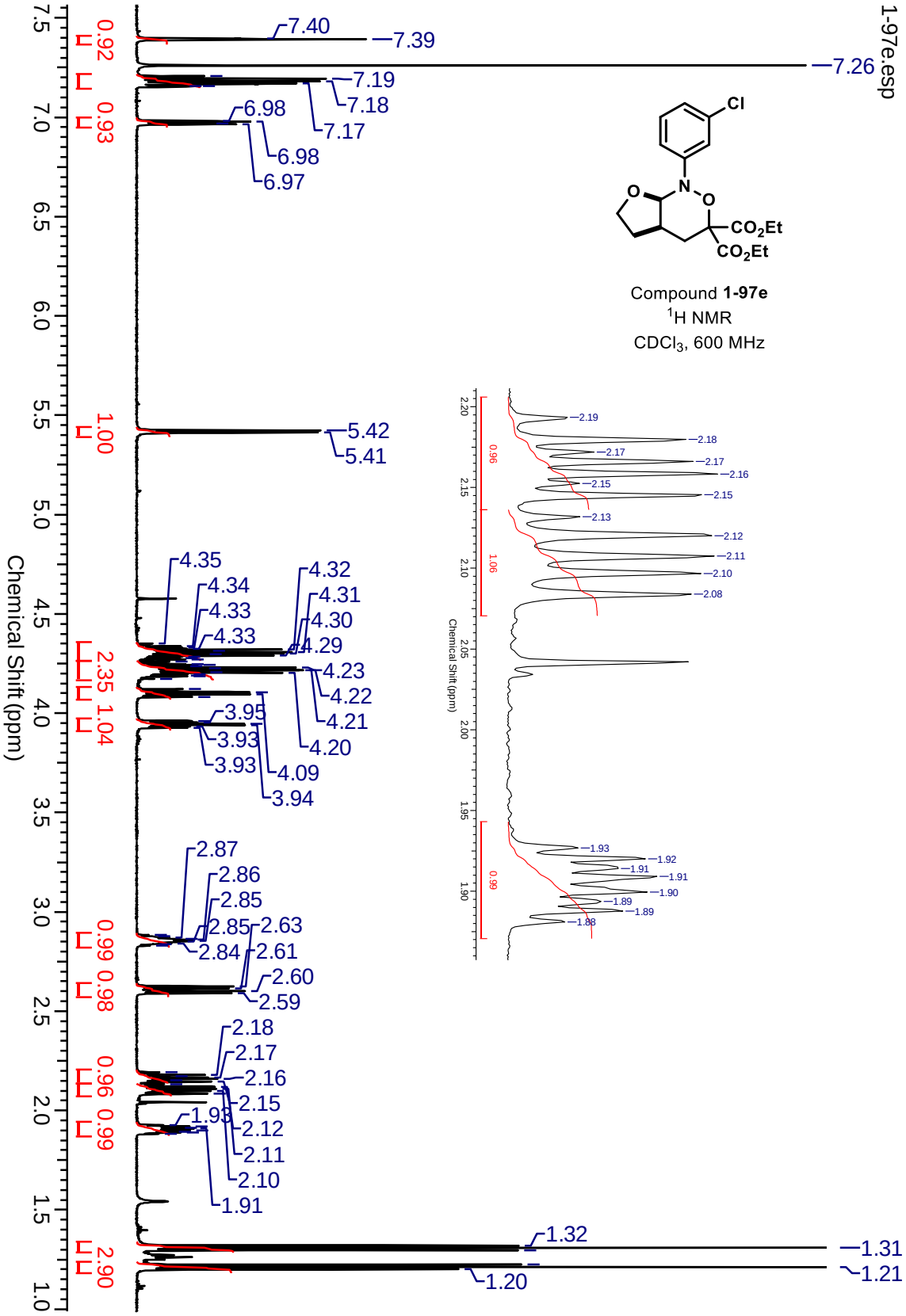
nOe correlations of 1-97c

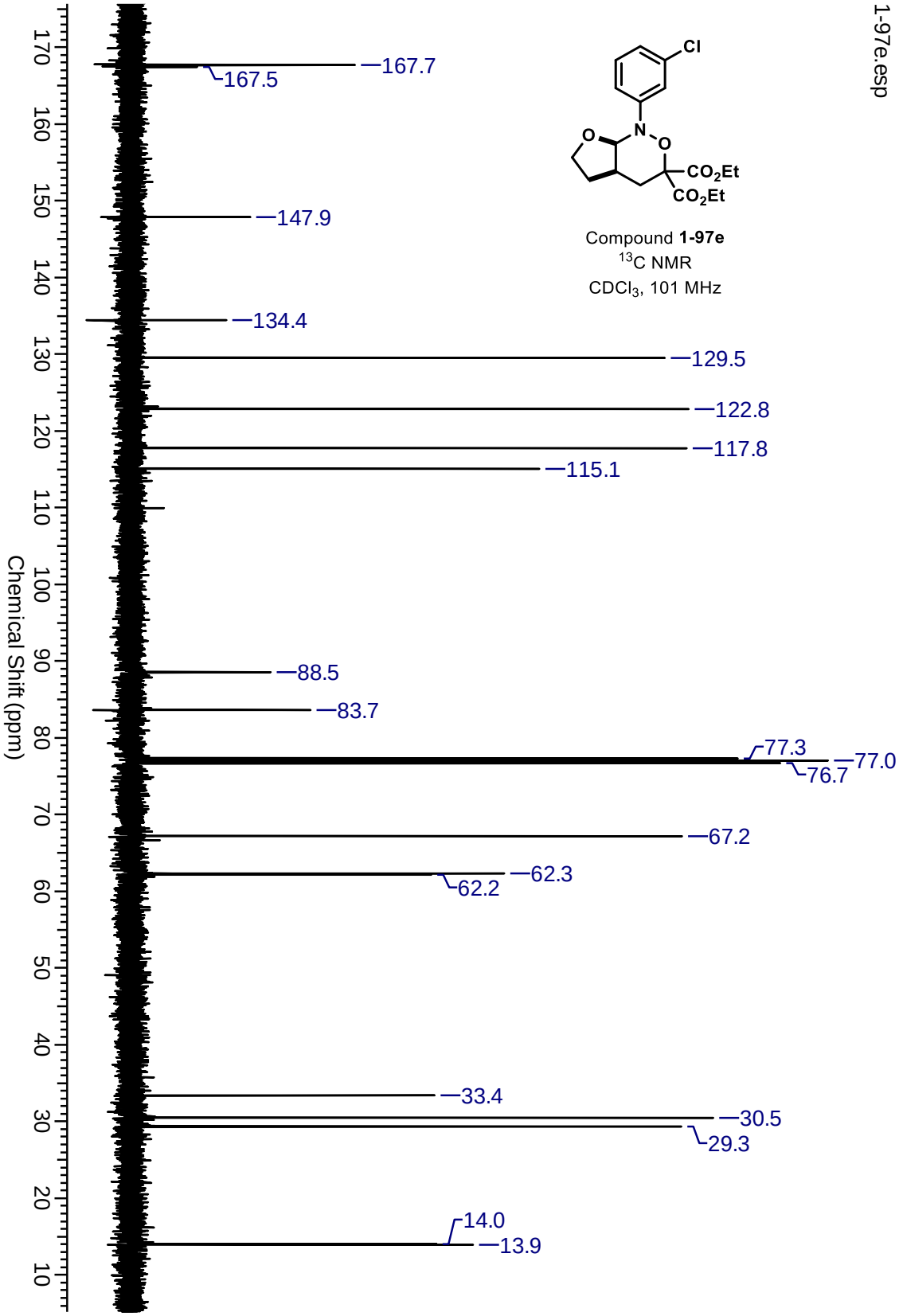


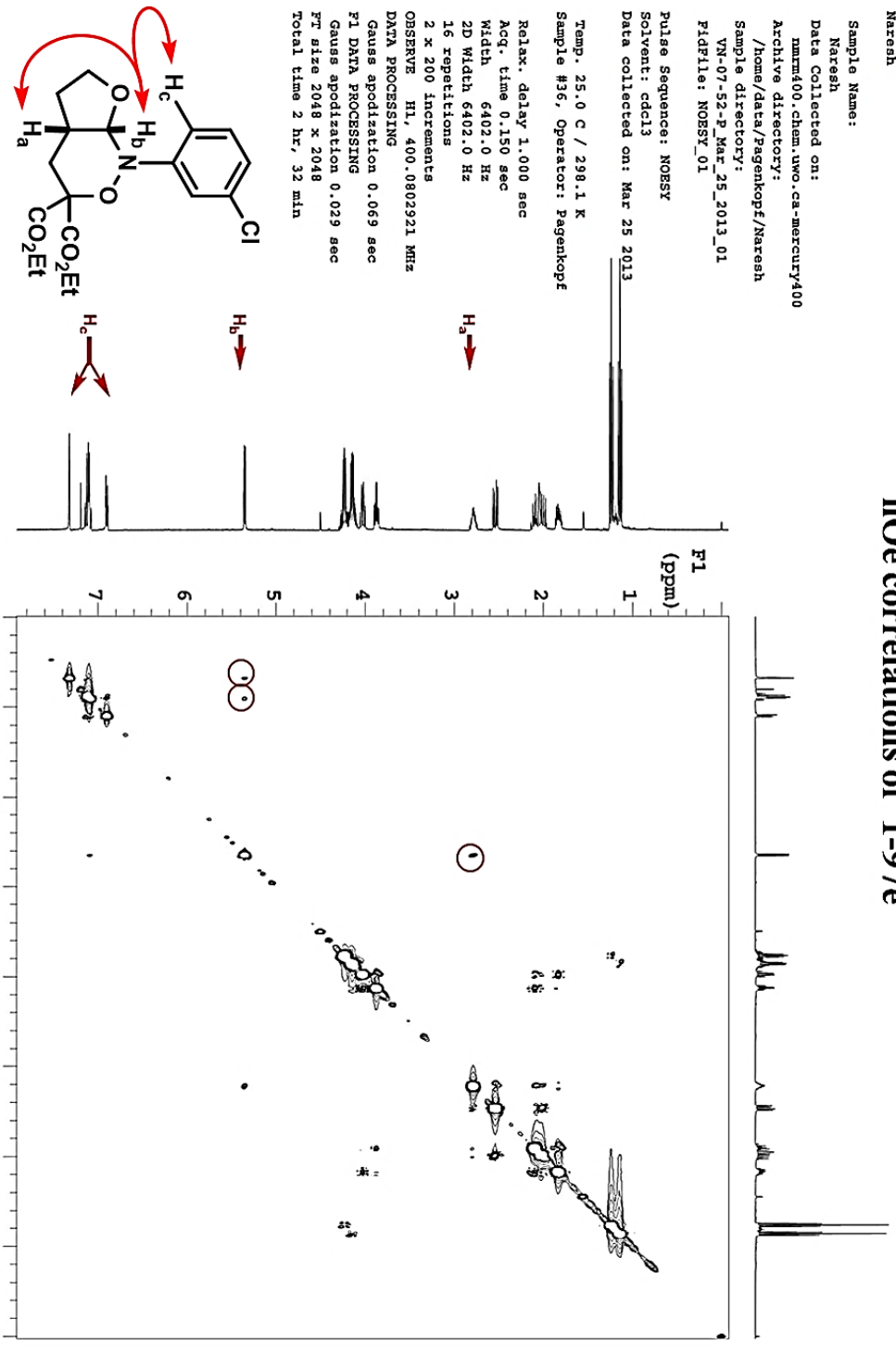


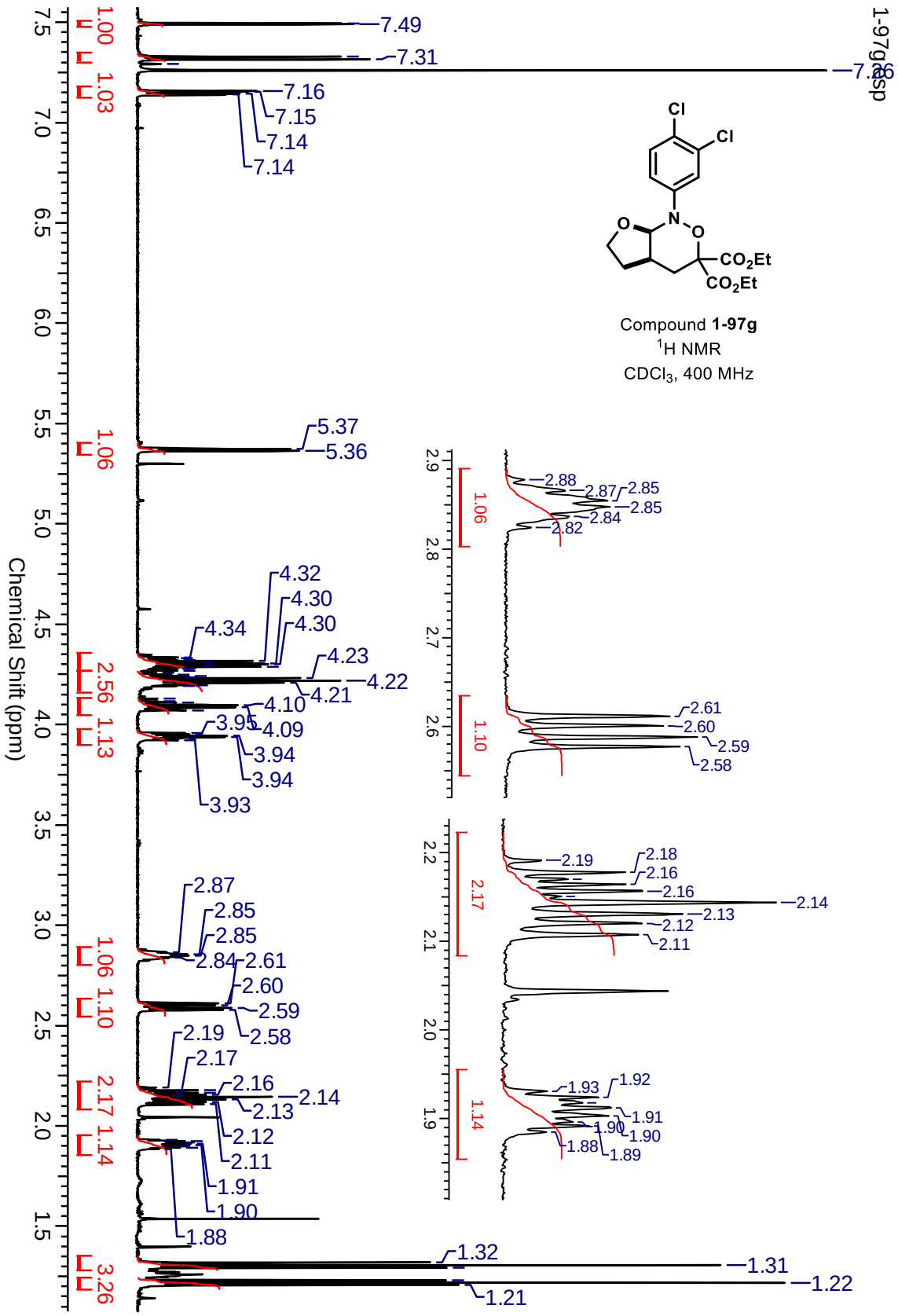


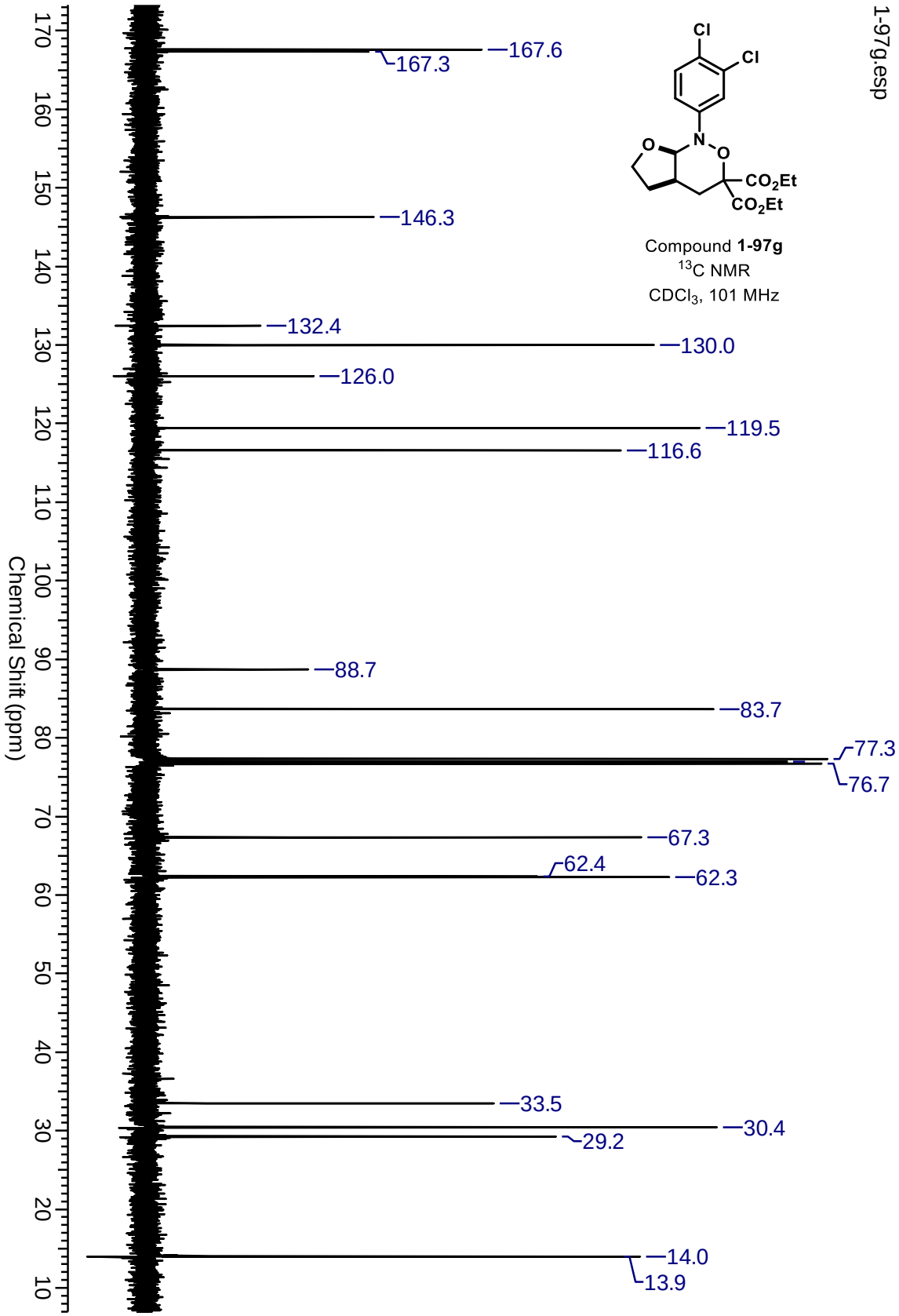


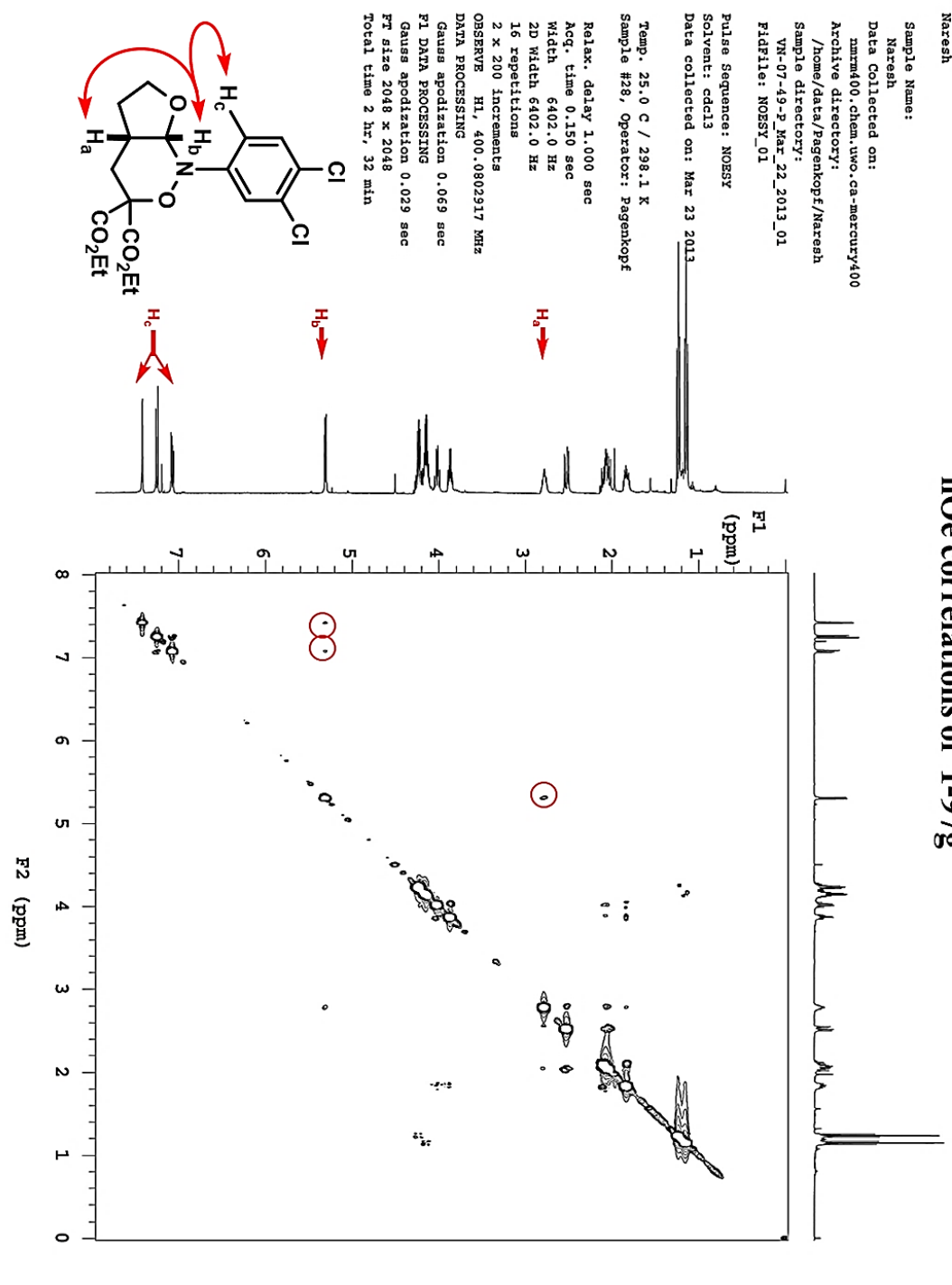


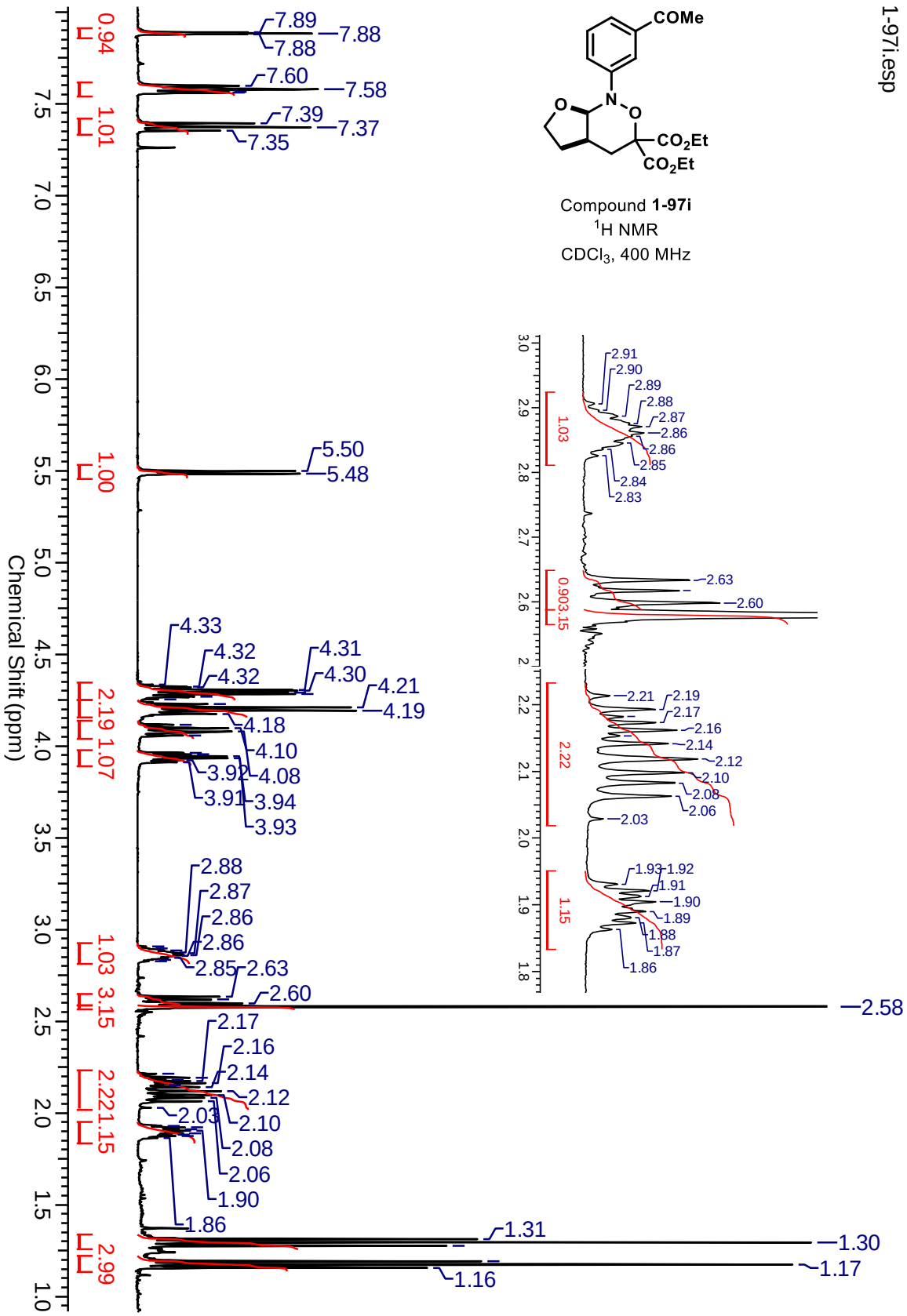


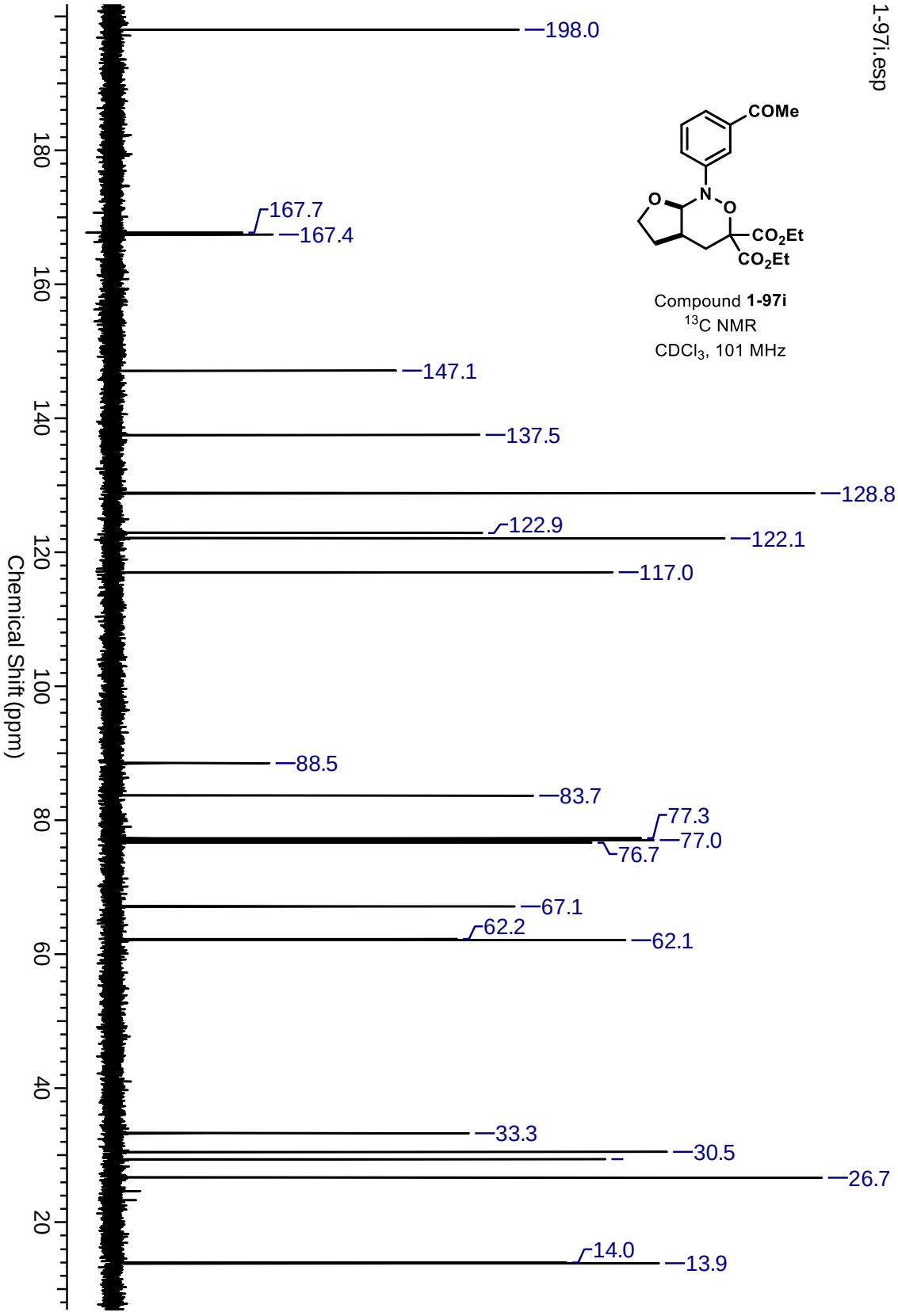


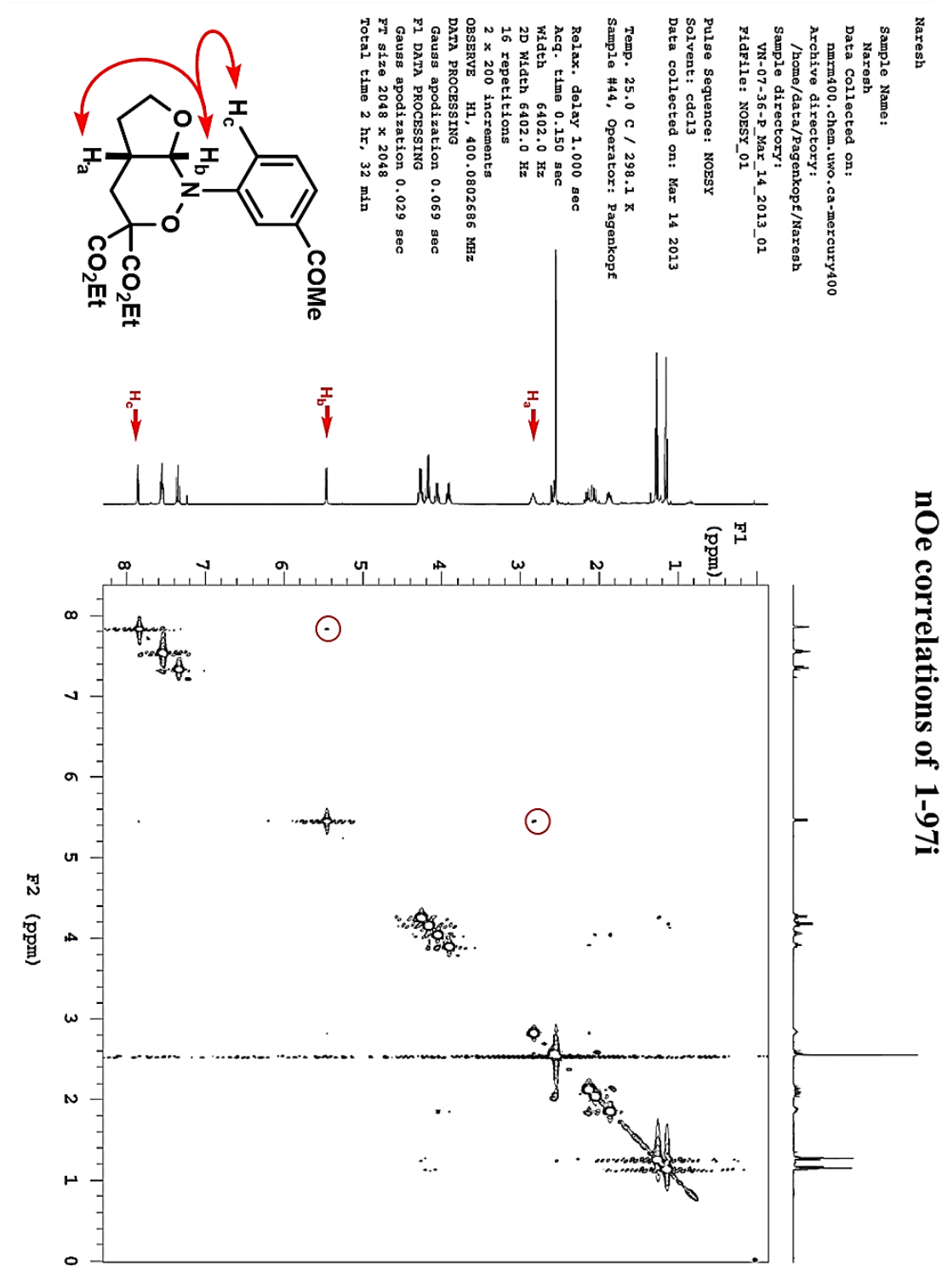




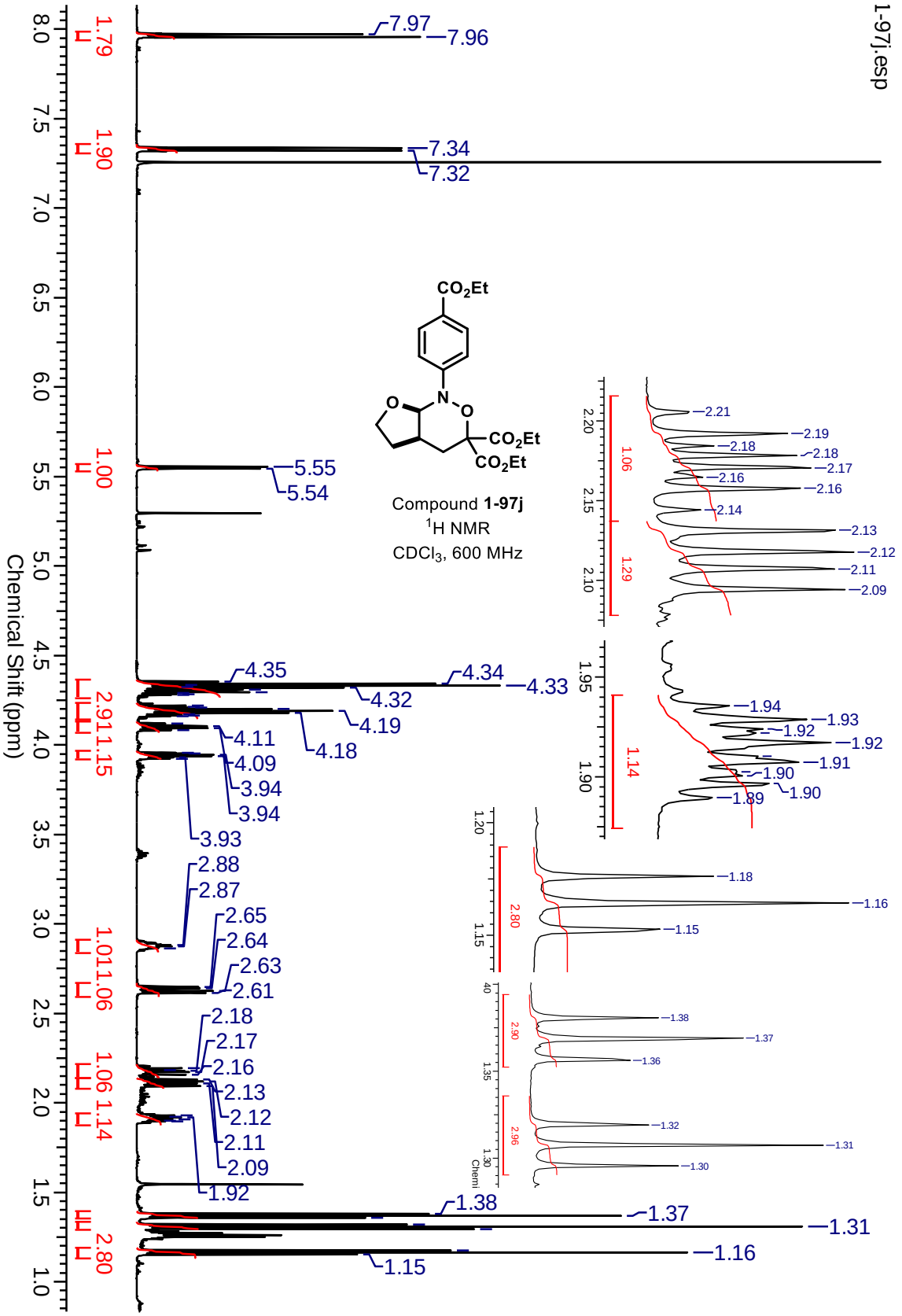


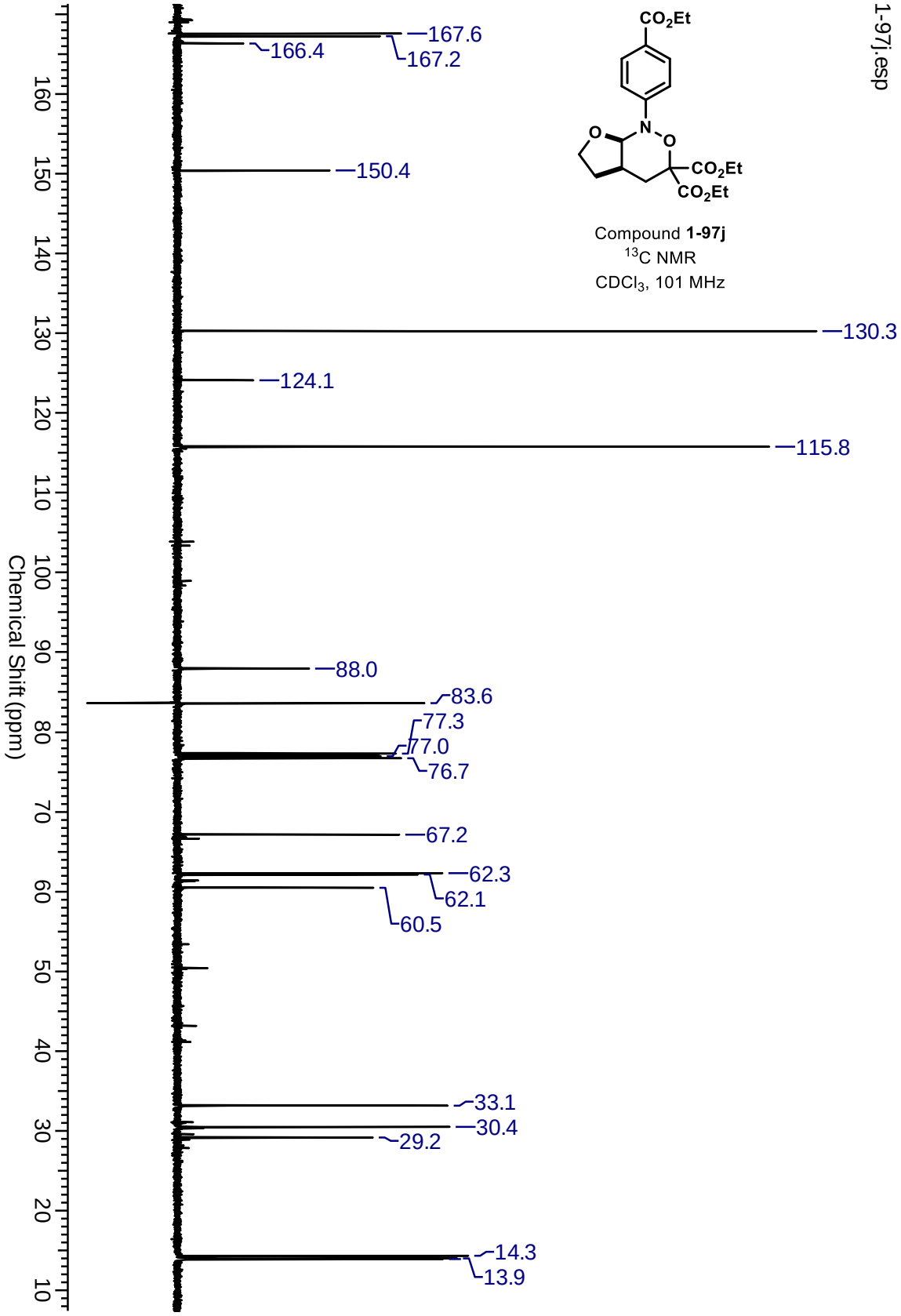


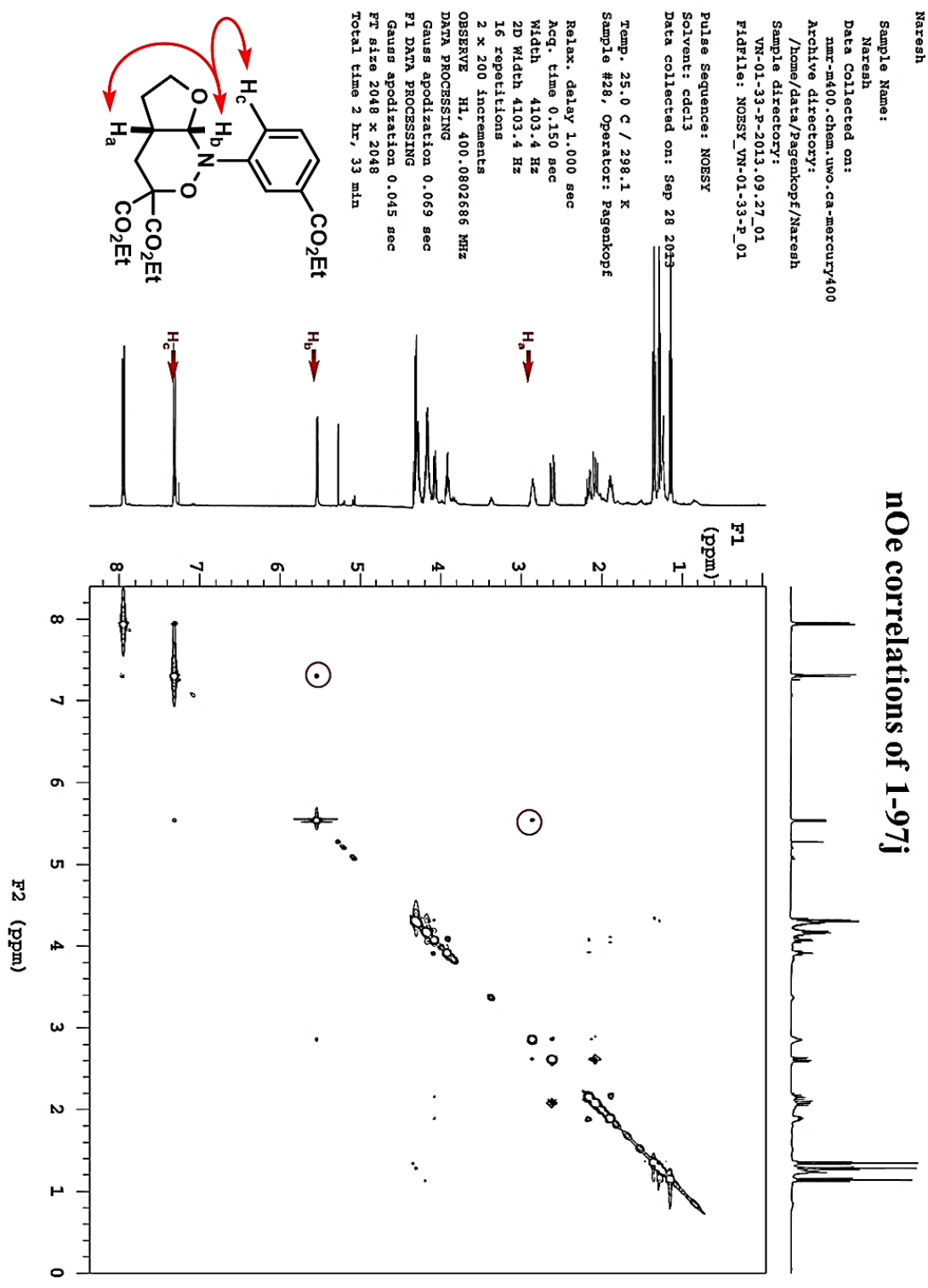


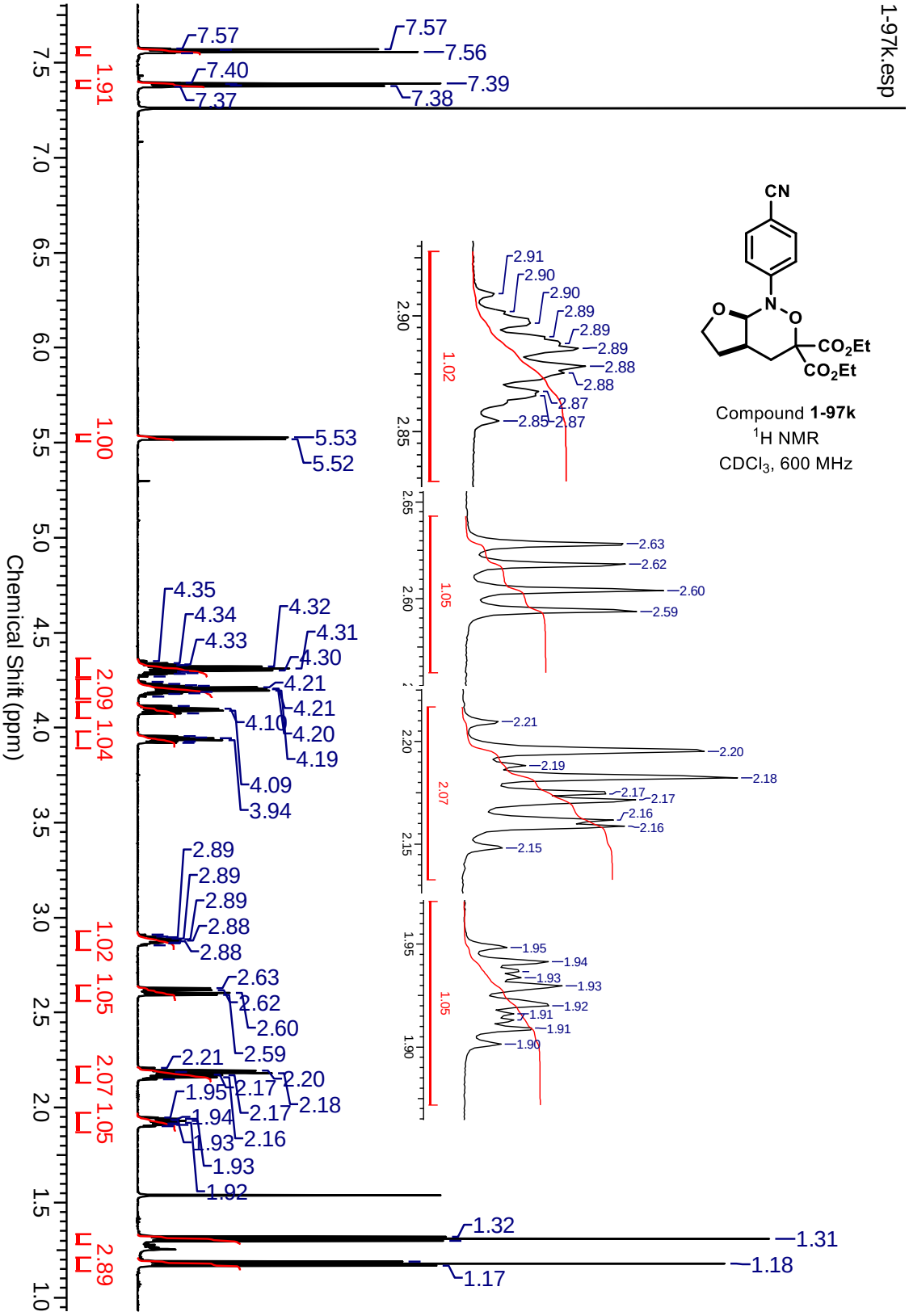


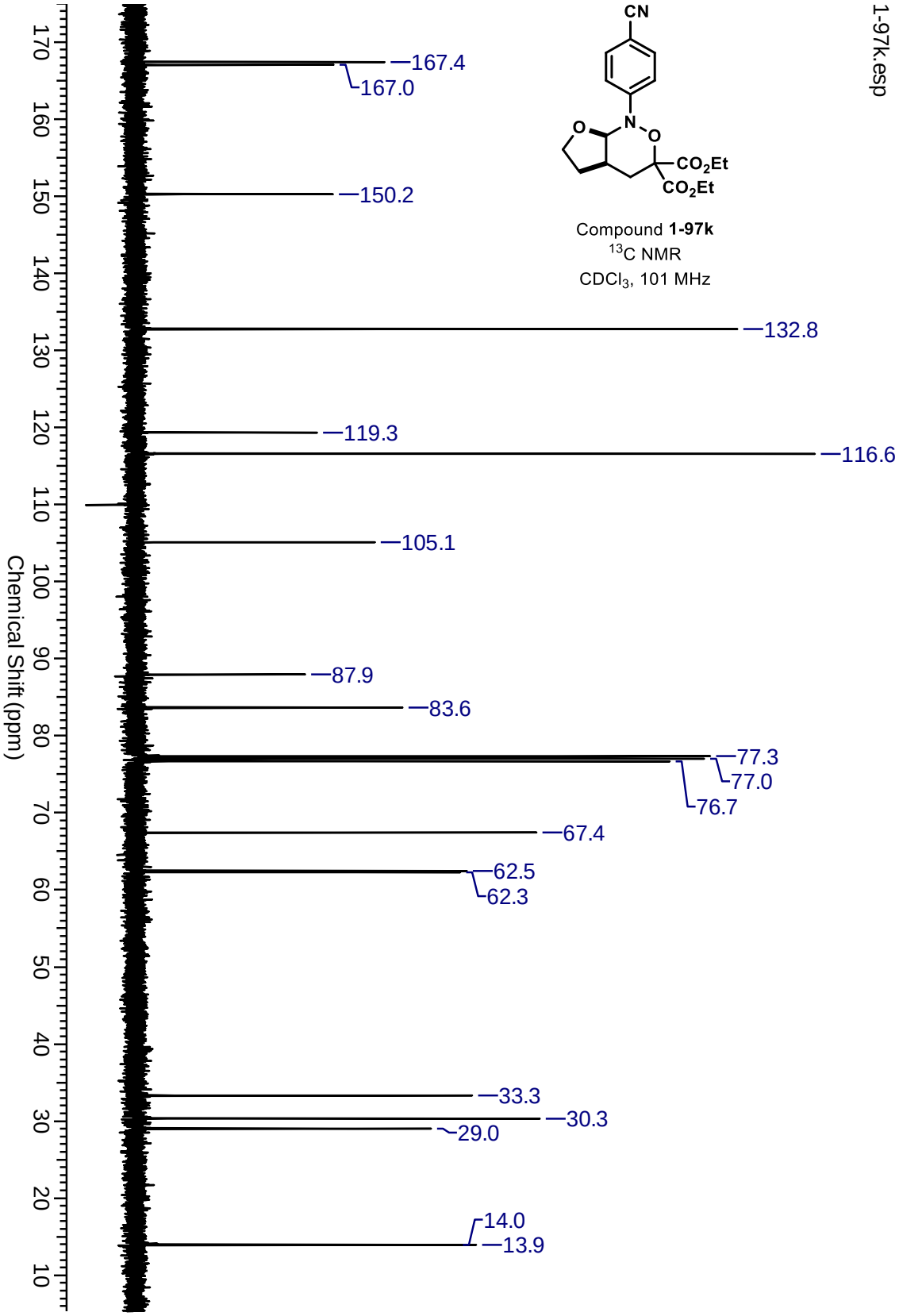
nOe correlations of 1-97i

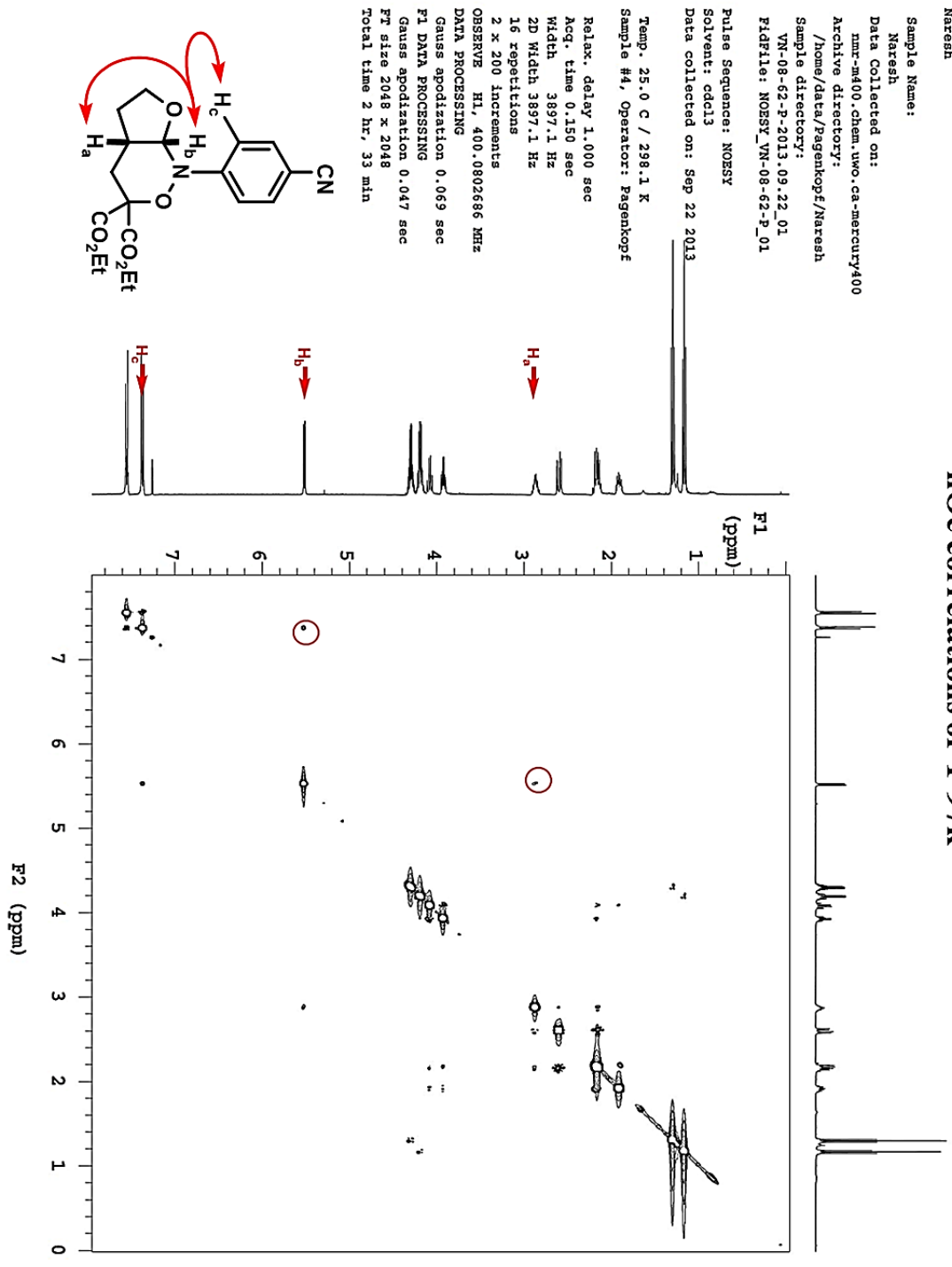




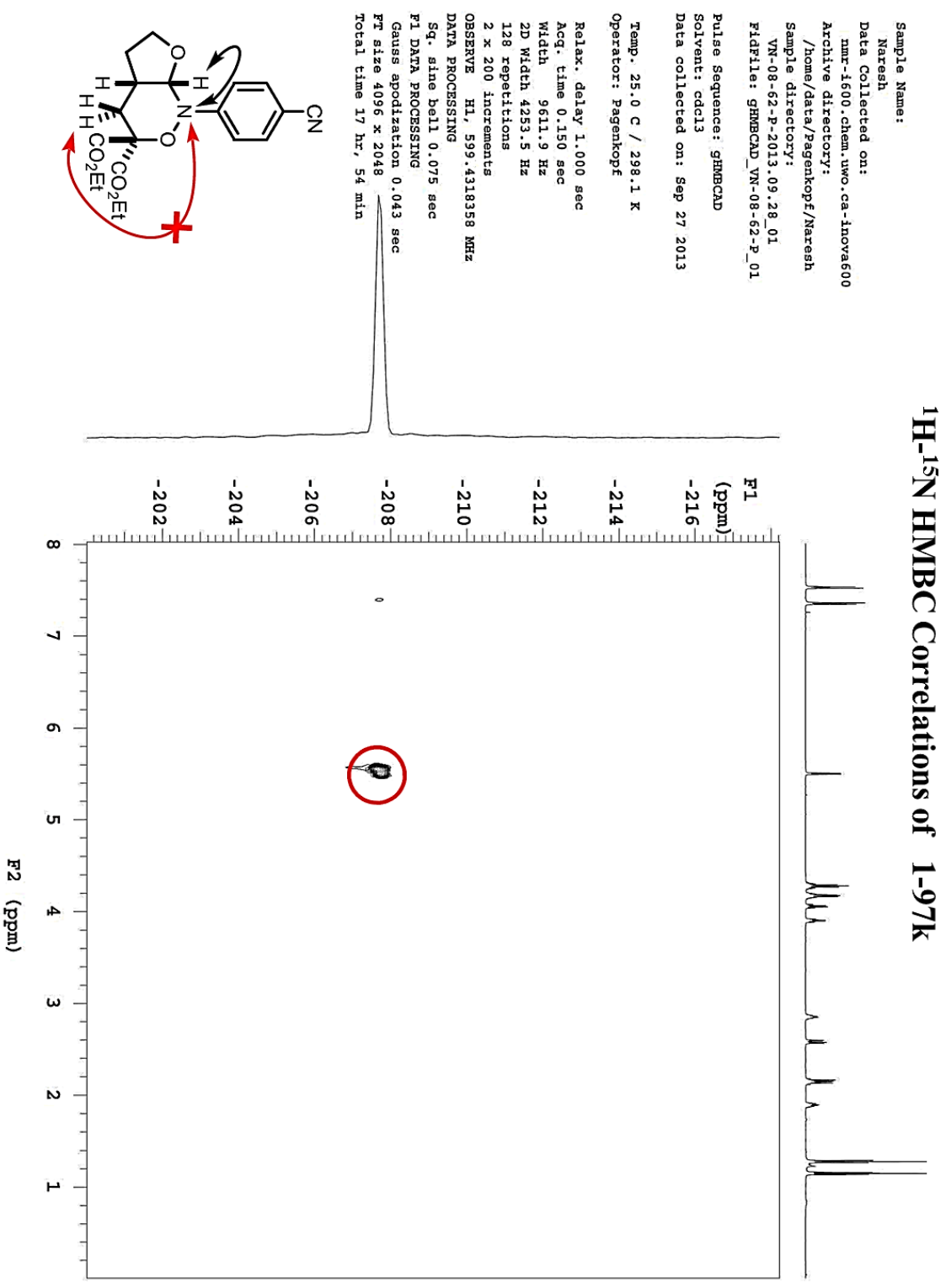


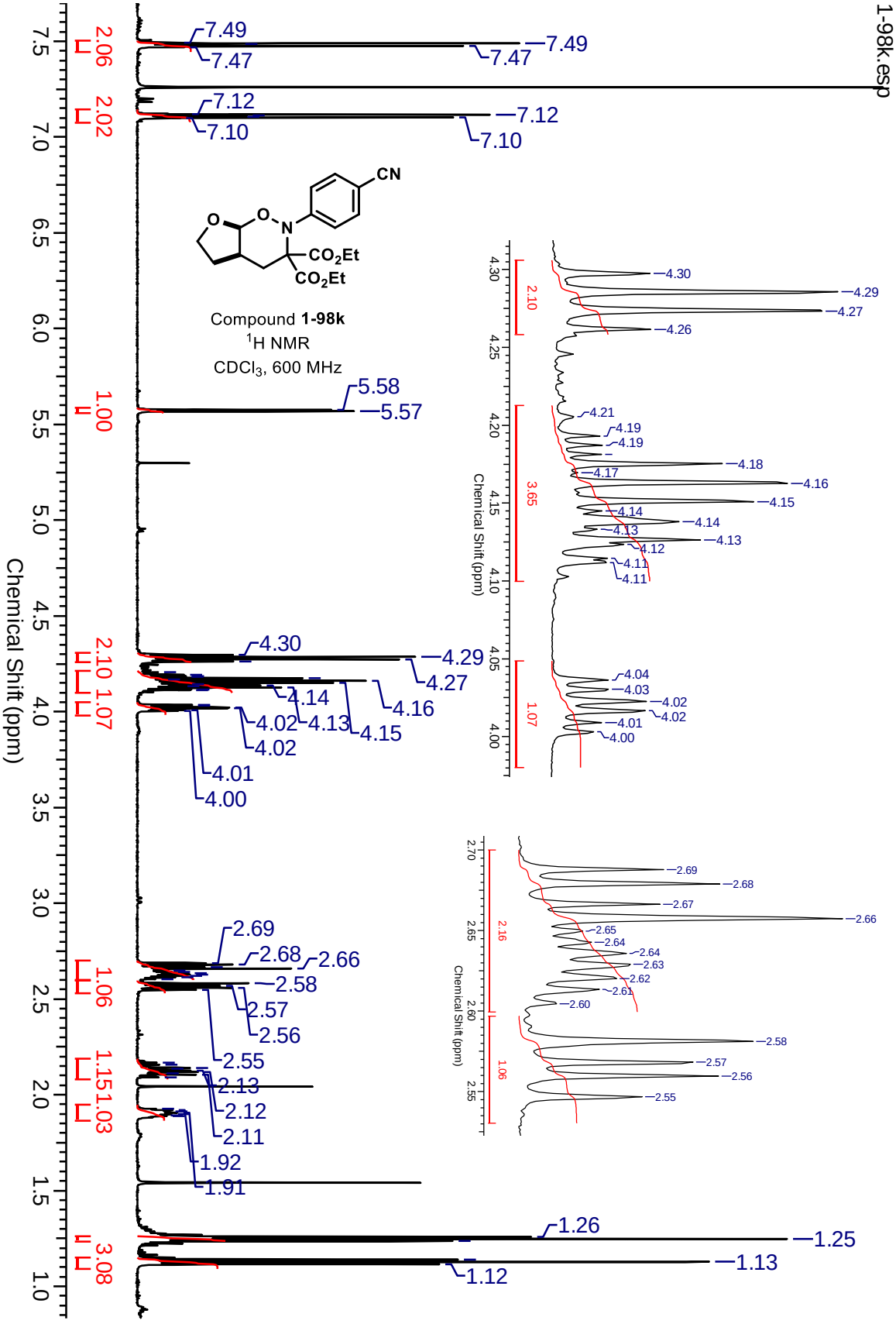


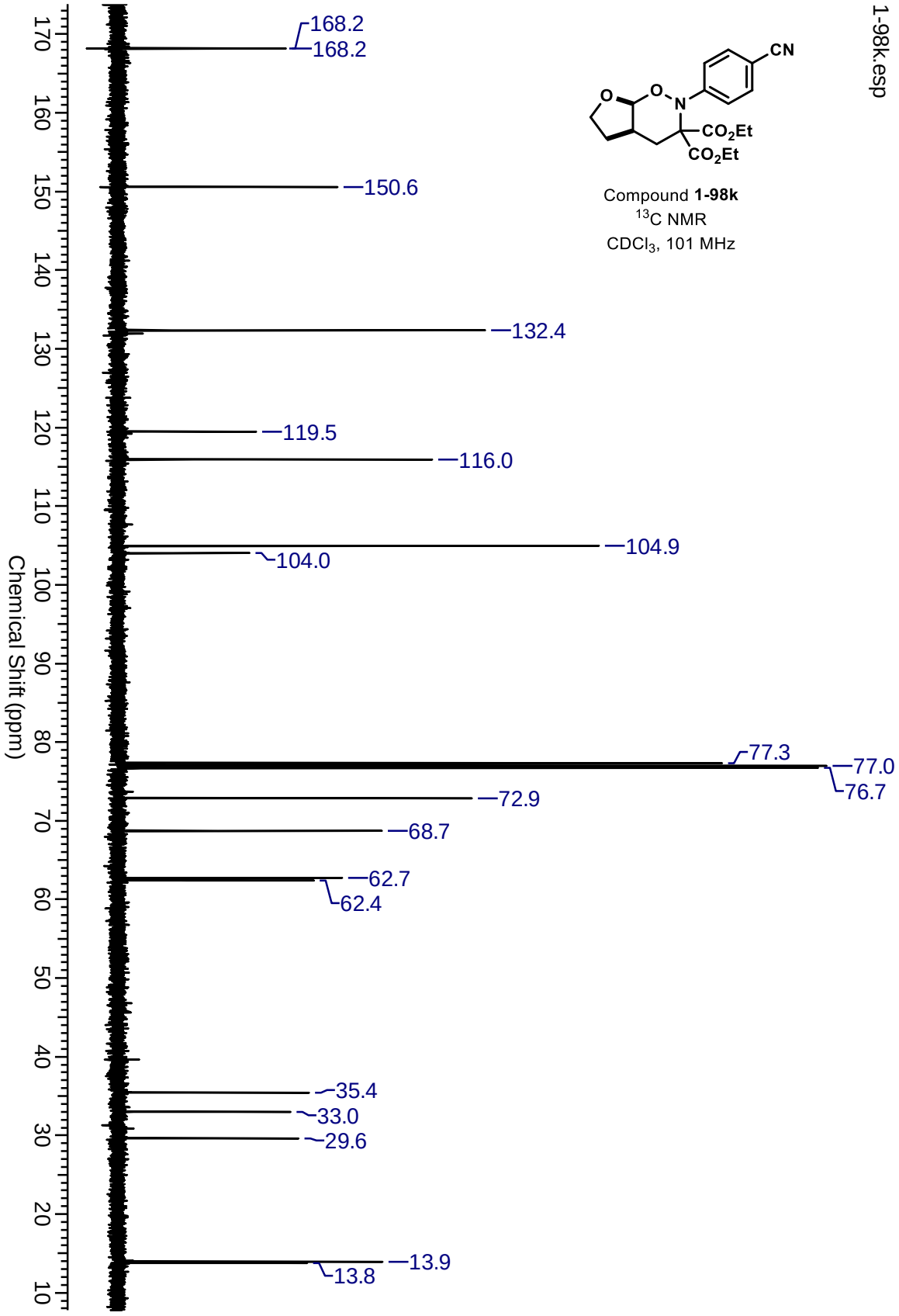


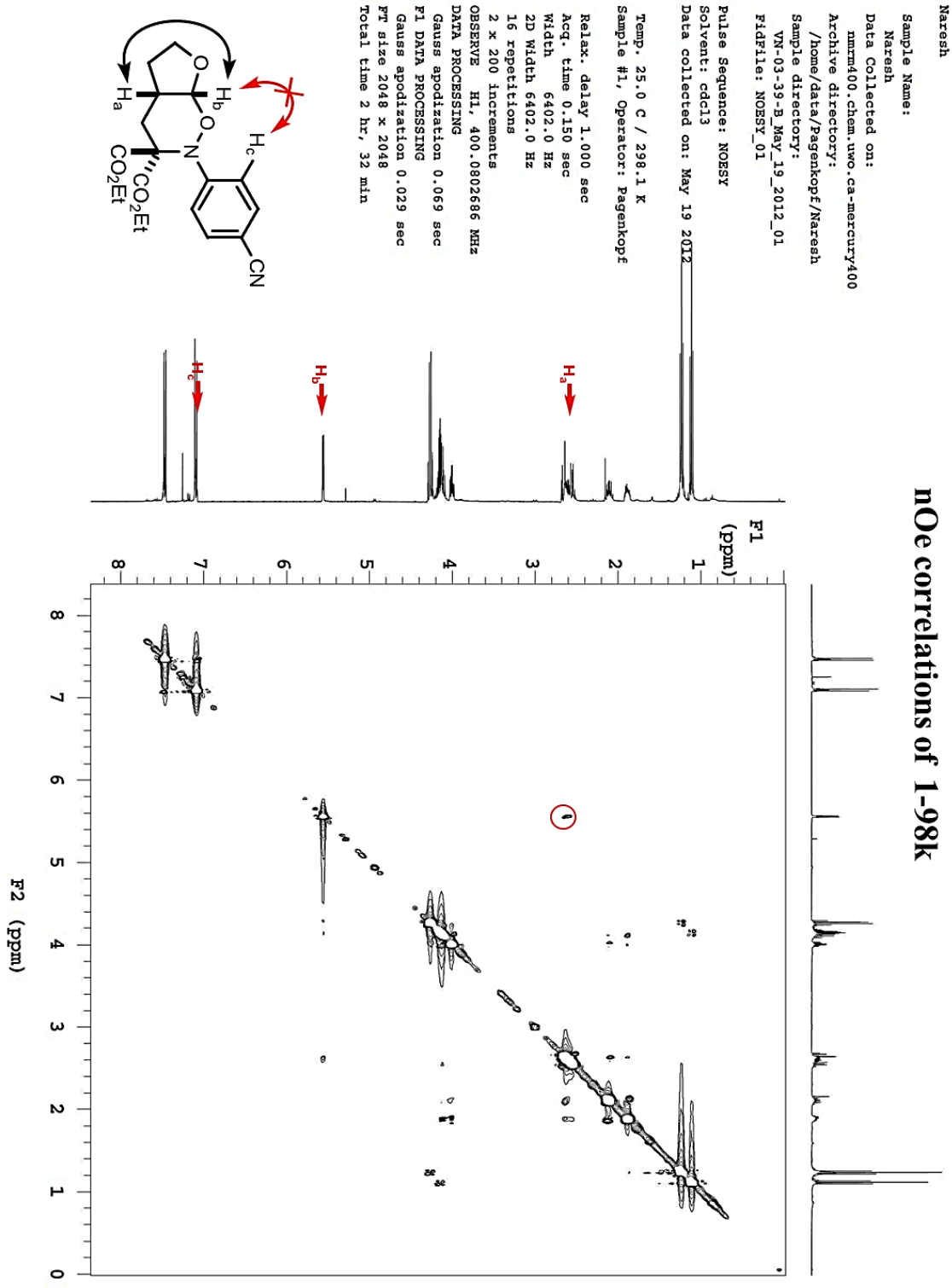


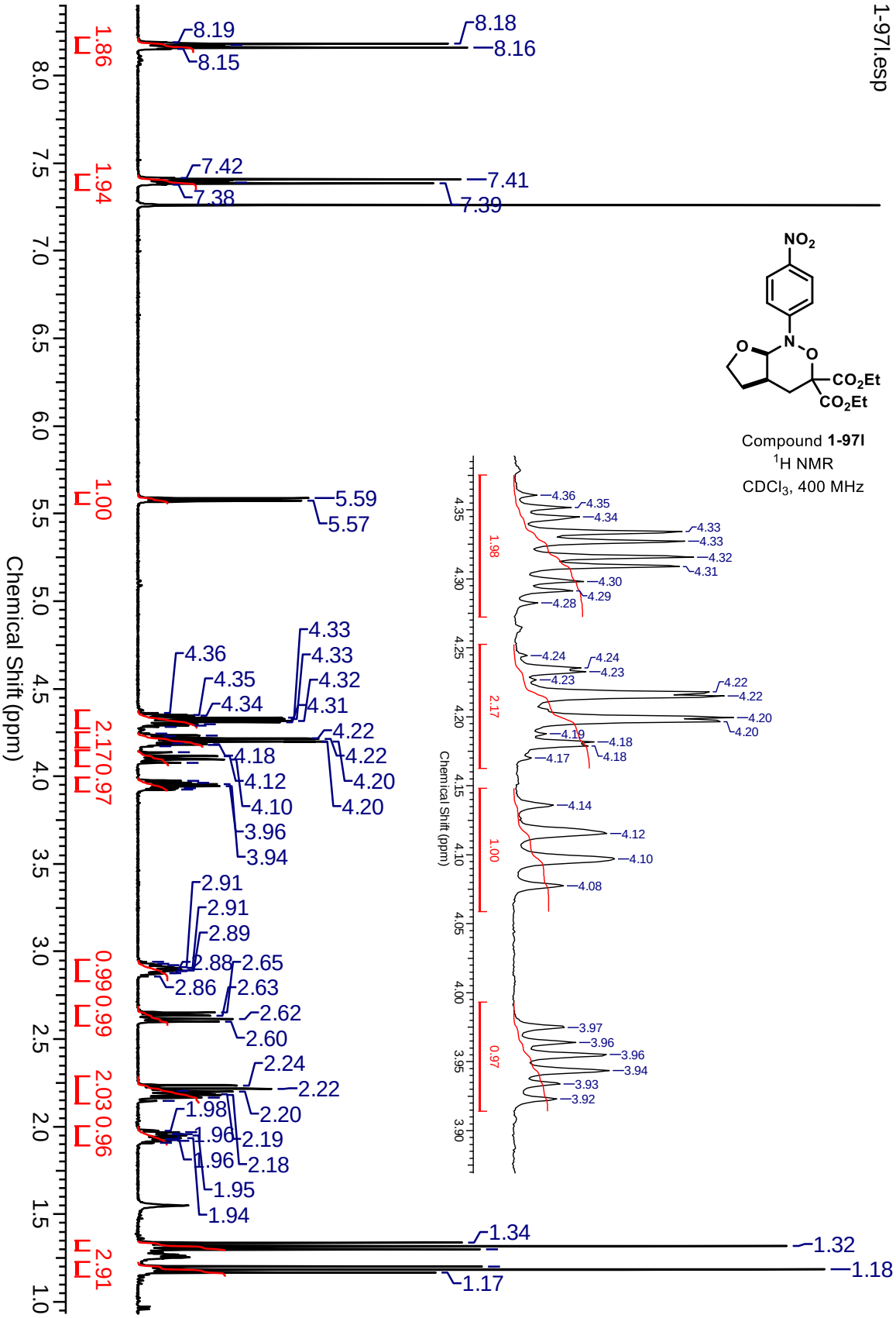
^{1}H-^{15}N HMBC Correlations of 1-97k

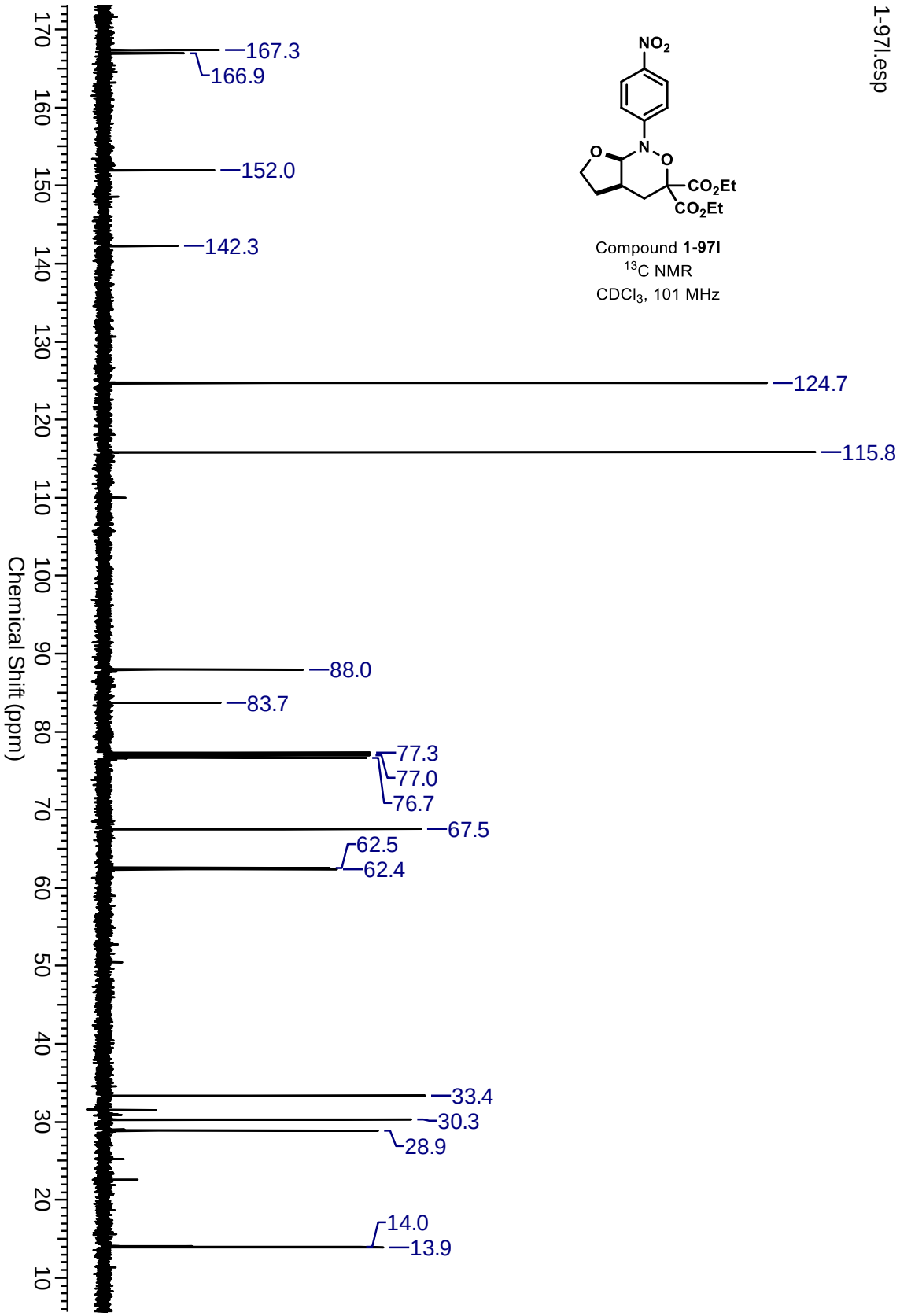




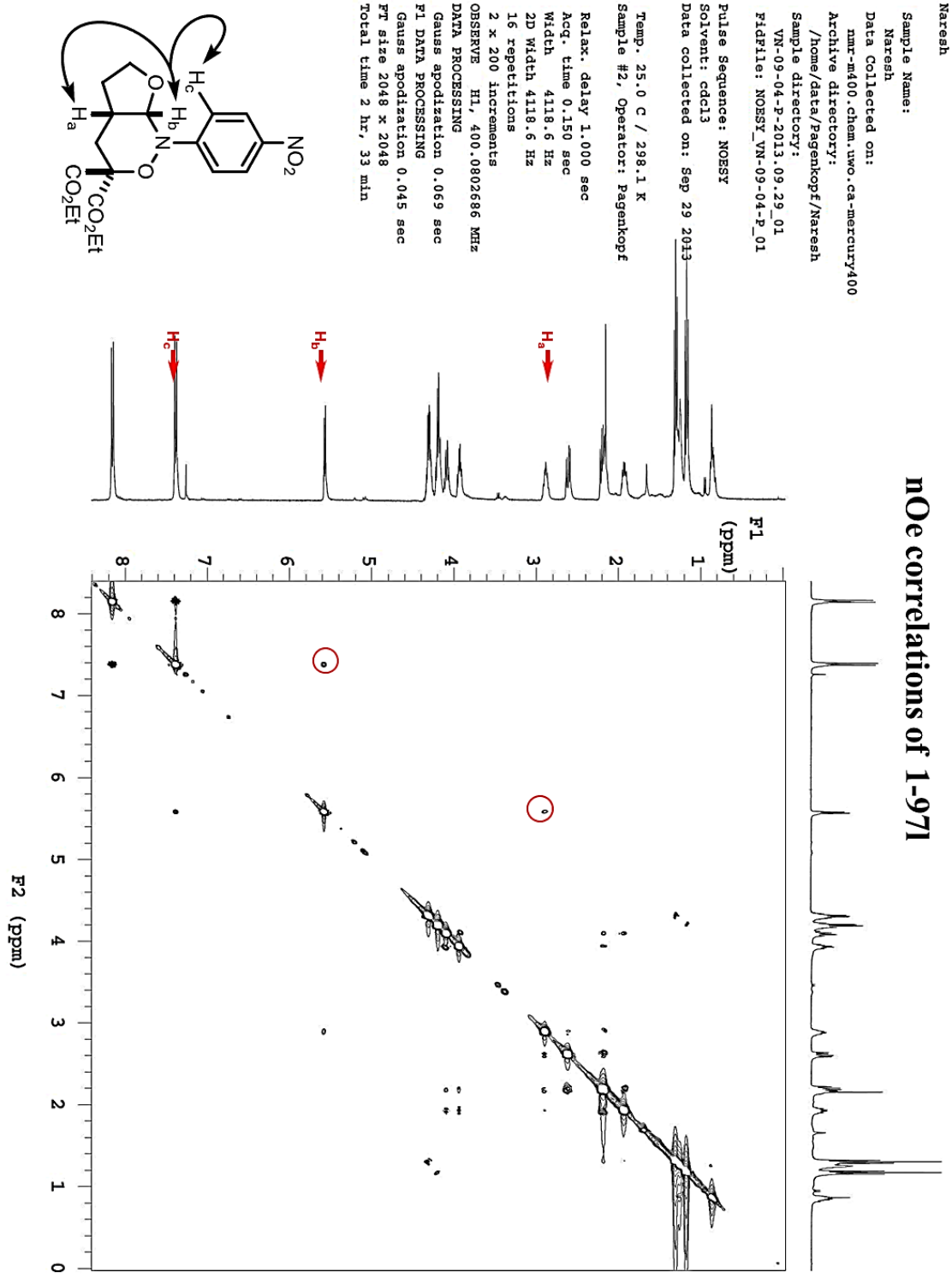




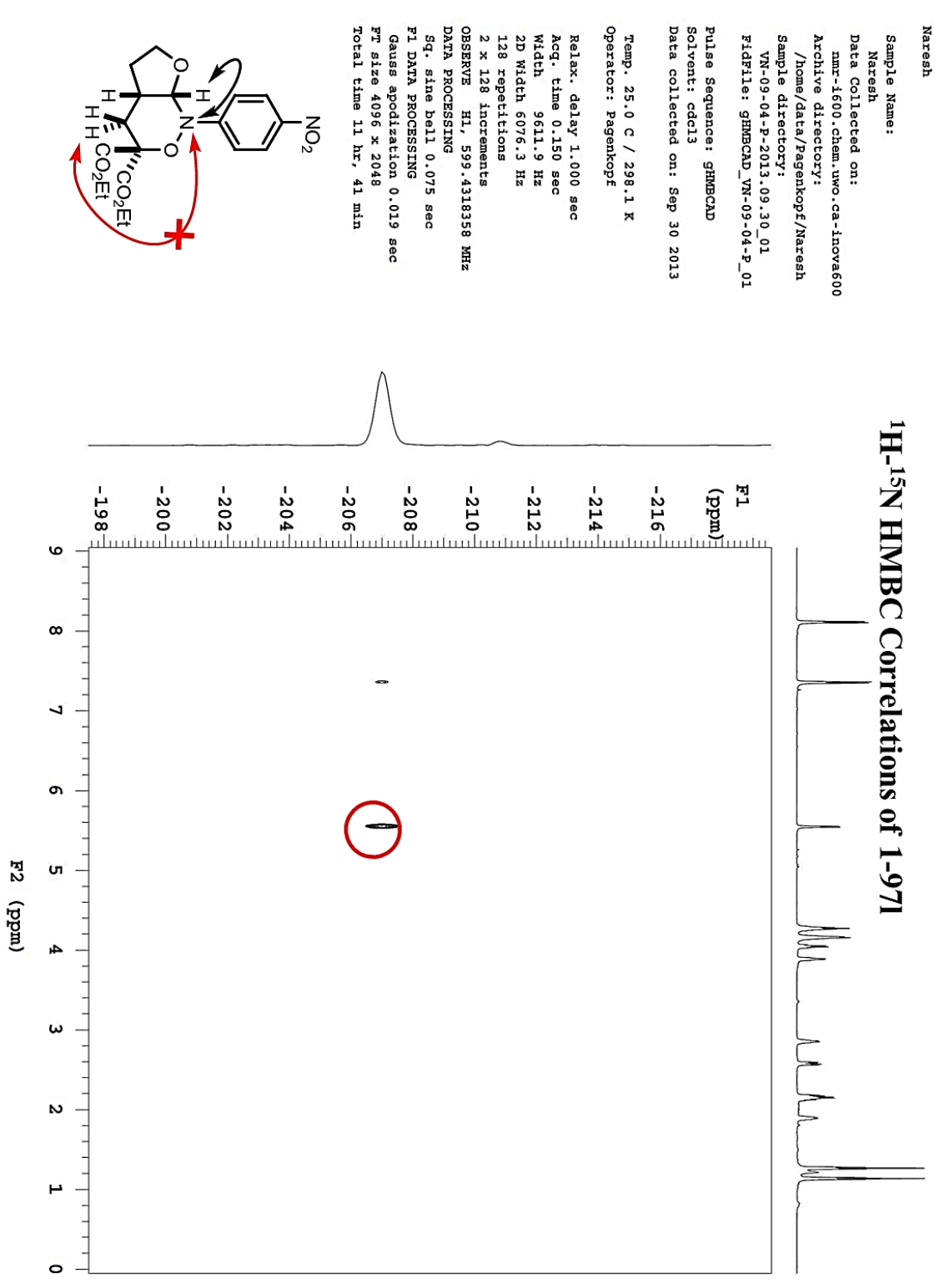


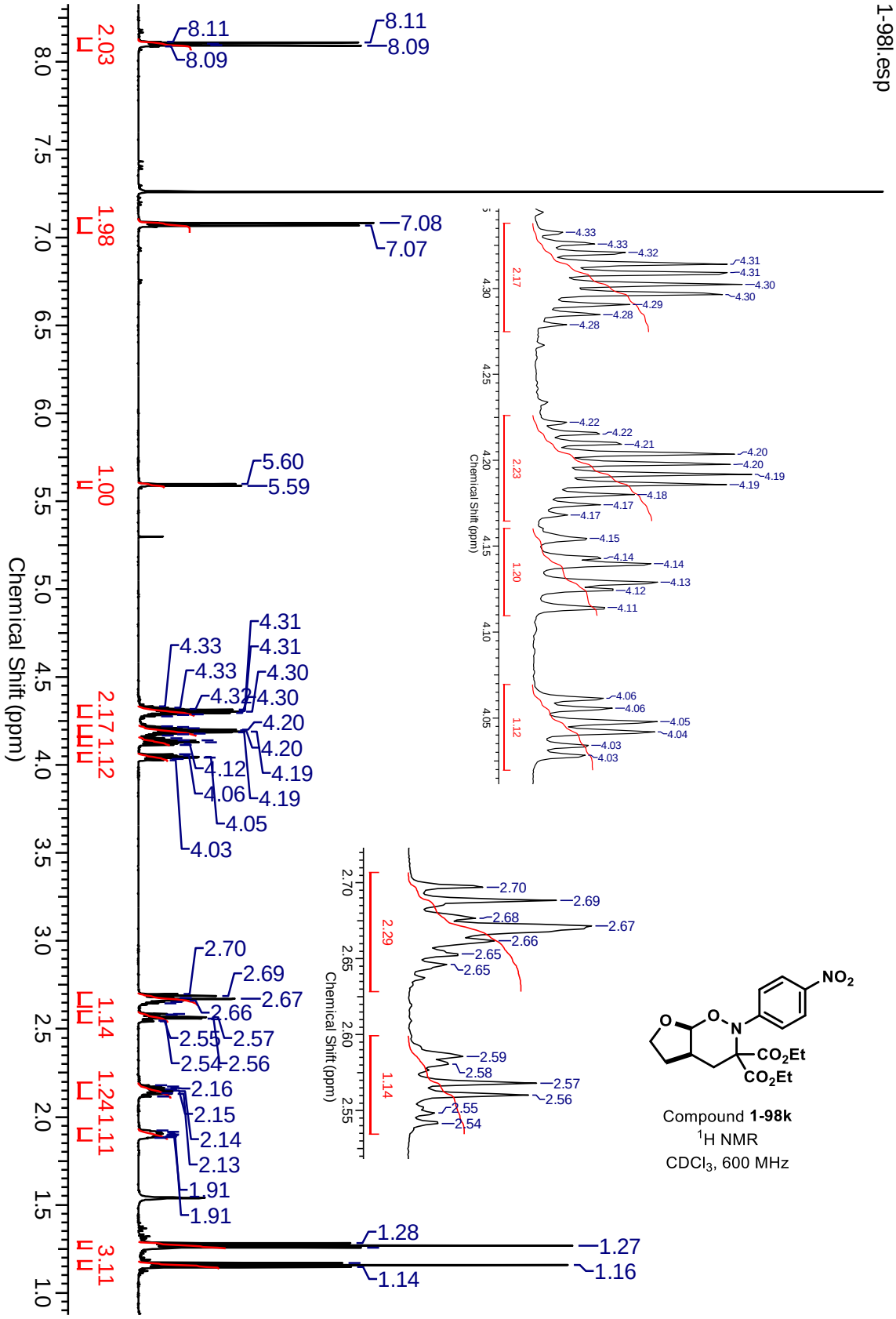


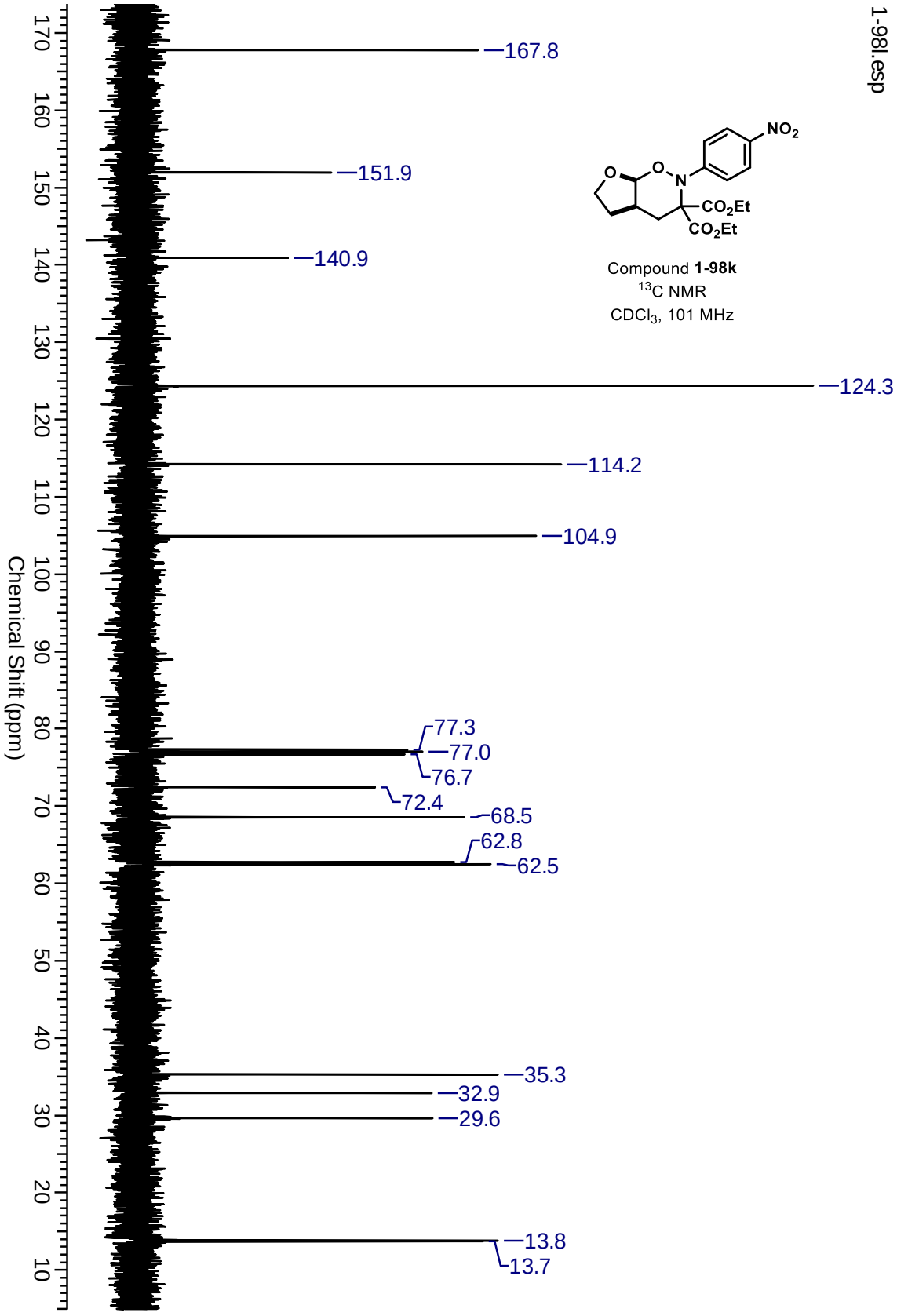
nOe correlations of 1-97l

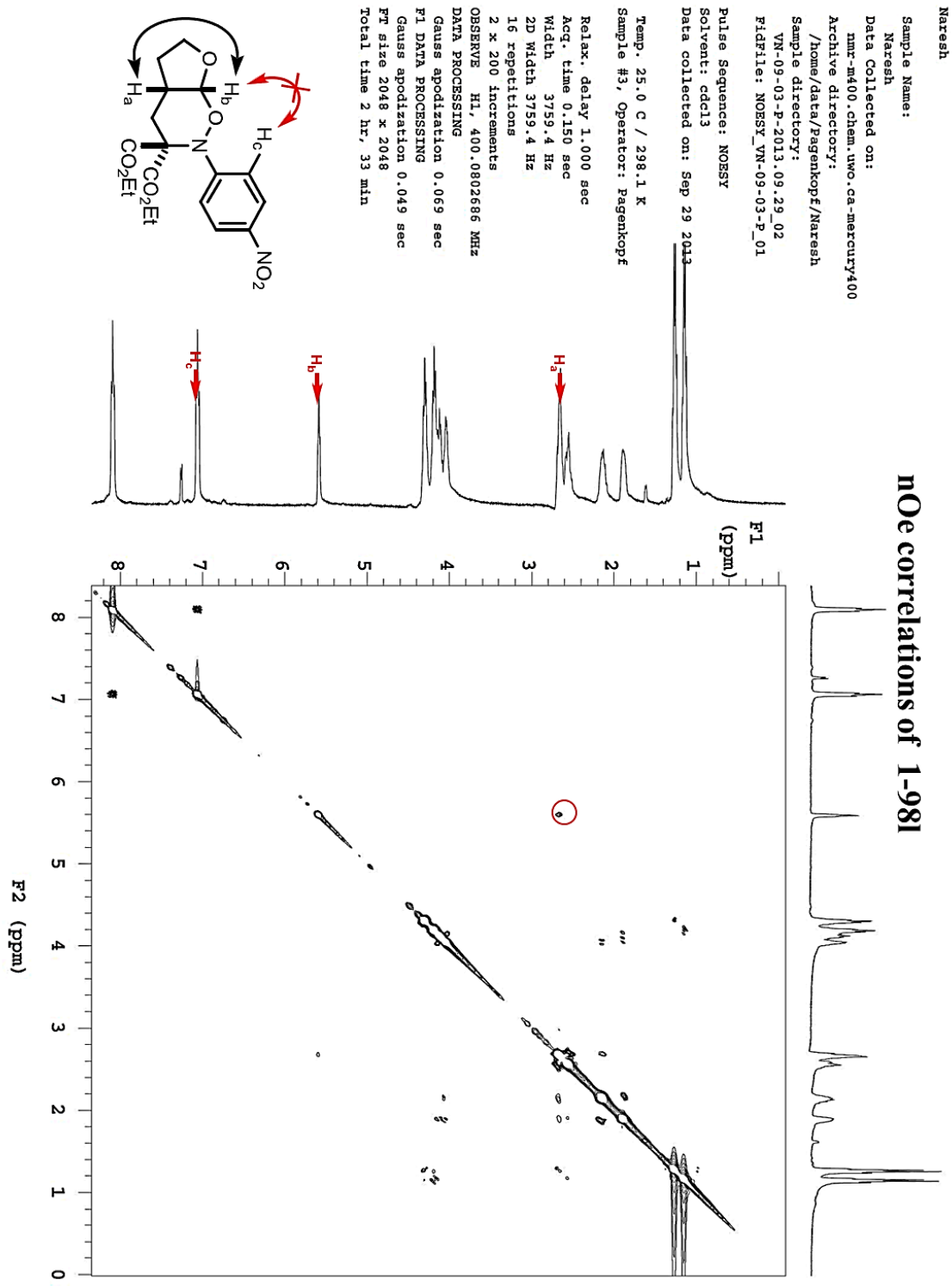


^{1}H-^{15}N HMBC Correlations of 1-97l

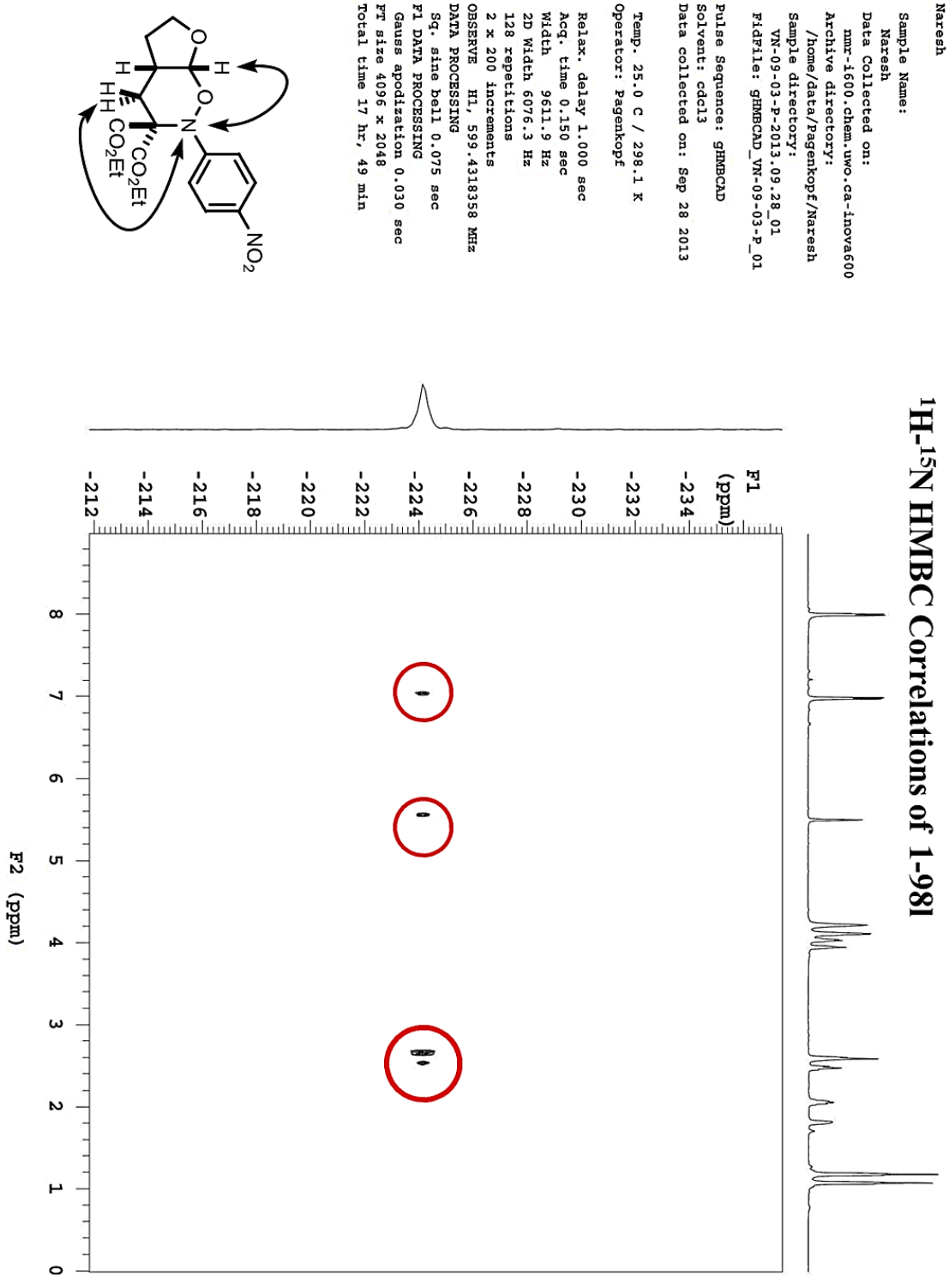


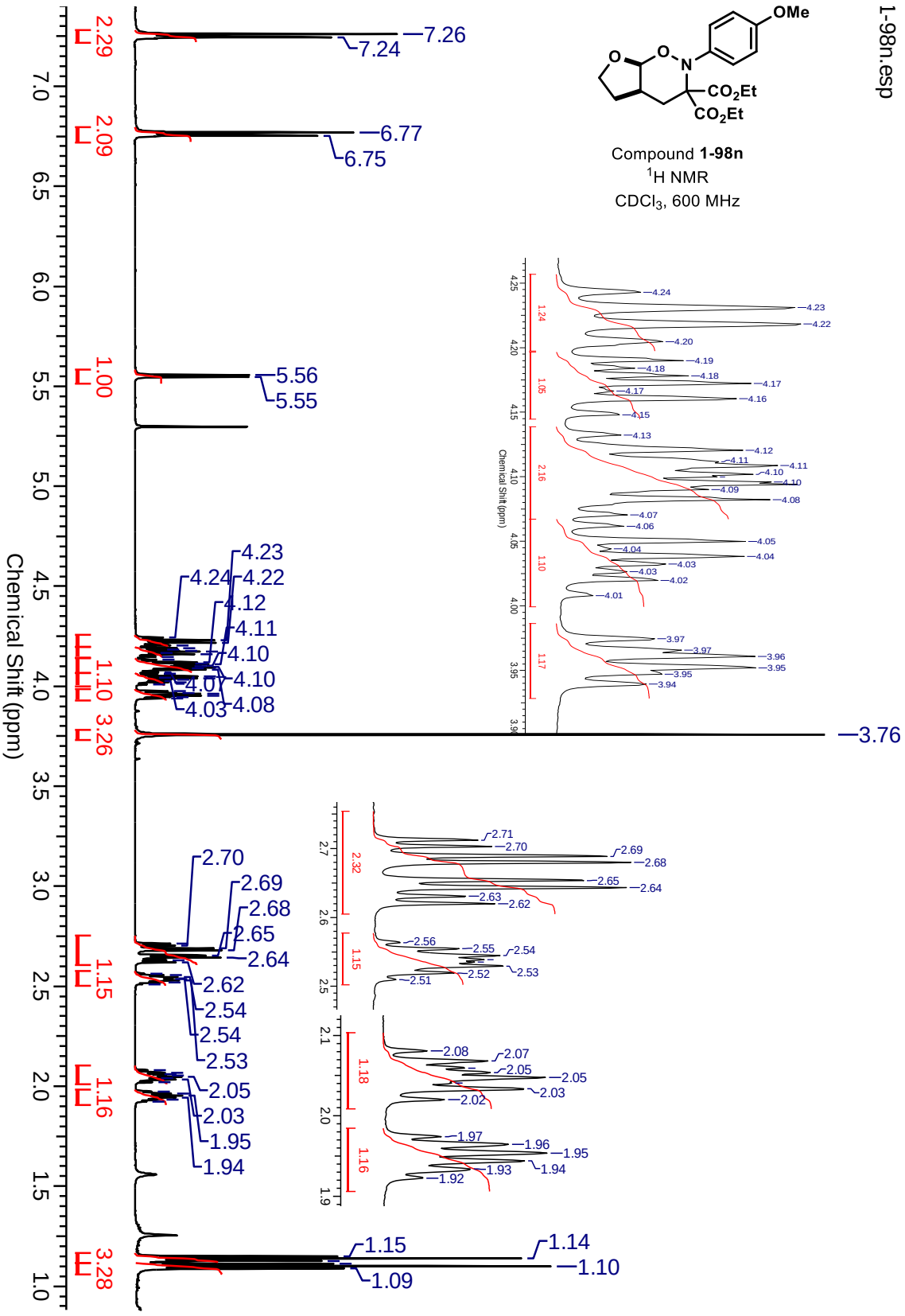


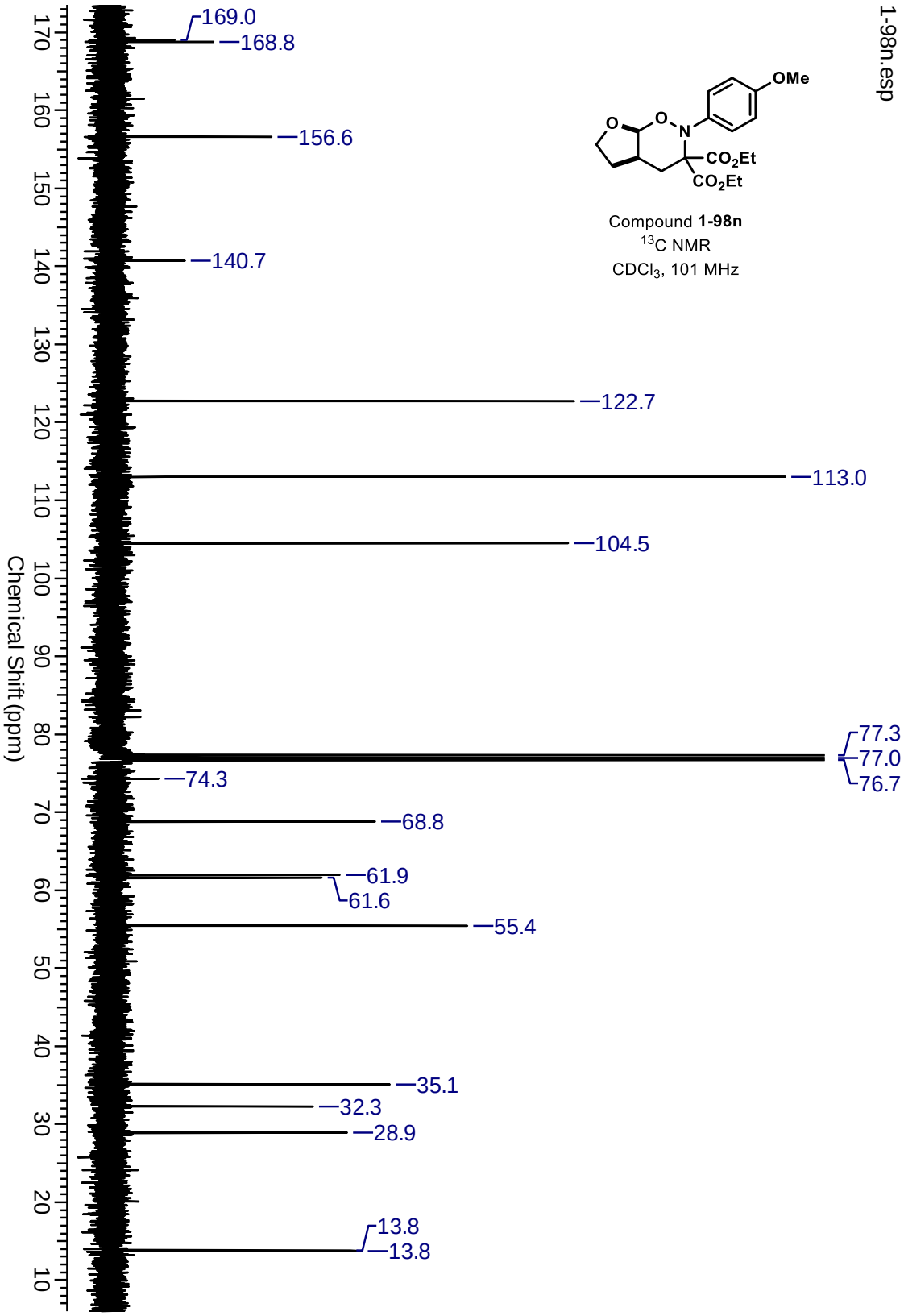




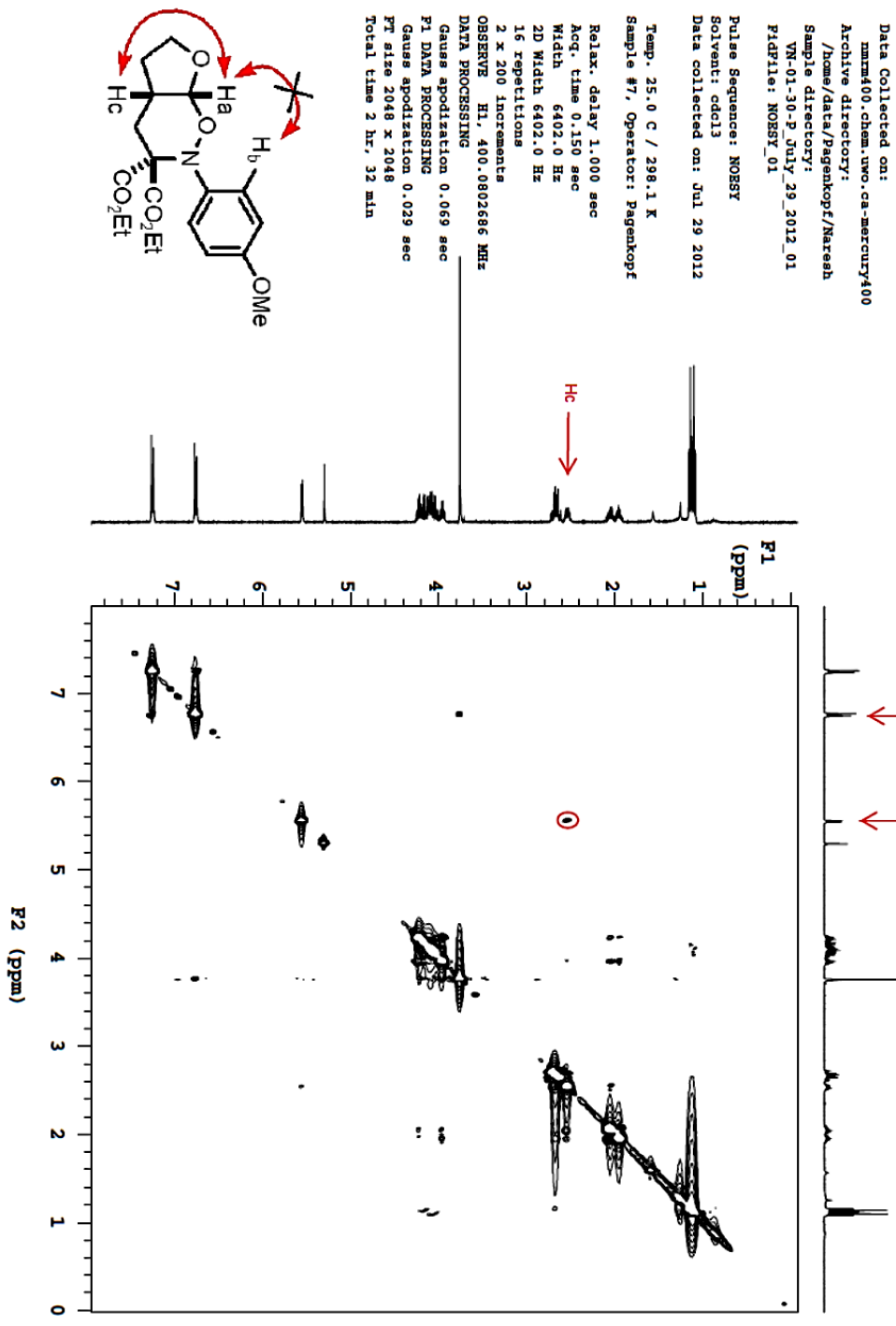
^{1}H-^{15}N HMBC Correlations of 1-98l



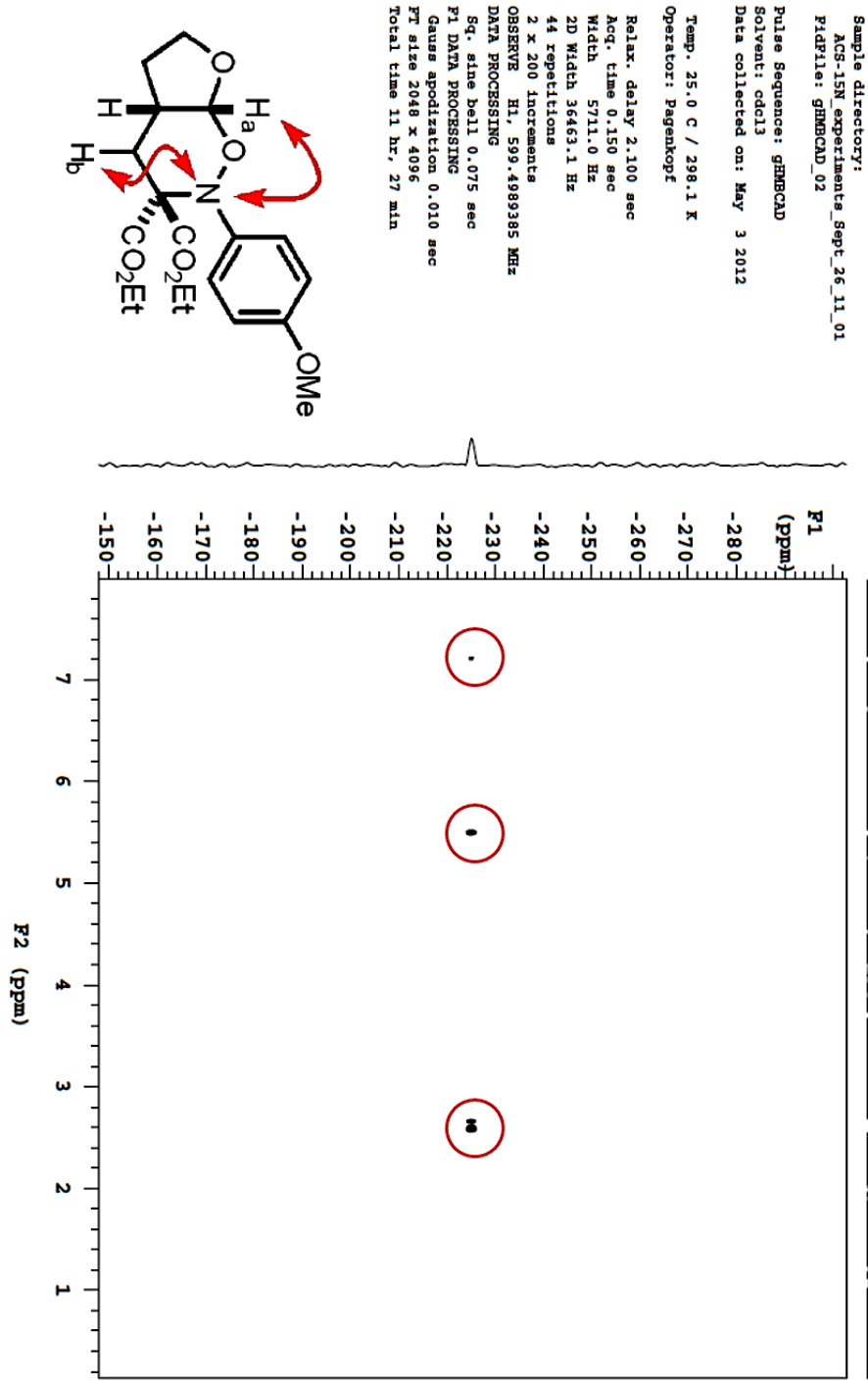


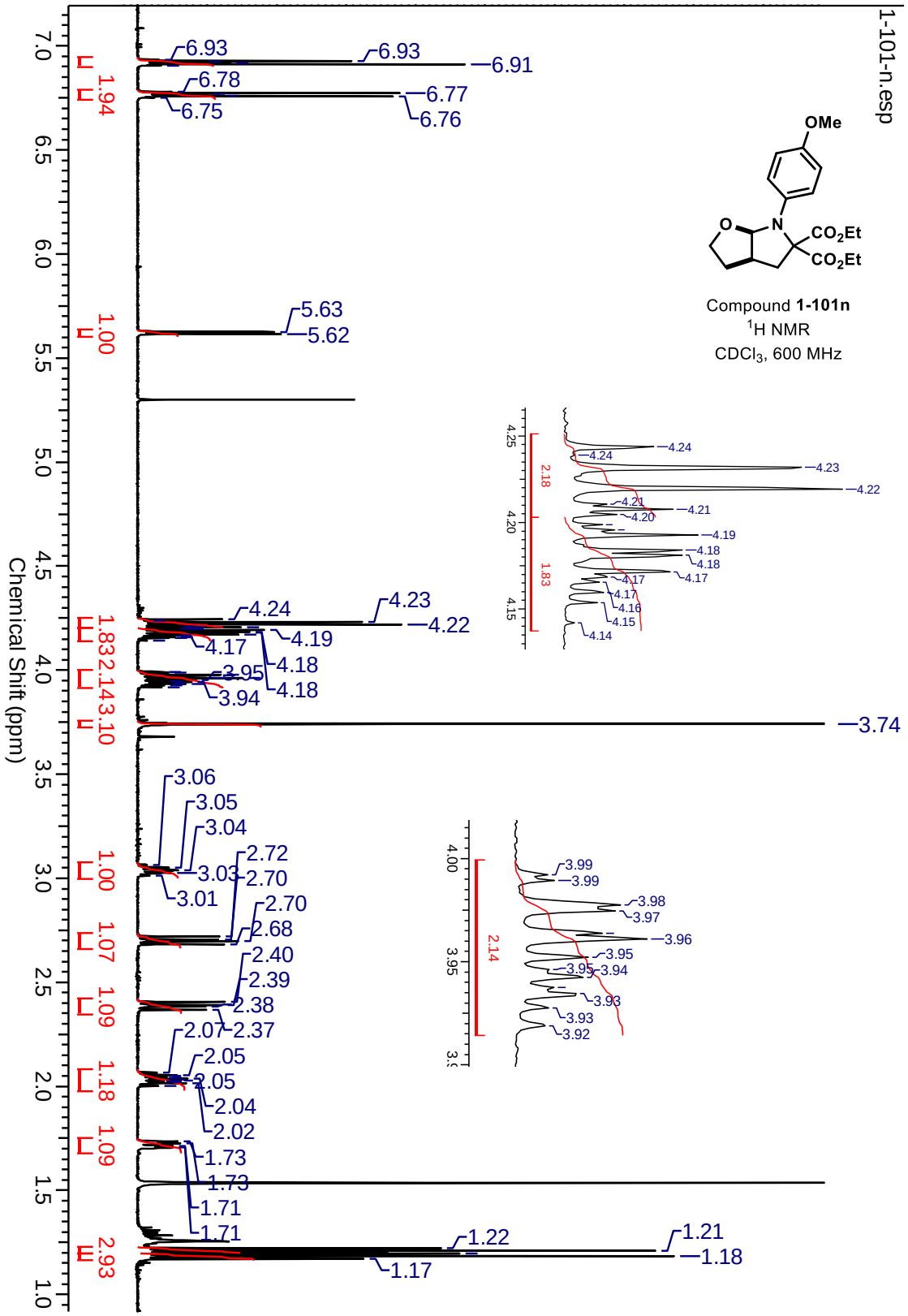


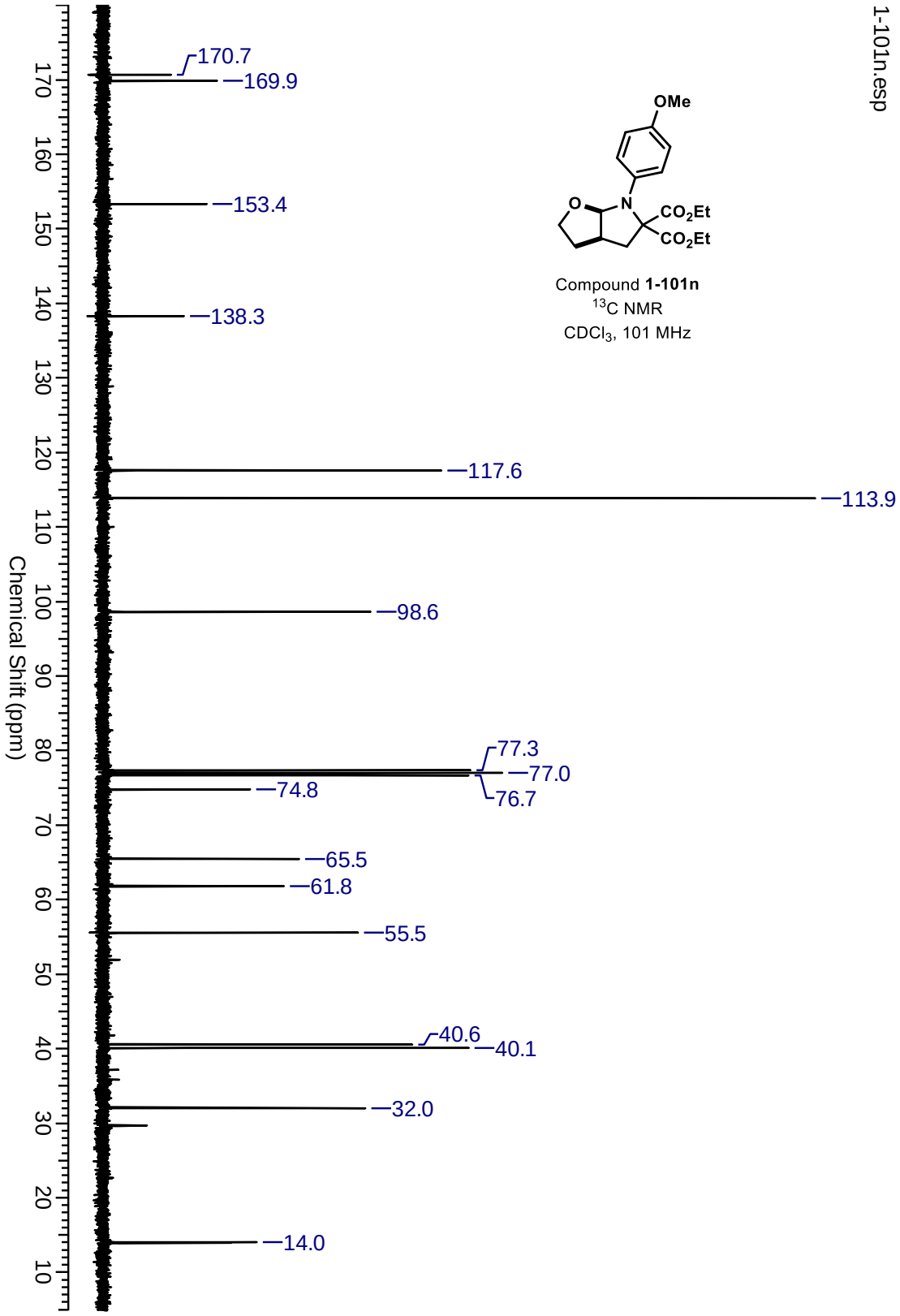
nOe Correlations of 1-98n



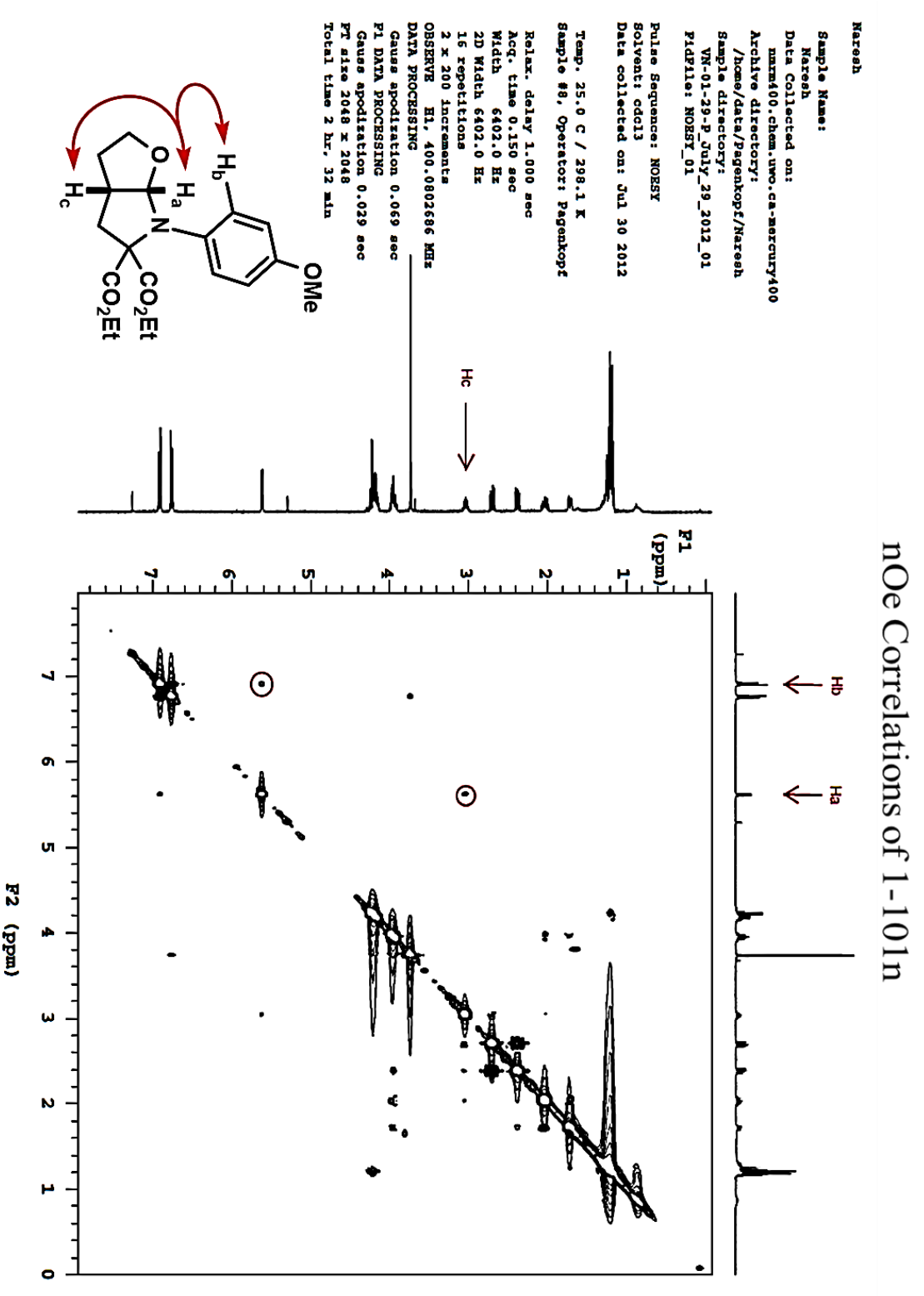
^{1}H - ^{15}N HMBC Correlations of 1-98n



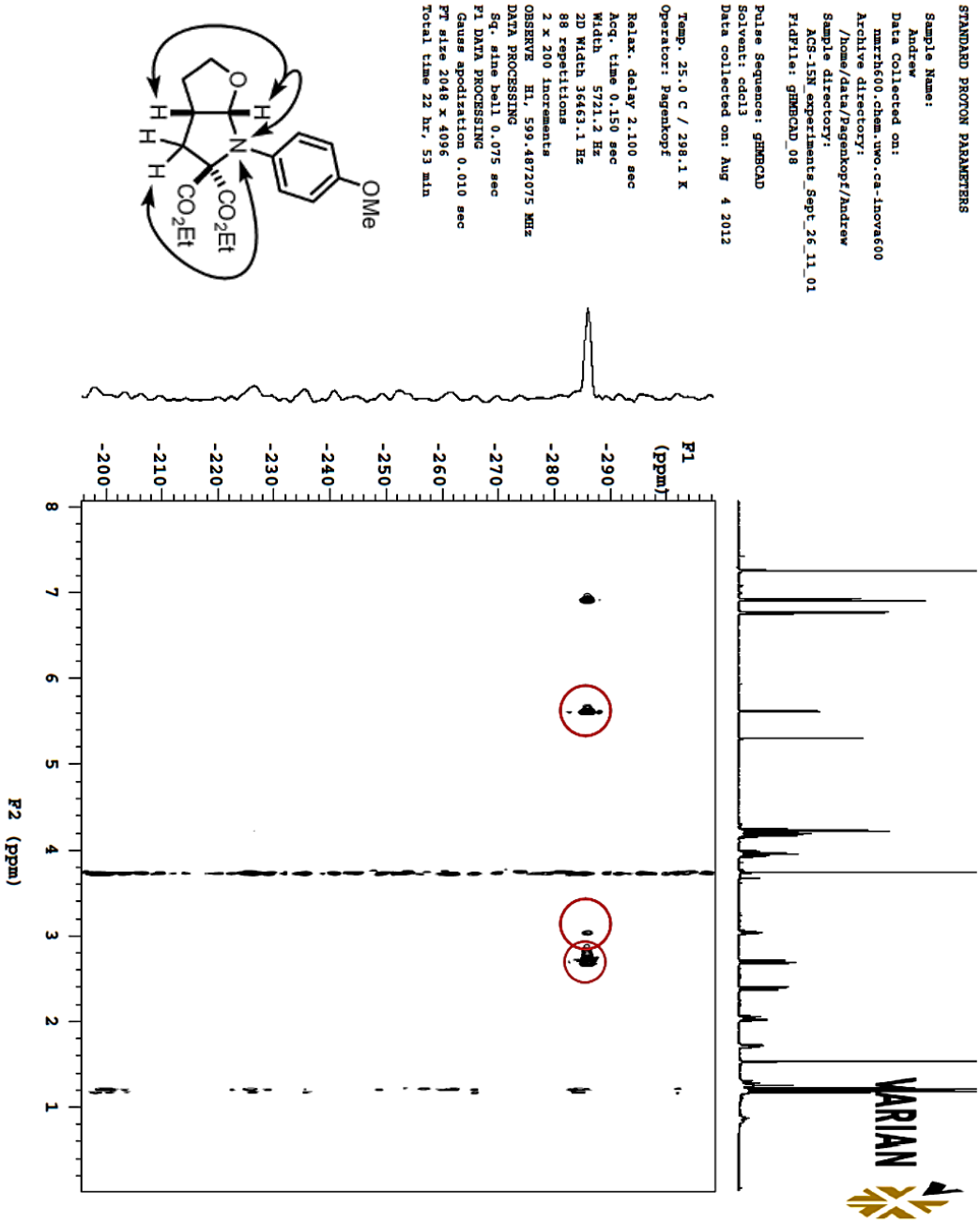


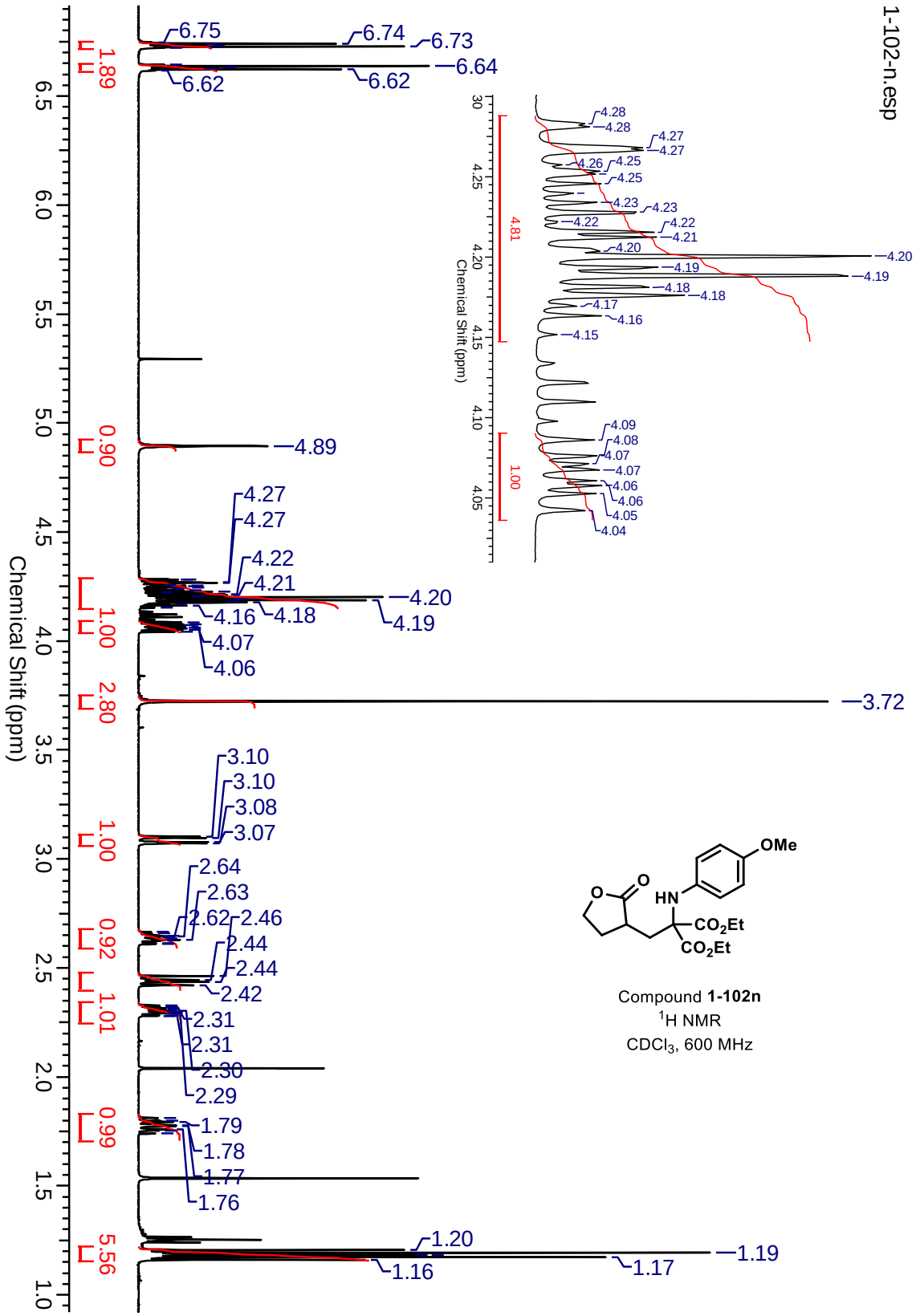


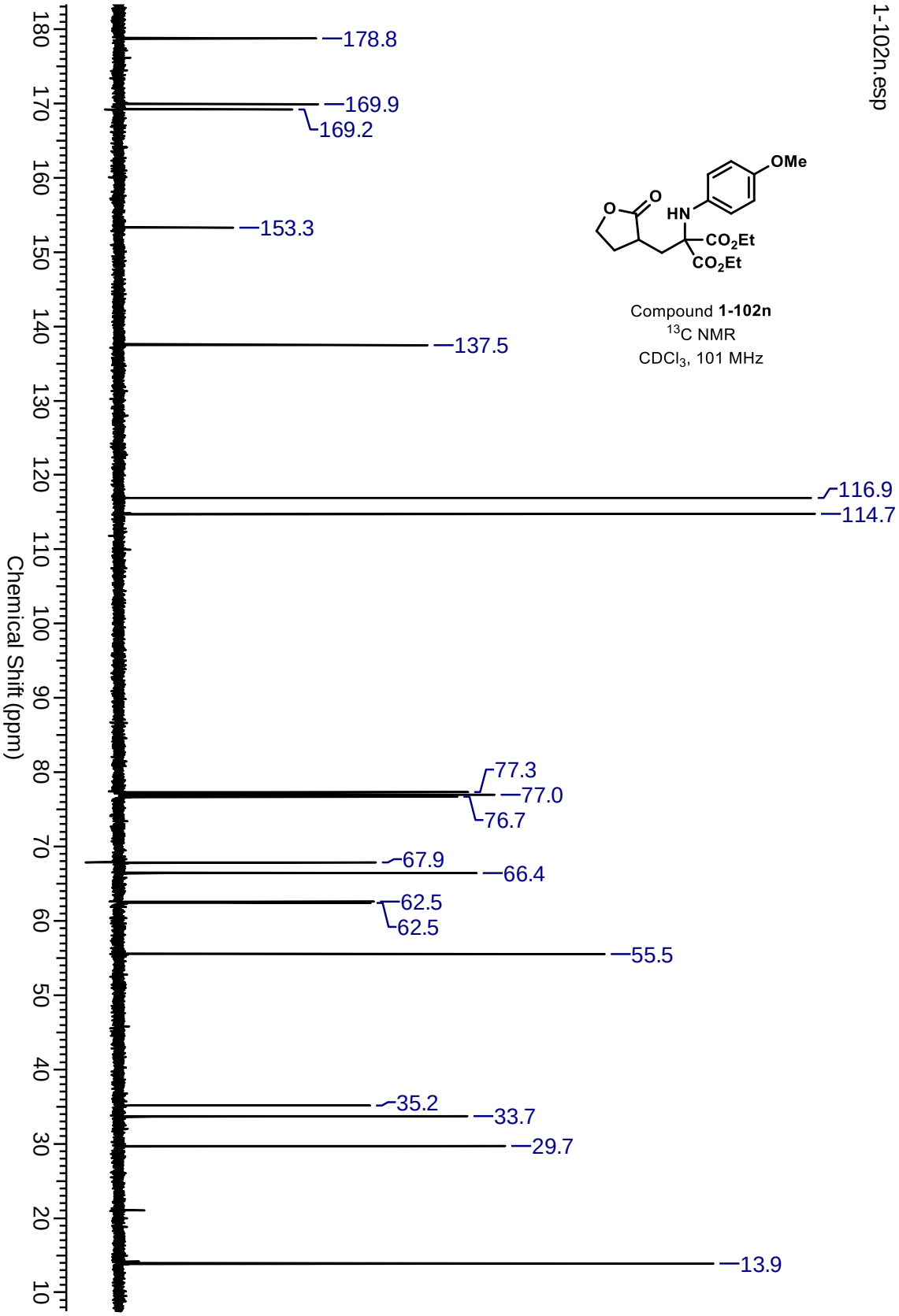
nOe Correlations of 1-101n

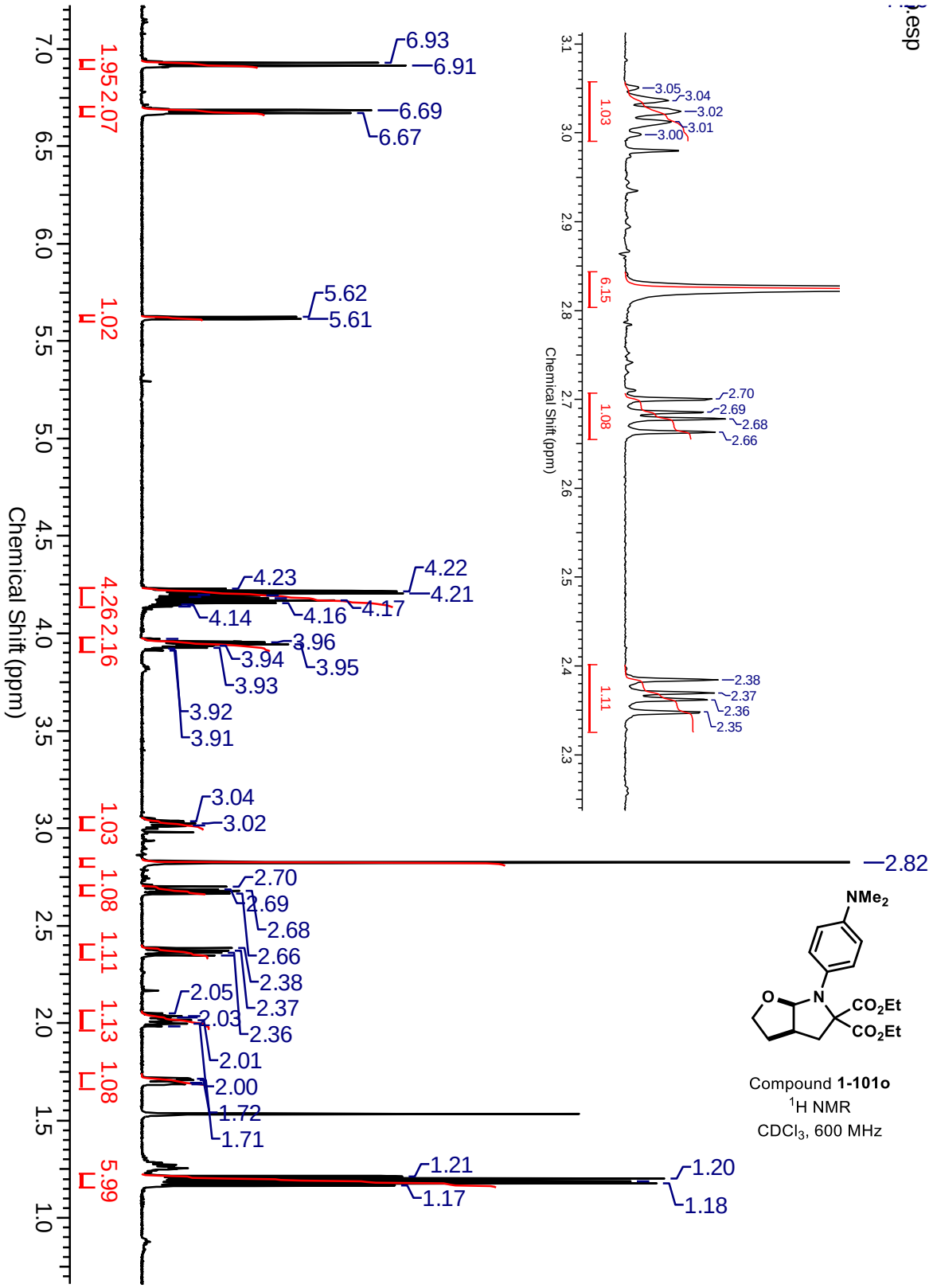


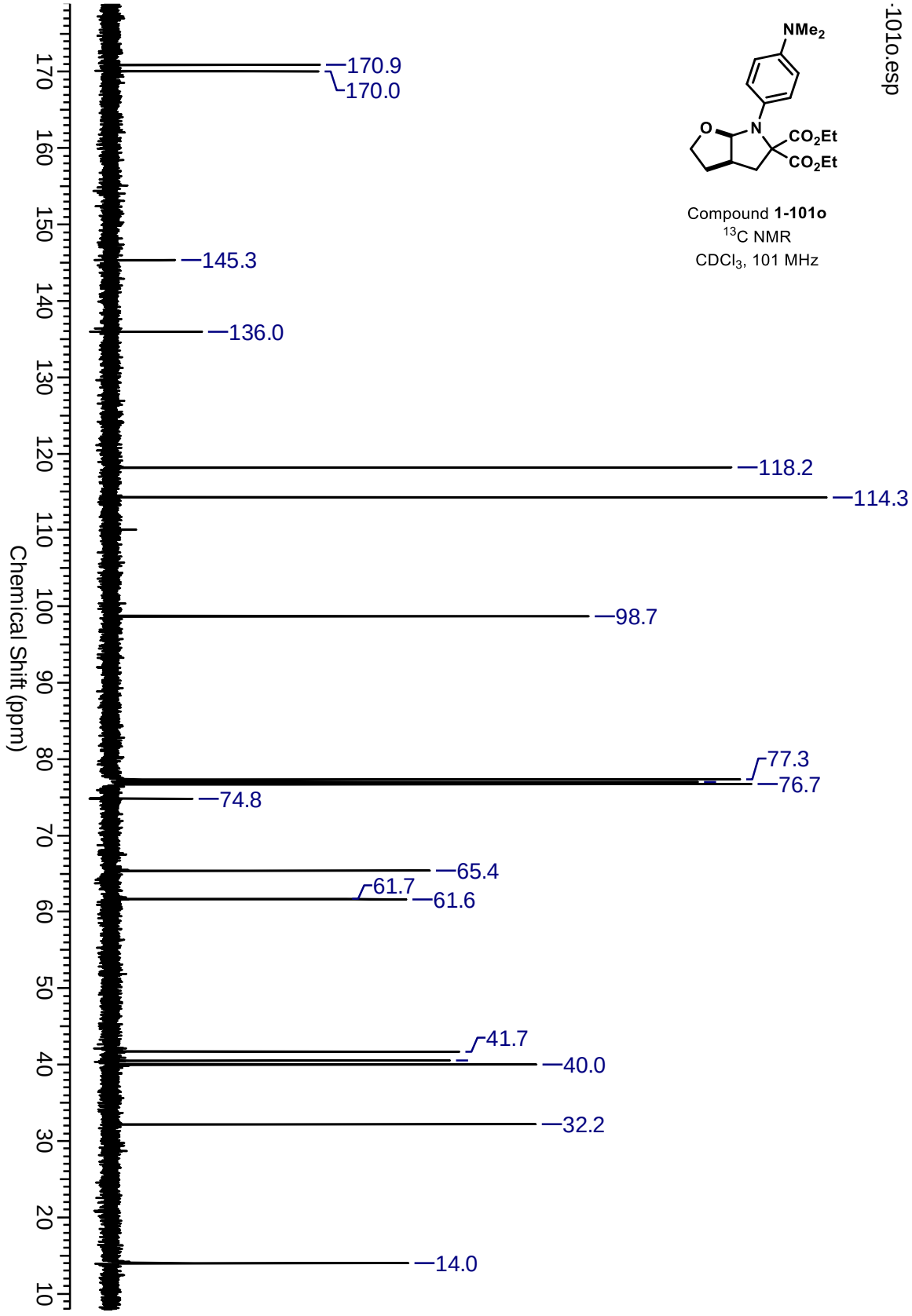
^{1}H - ^{15}N HMBC Correlations of 1-101n



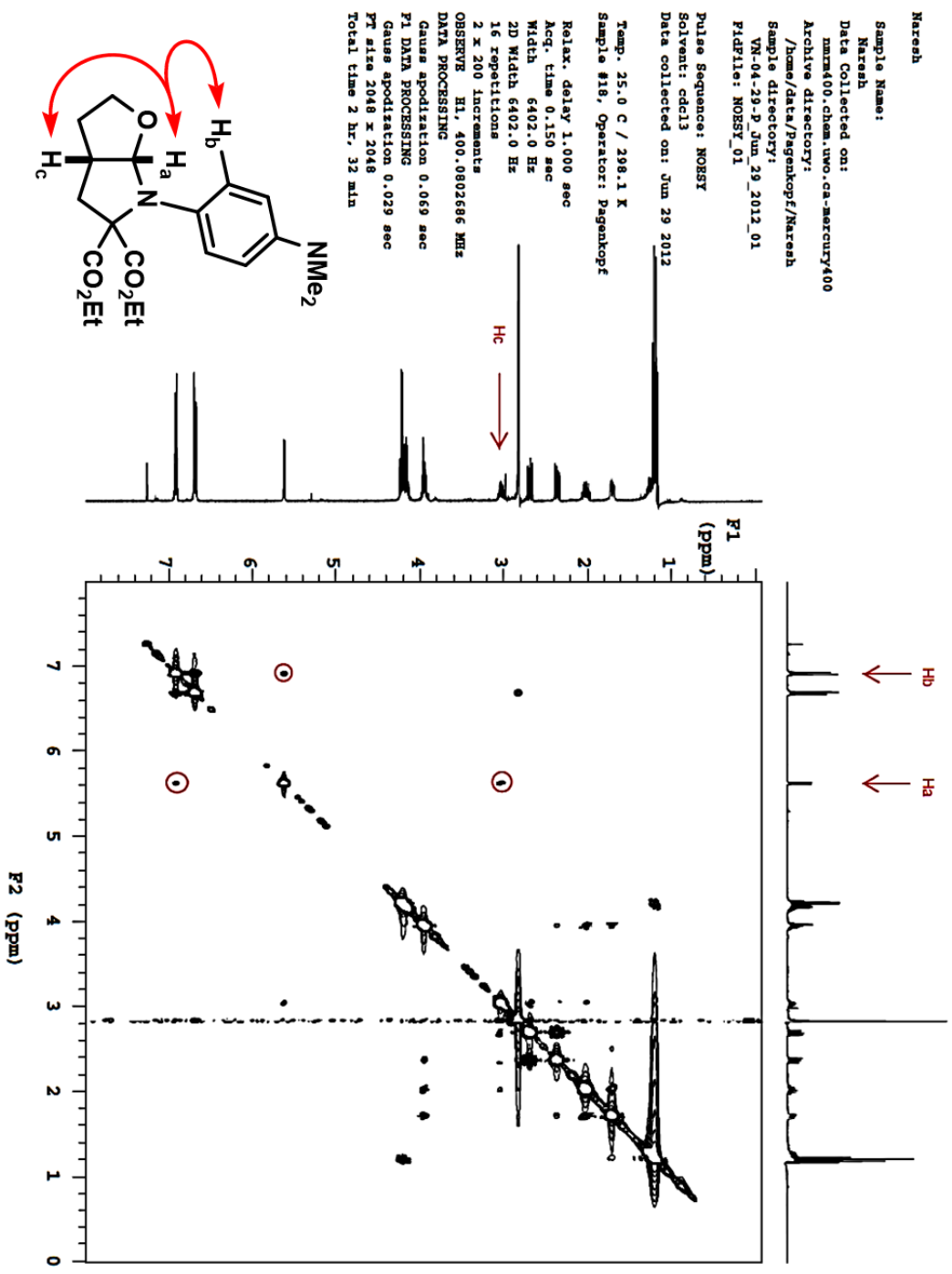


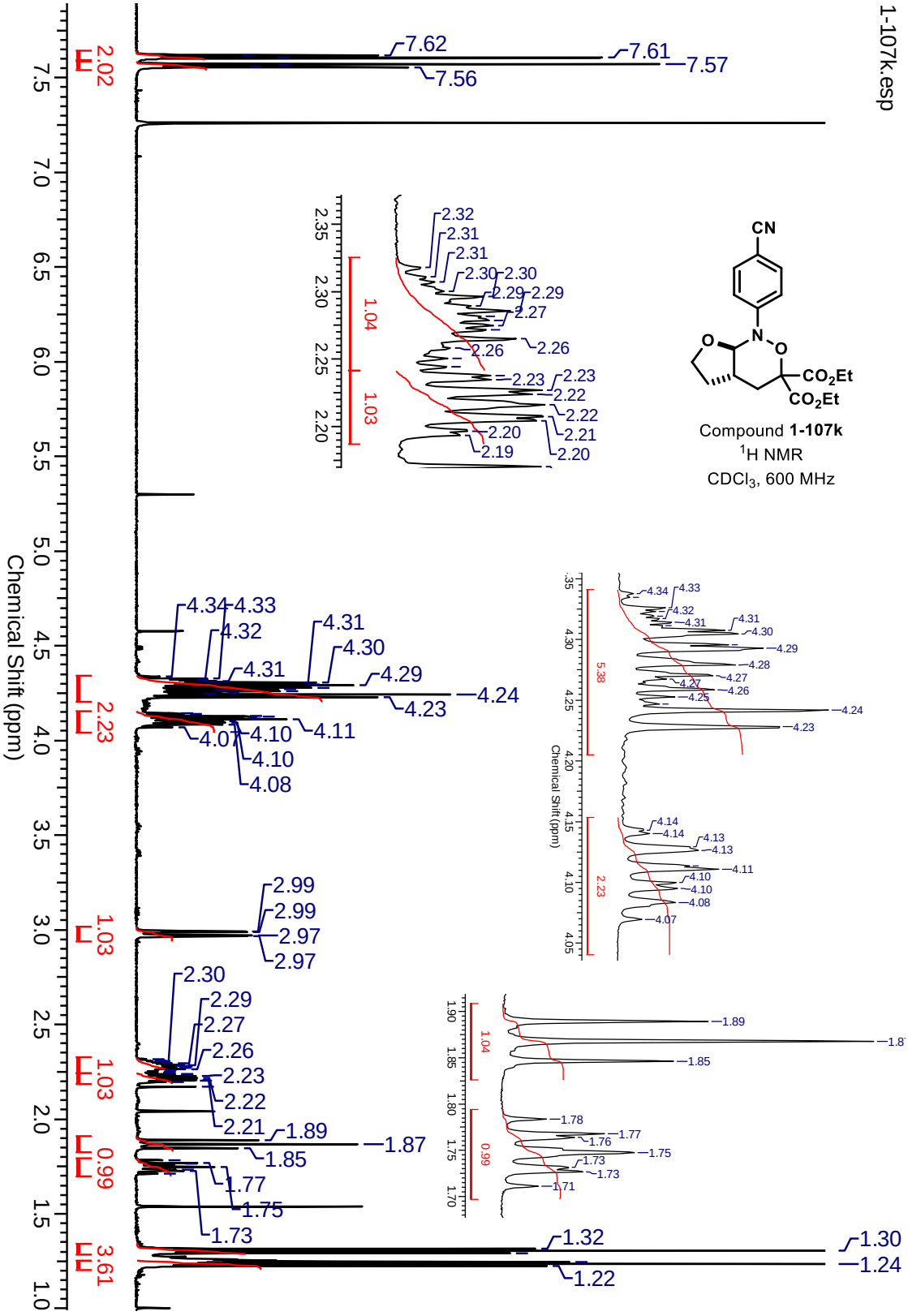


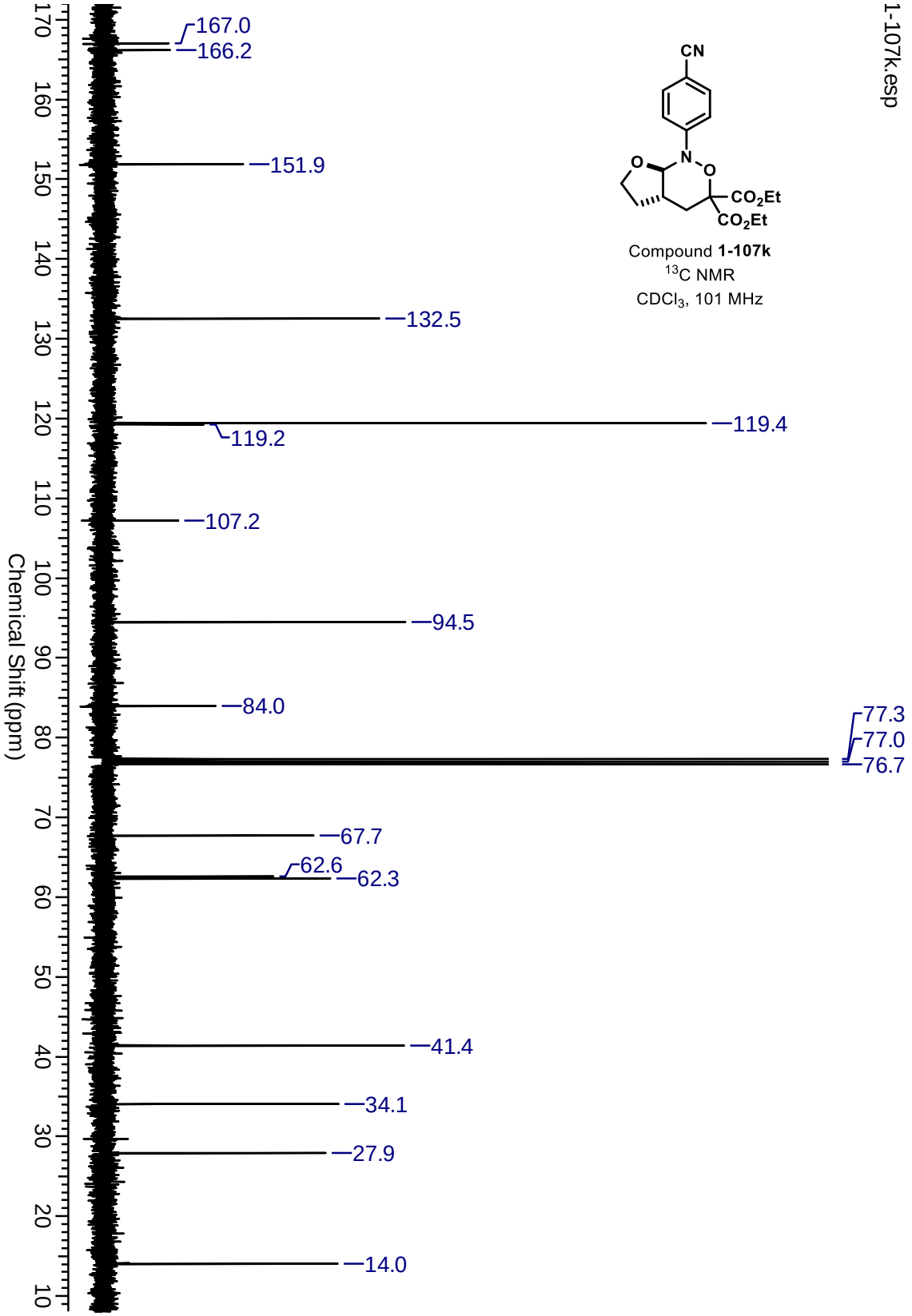


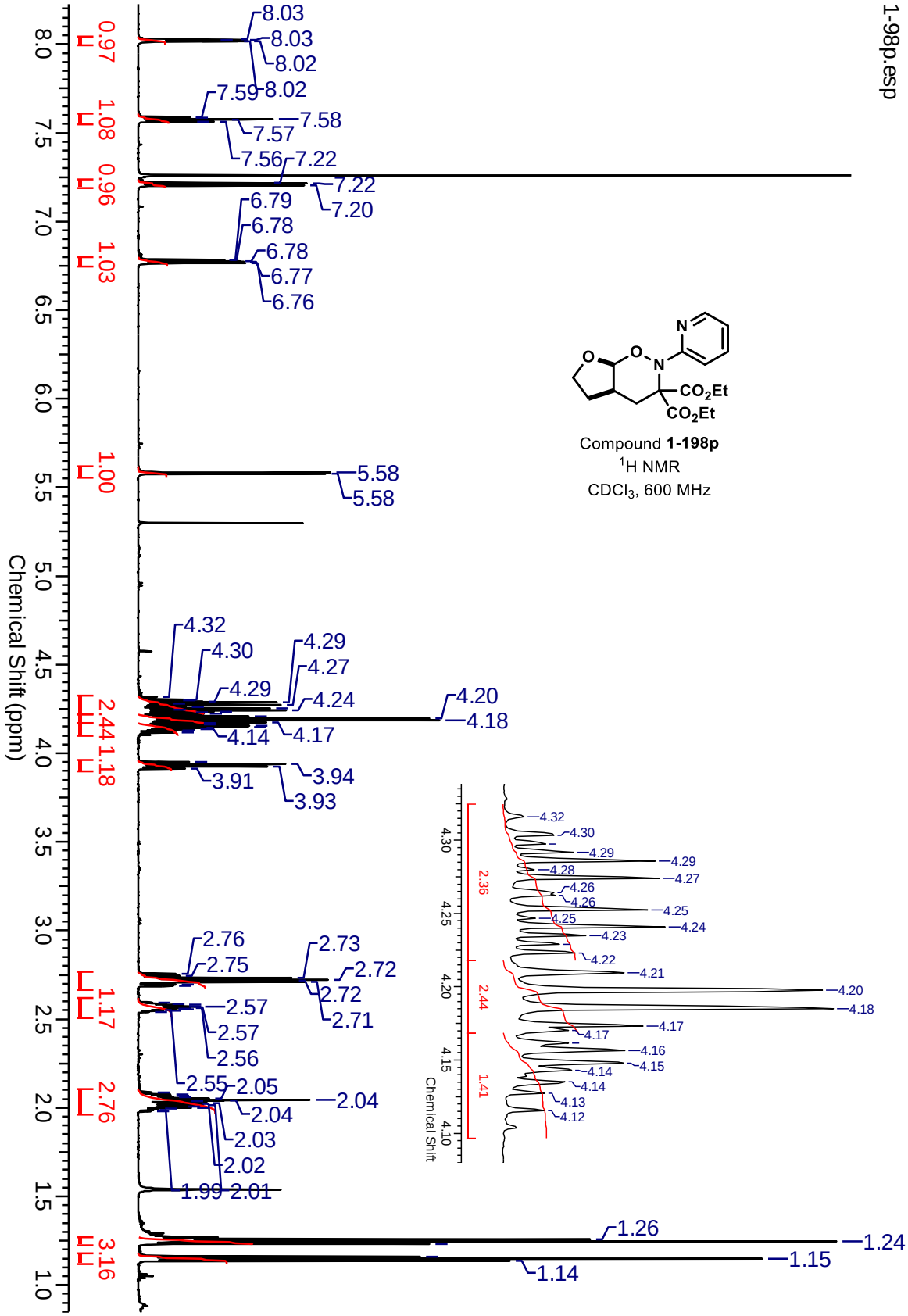


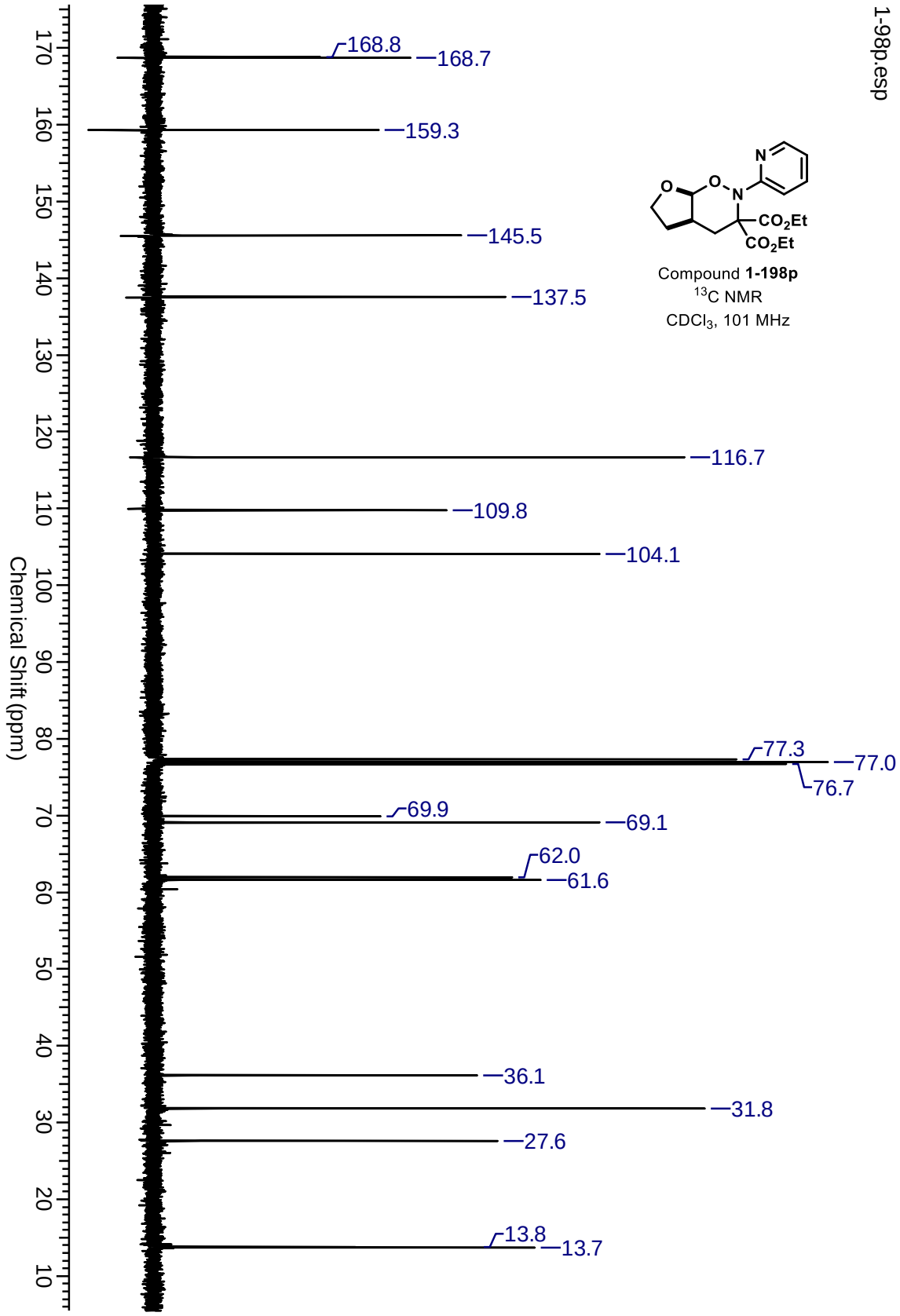
nOe Correlations of 1-101o

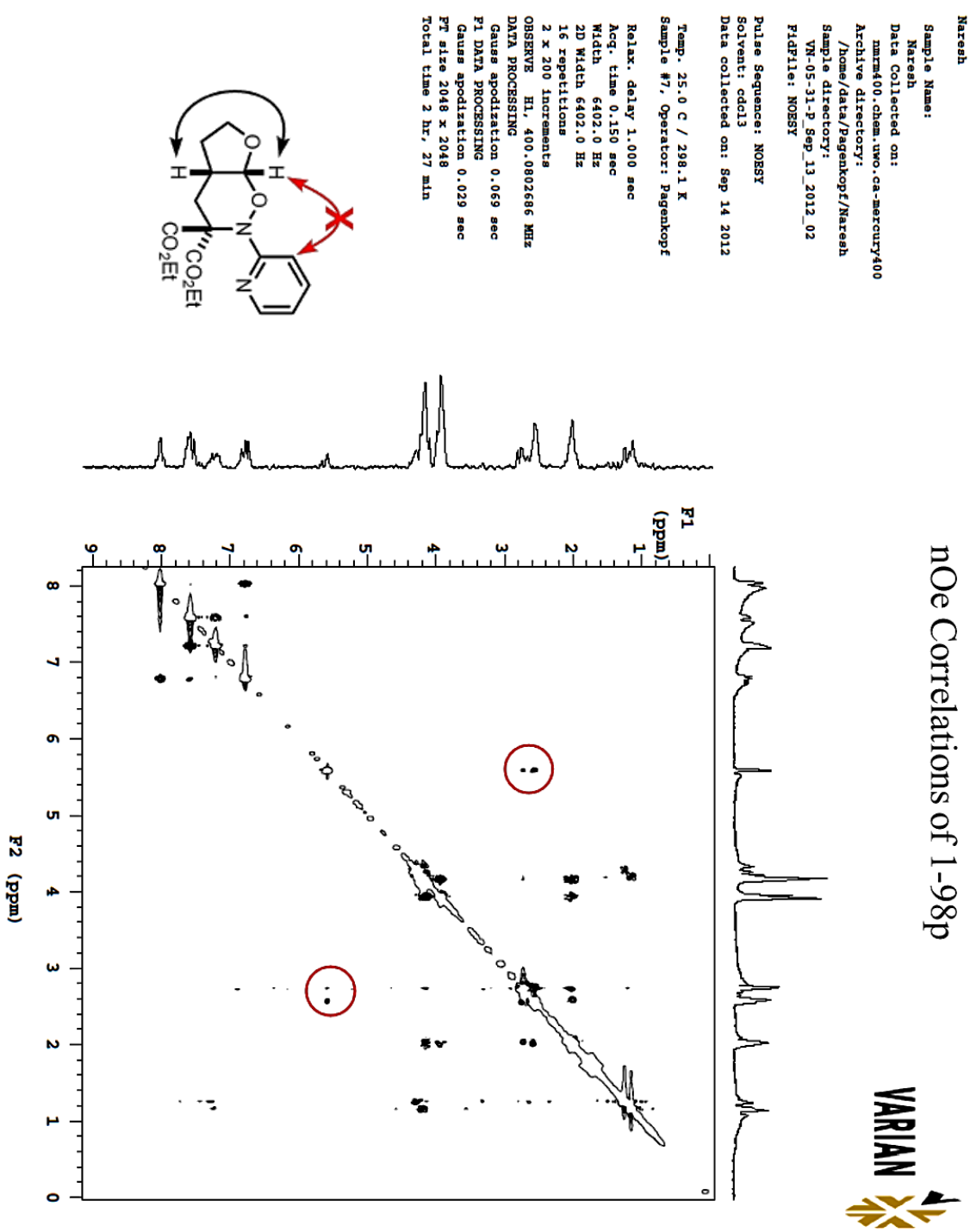


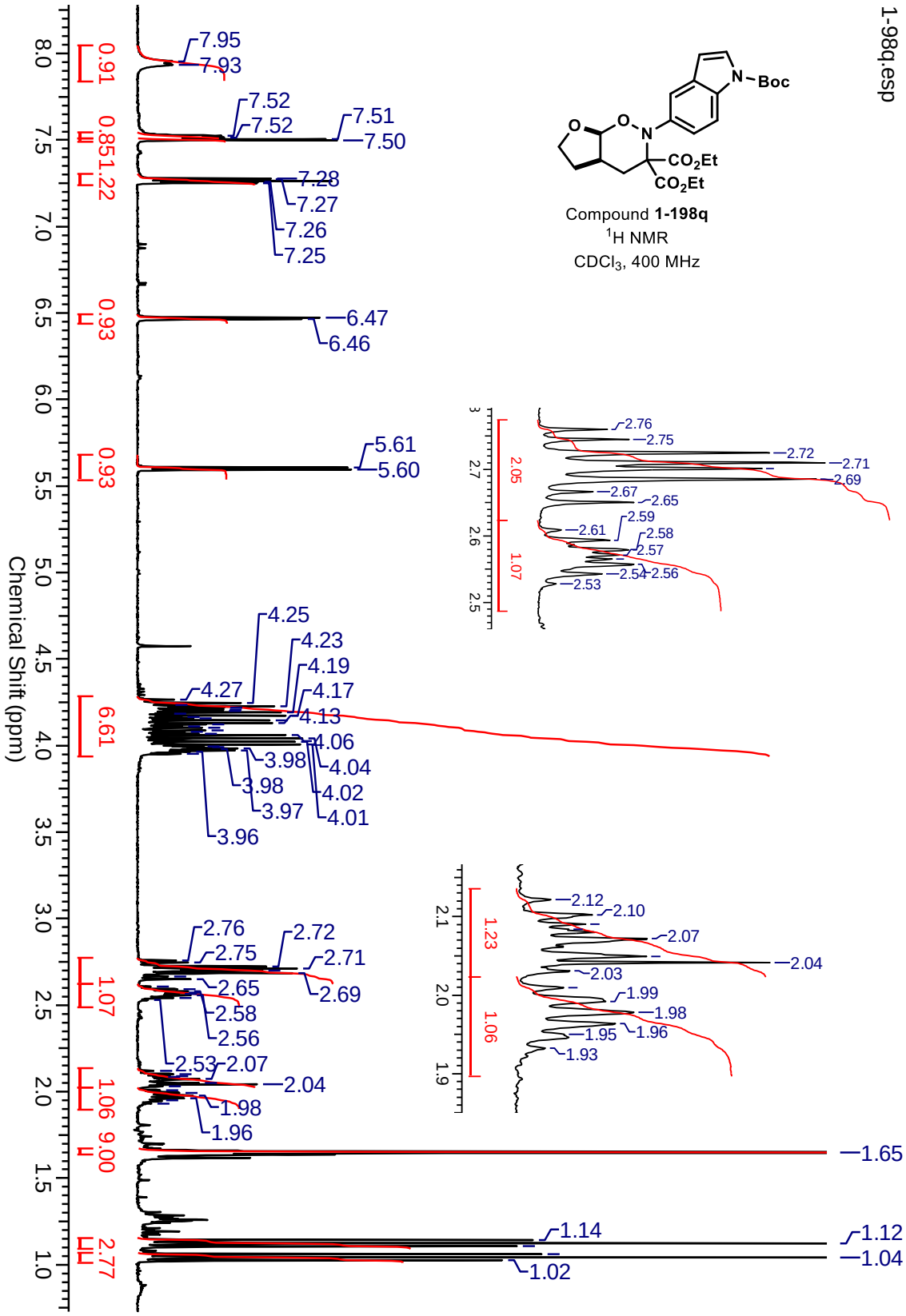


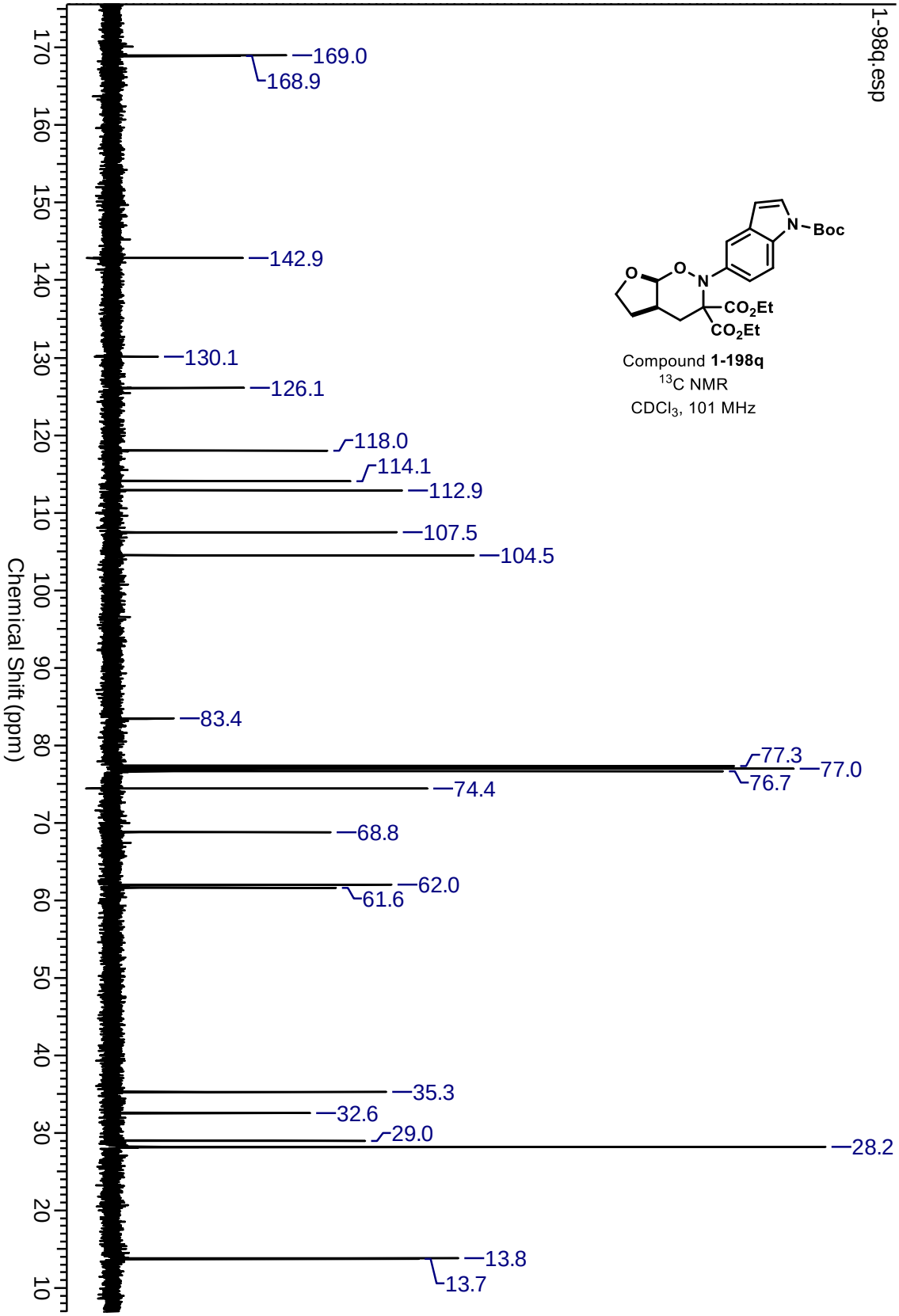




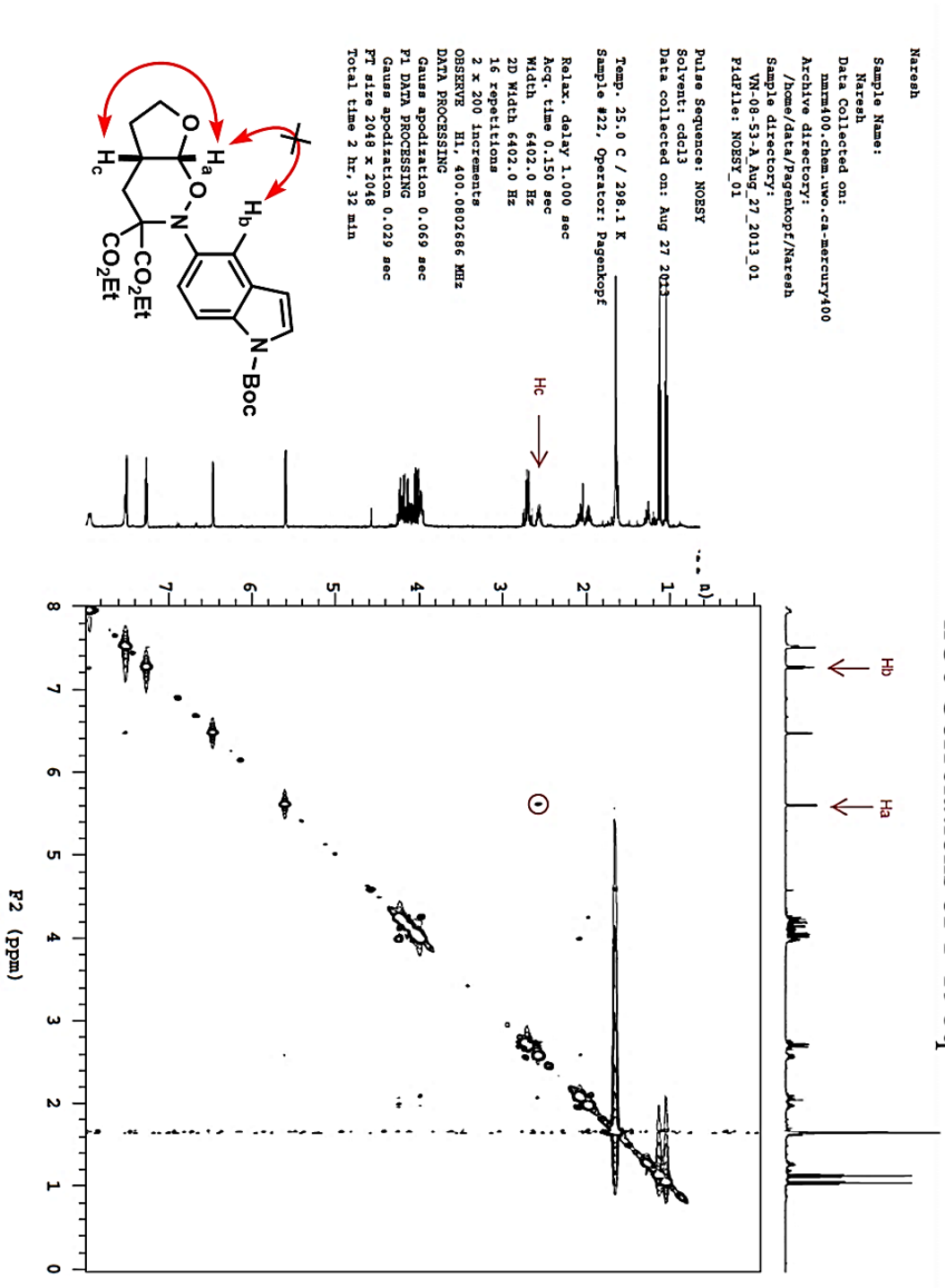


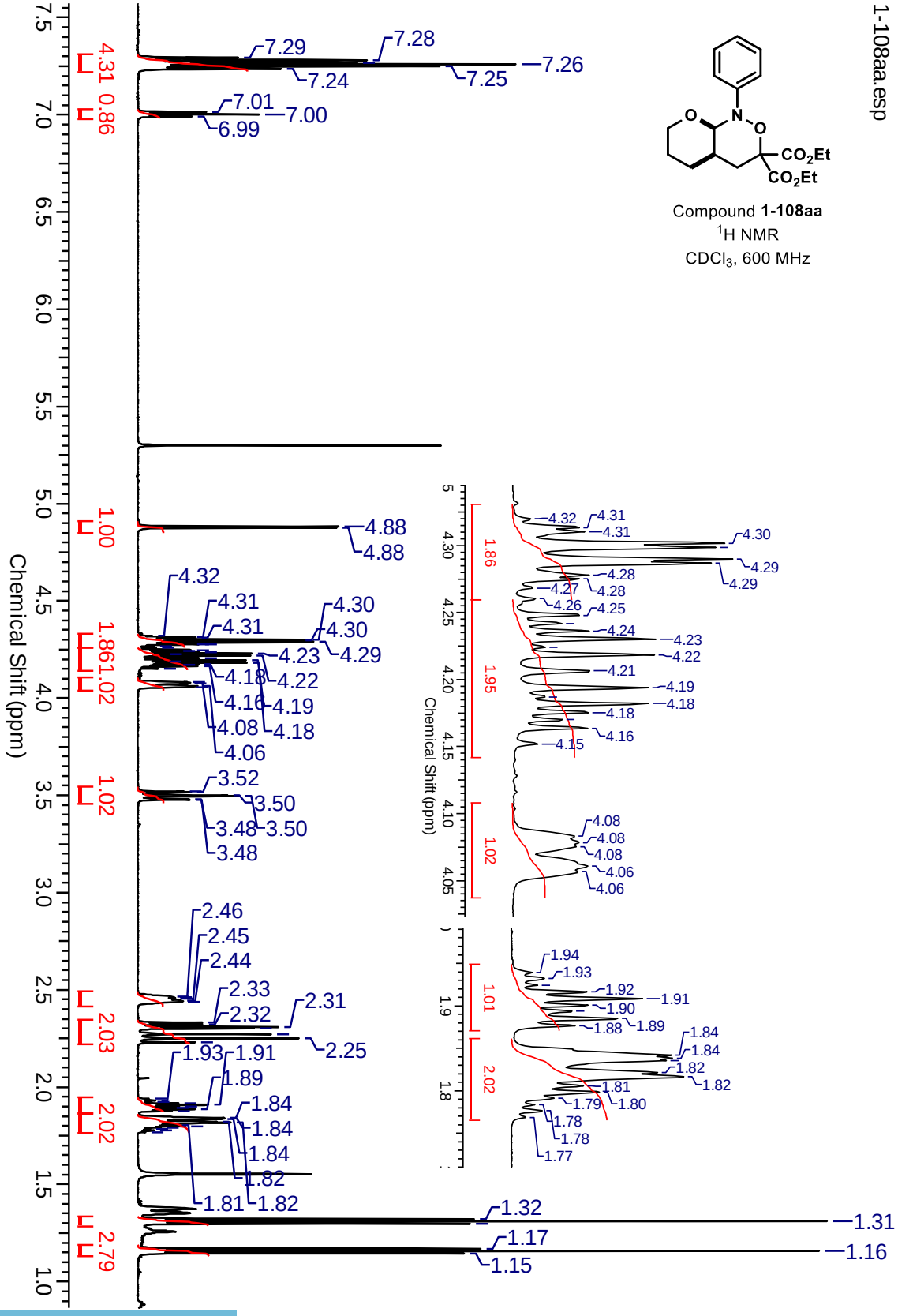


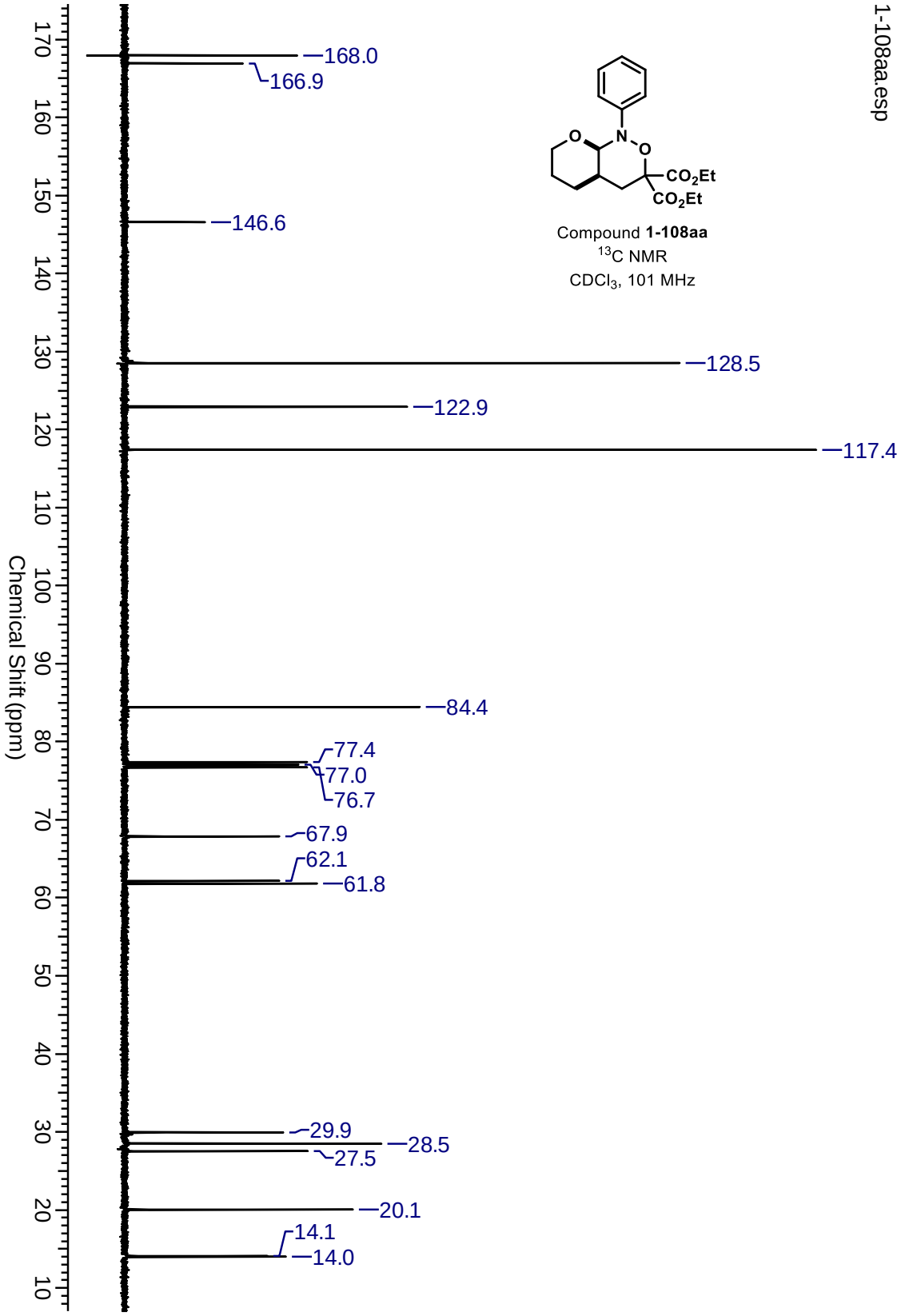


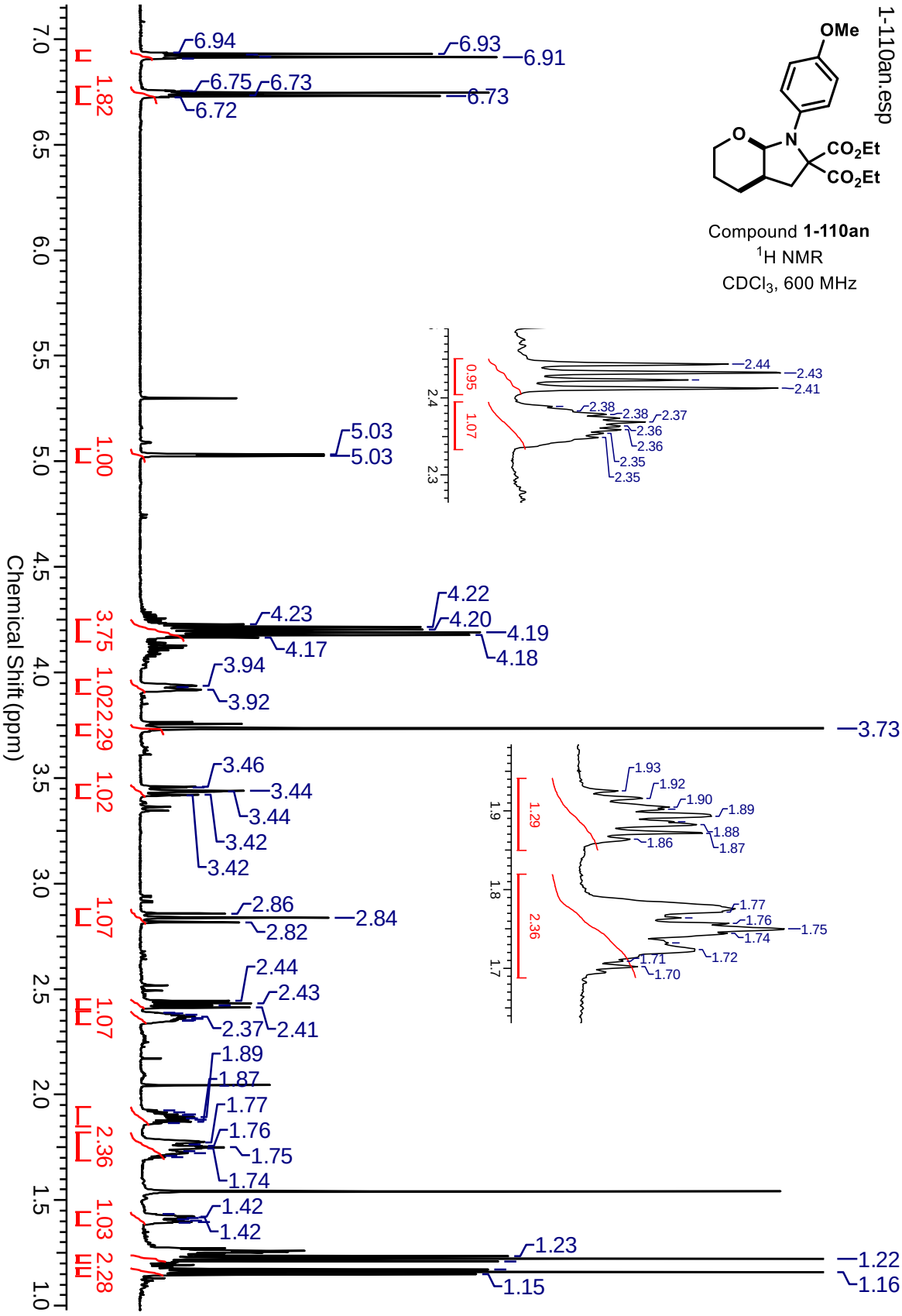


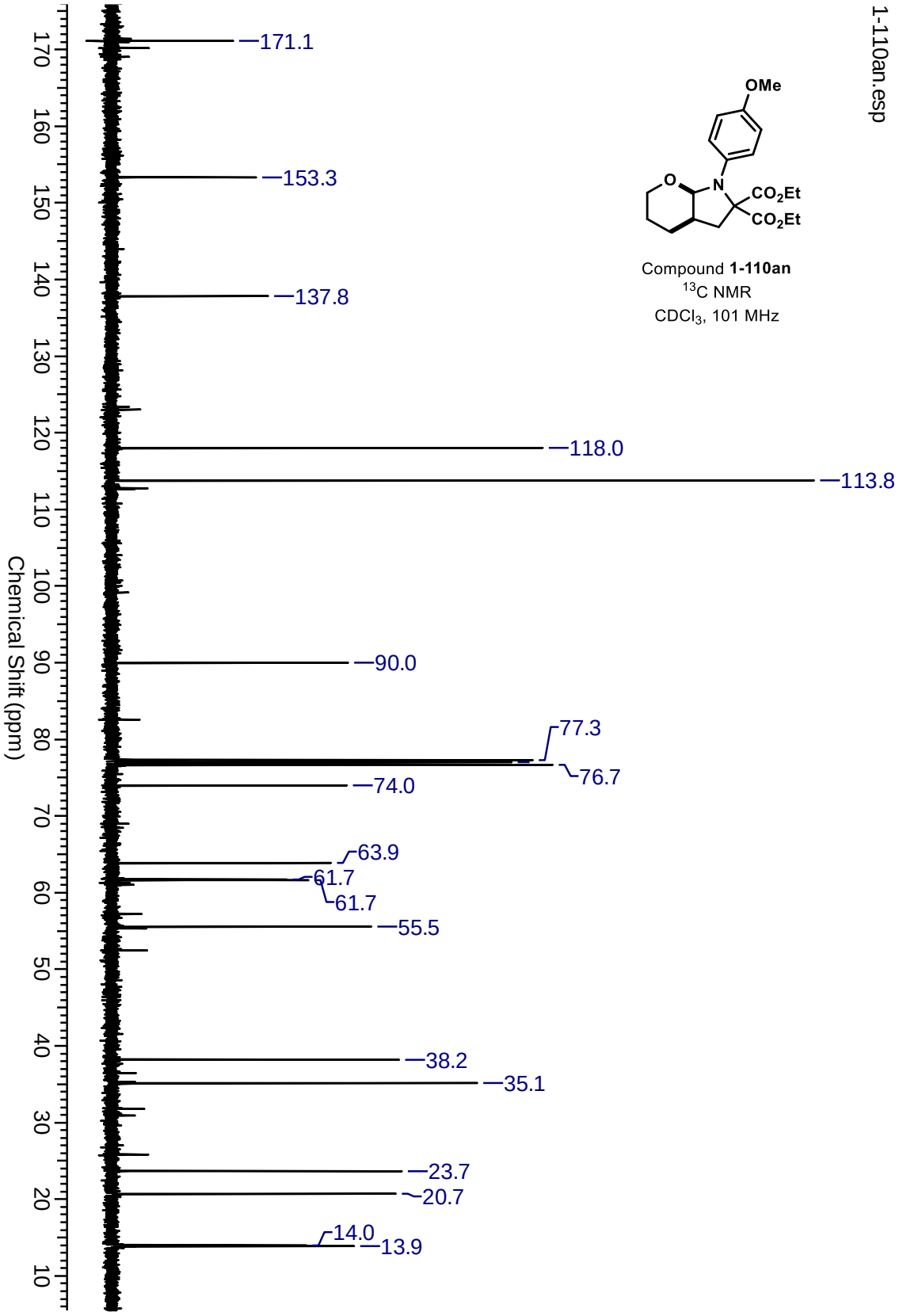
nOe Correlations of 1-198q



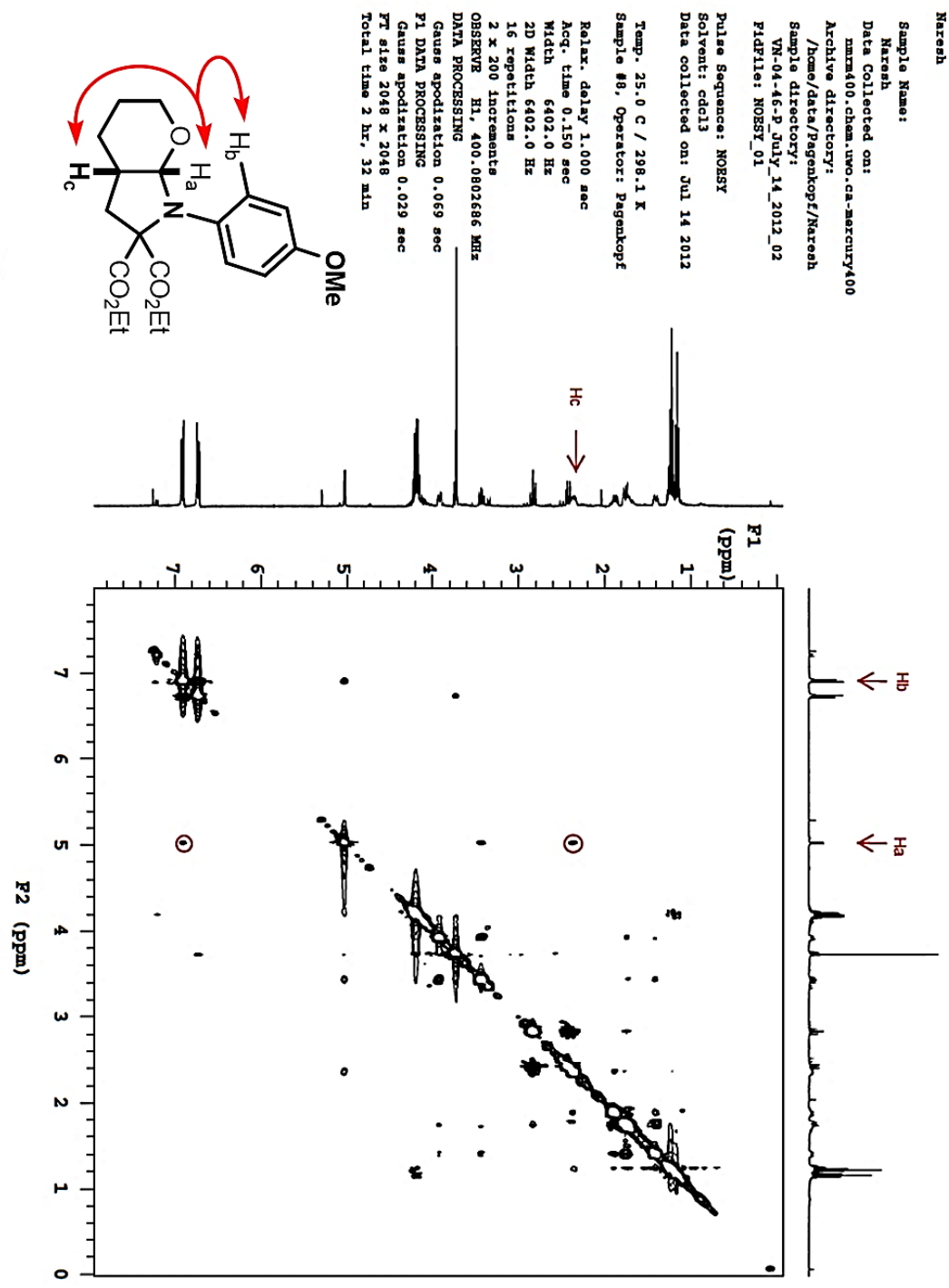


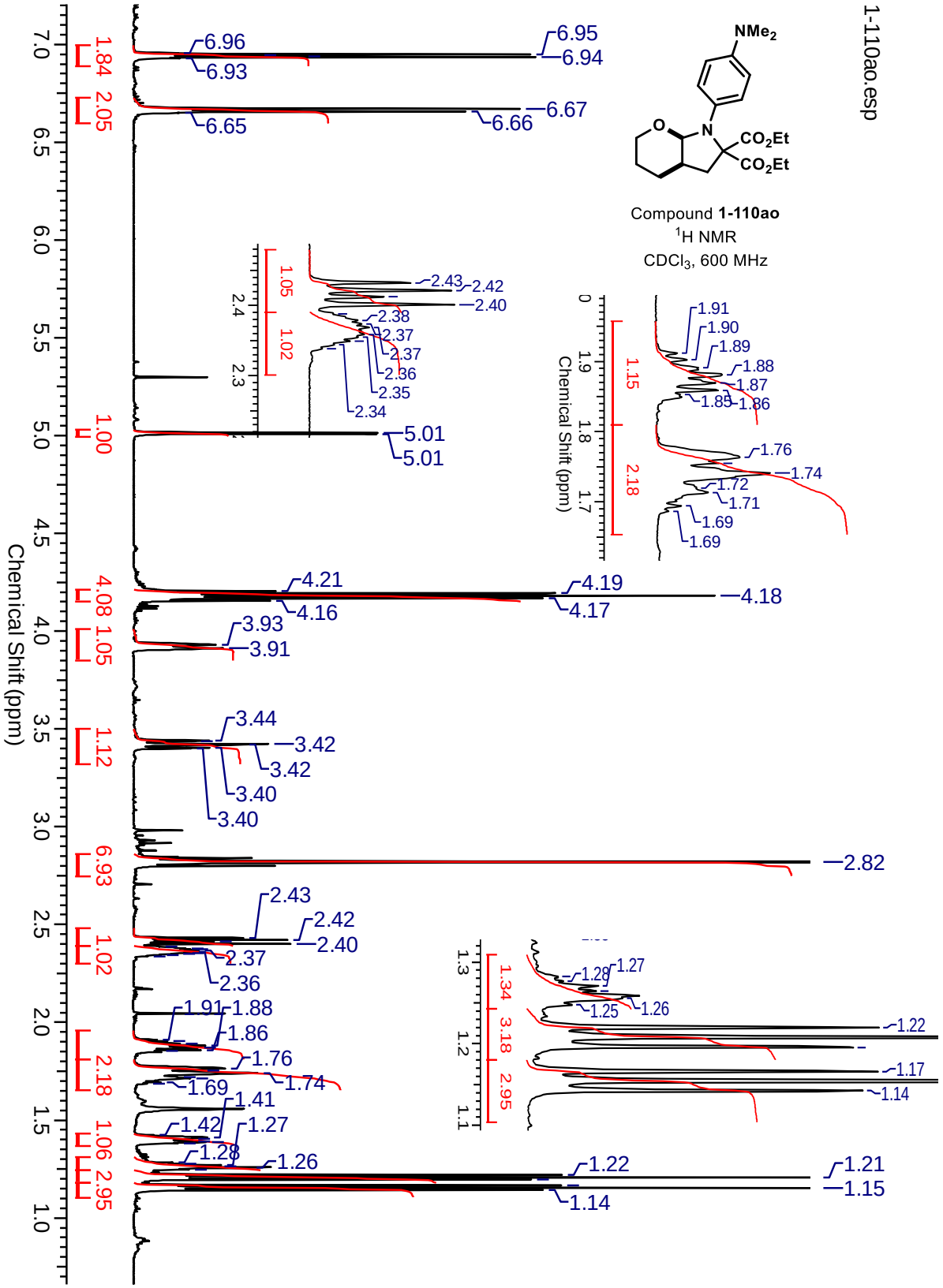


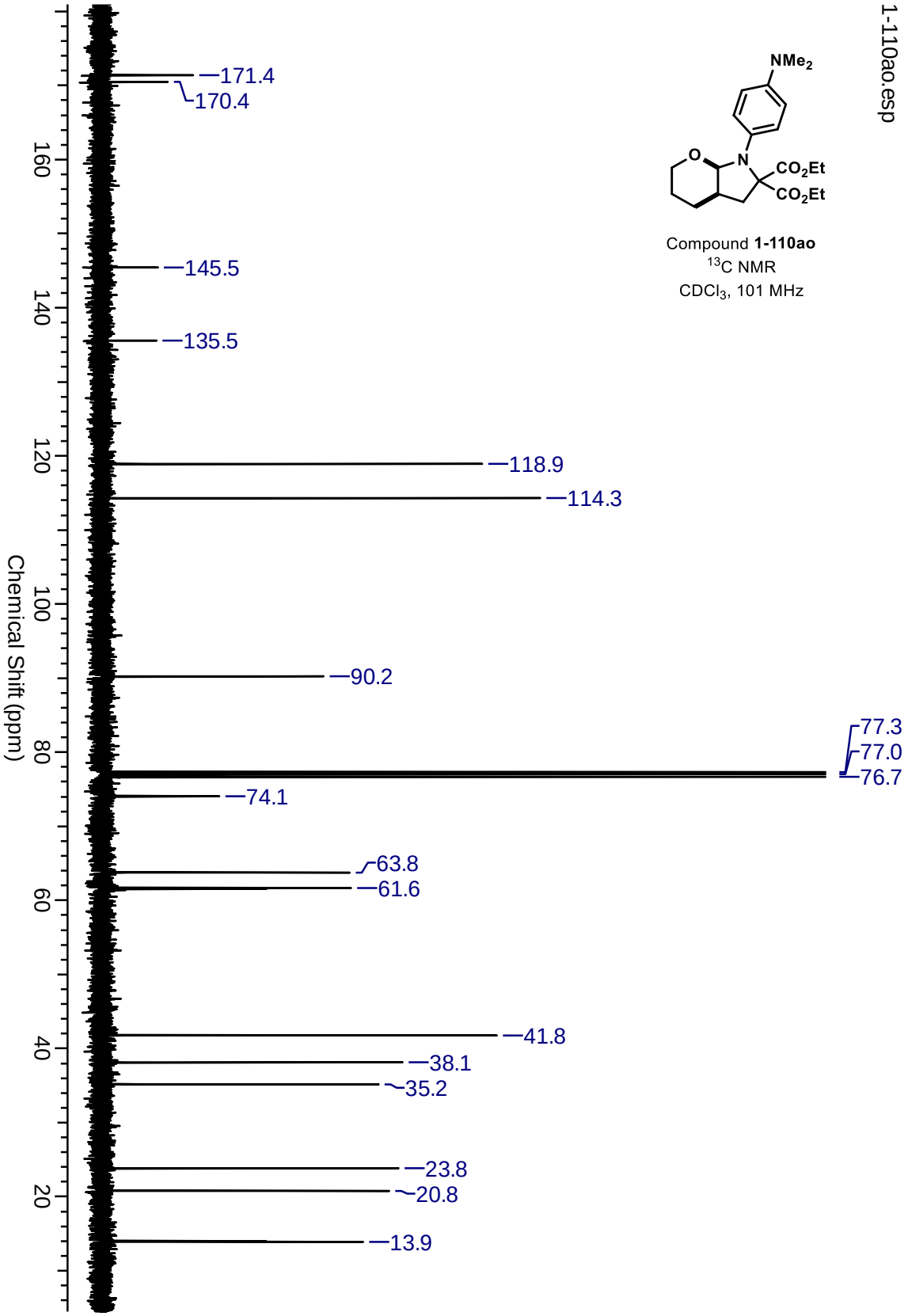


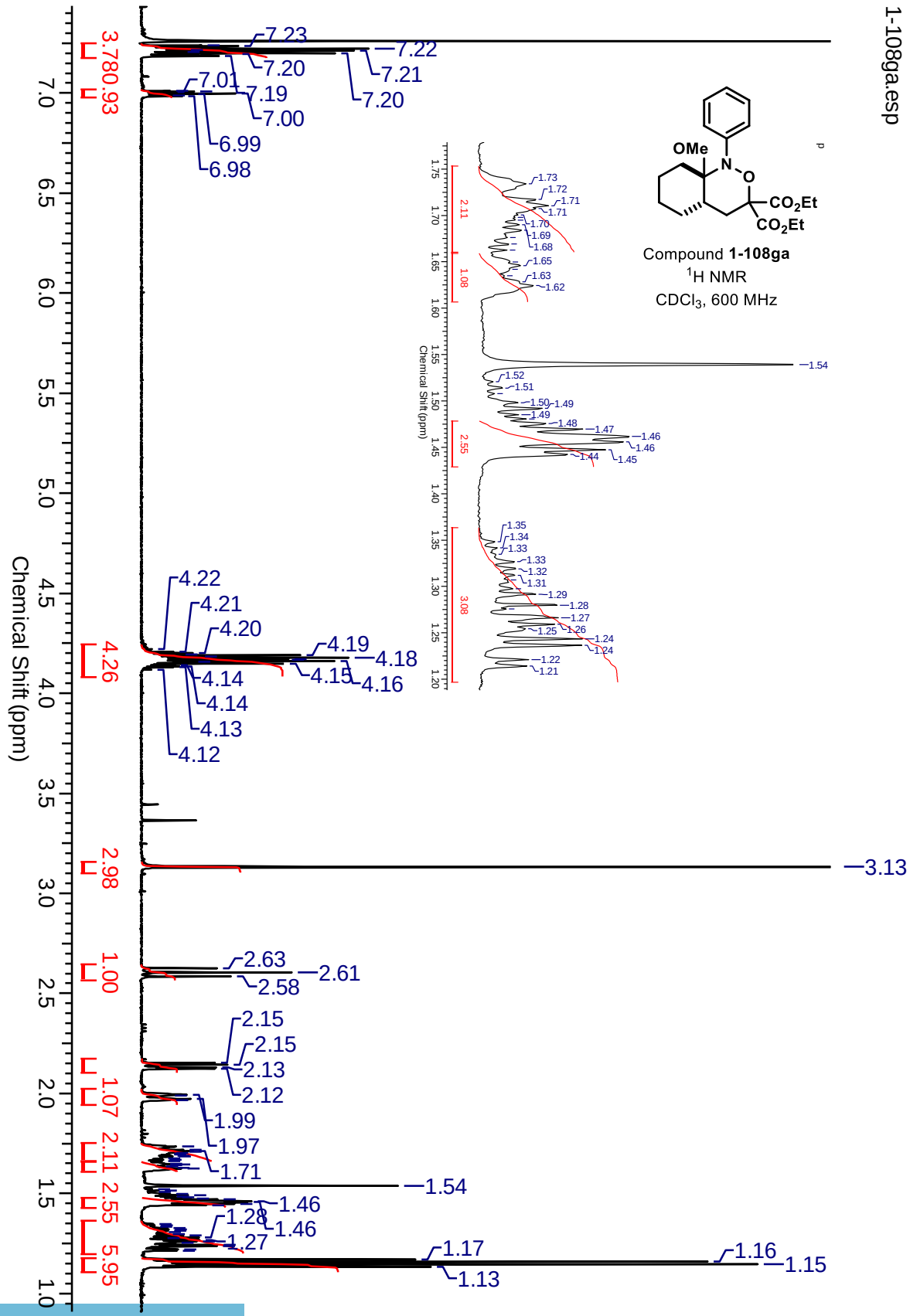


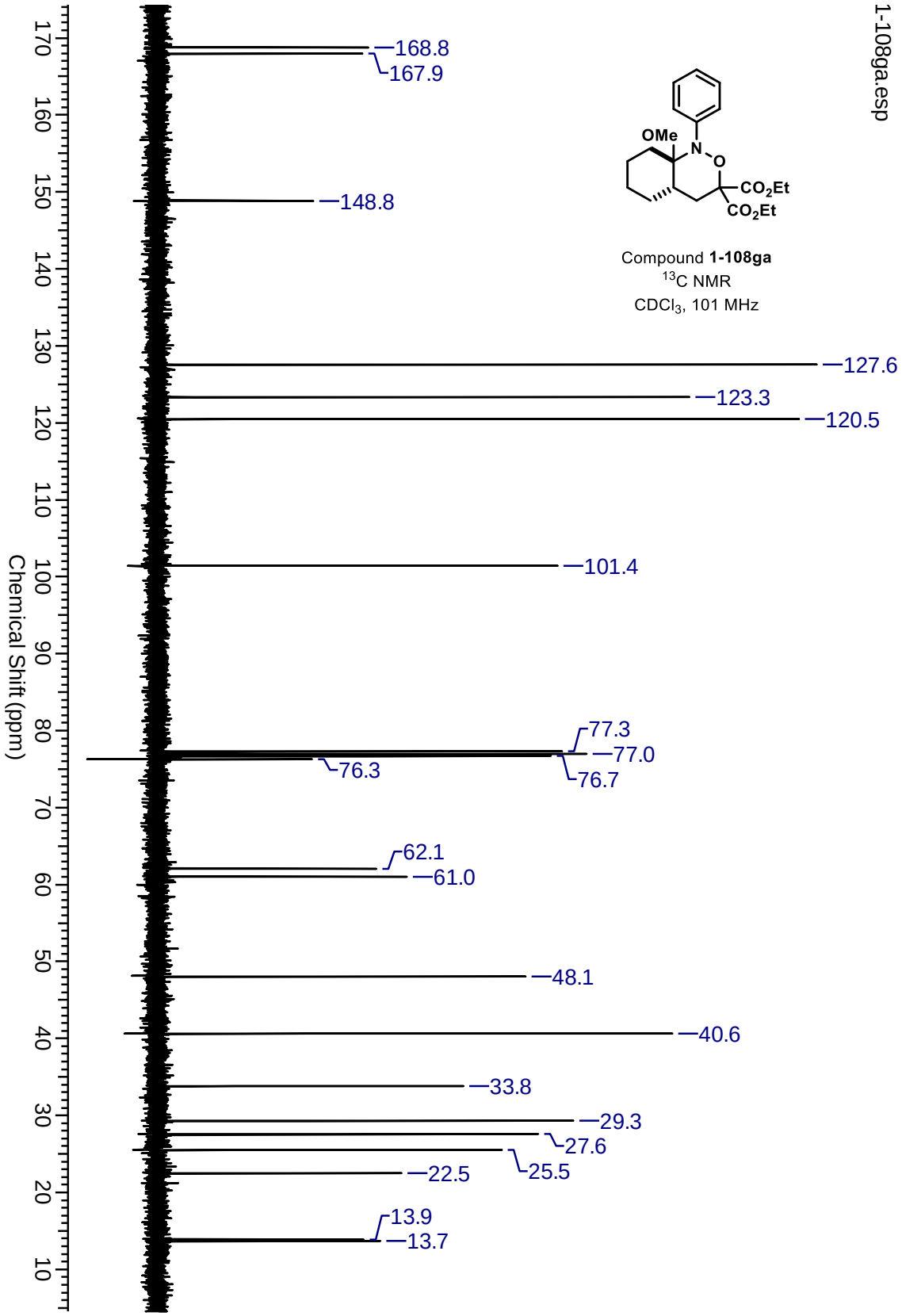
nOe Correlations of 1-110an

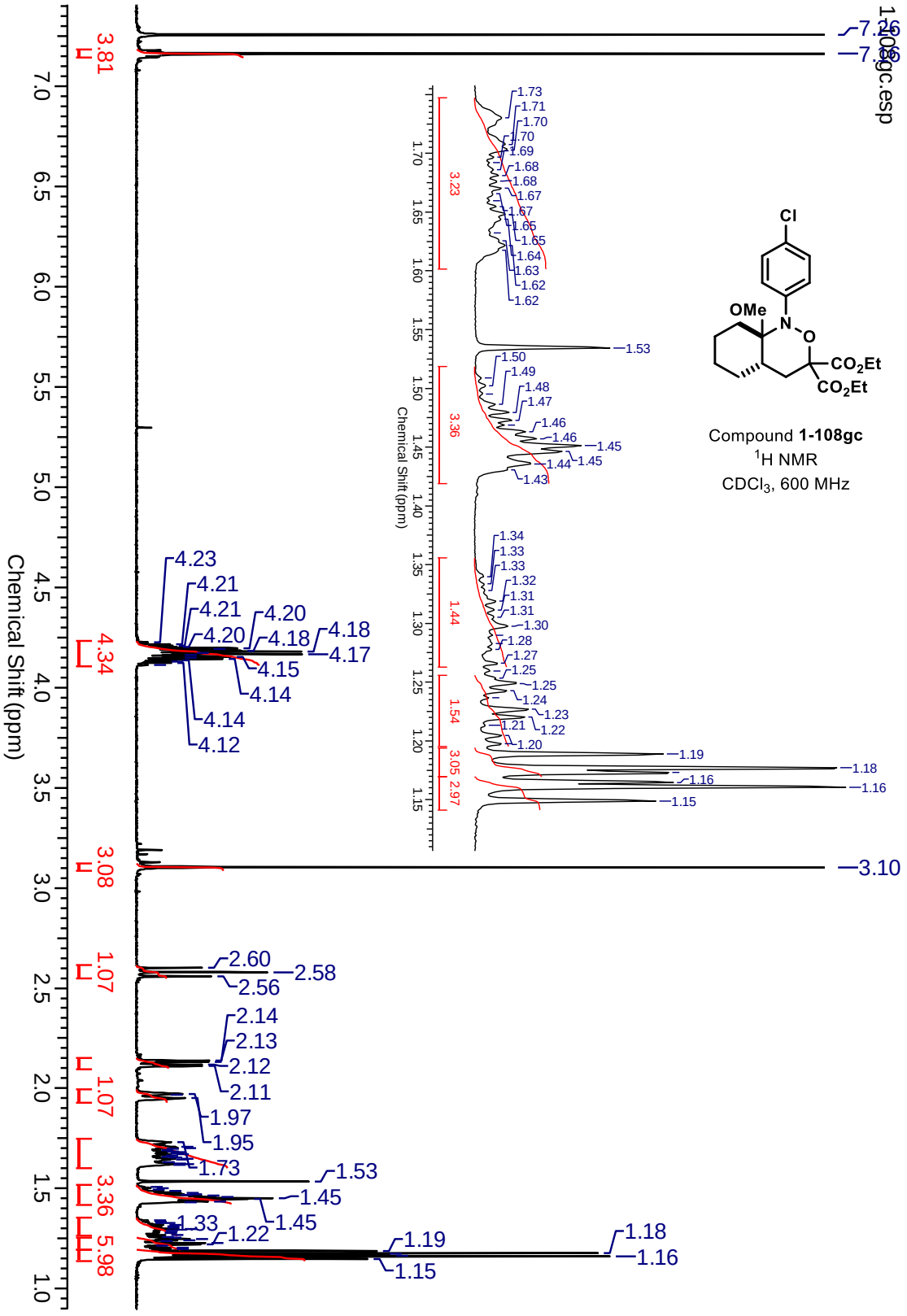


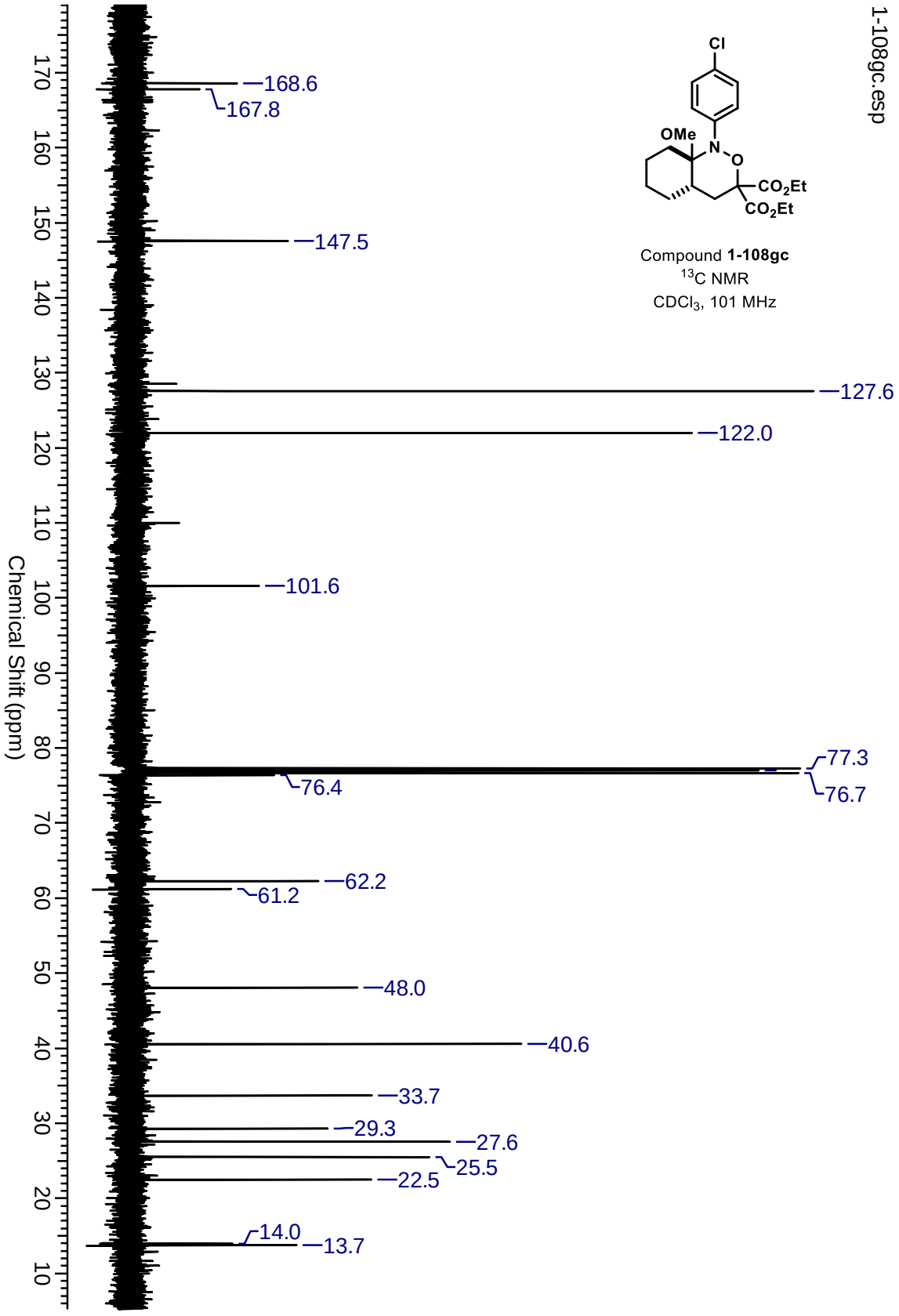


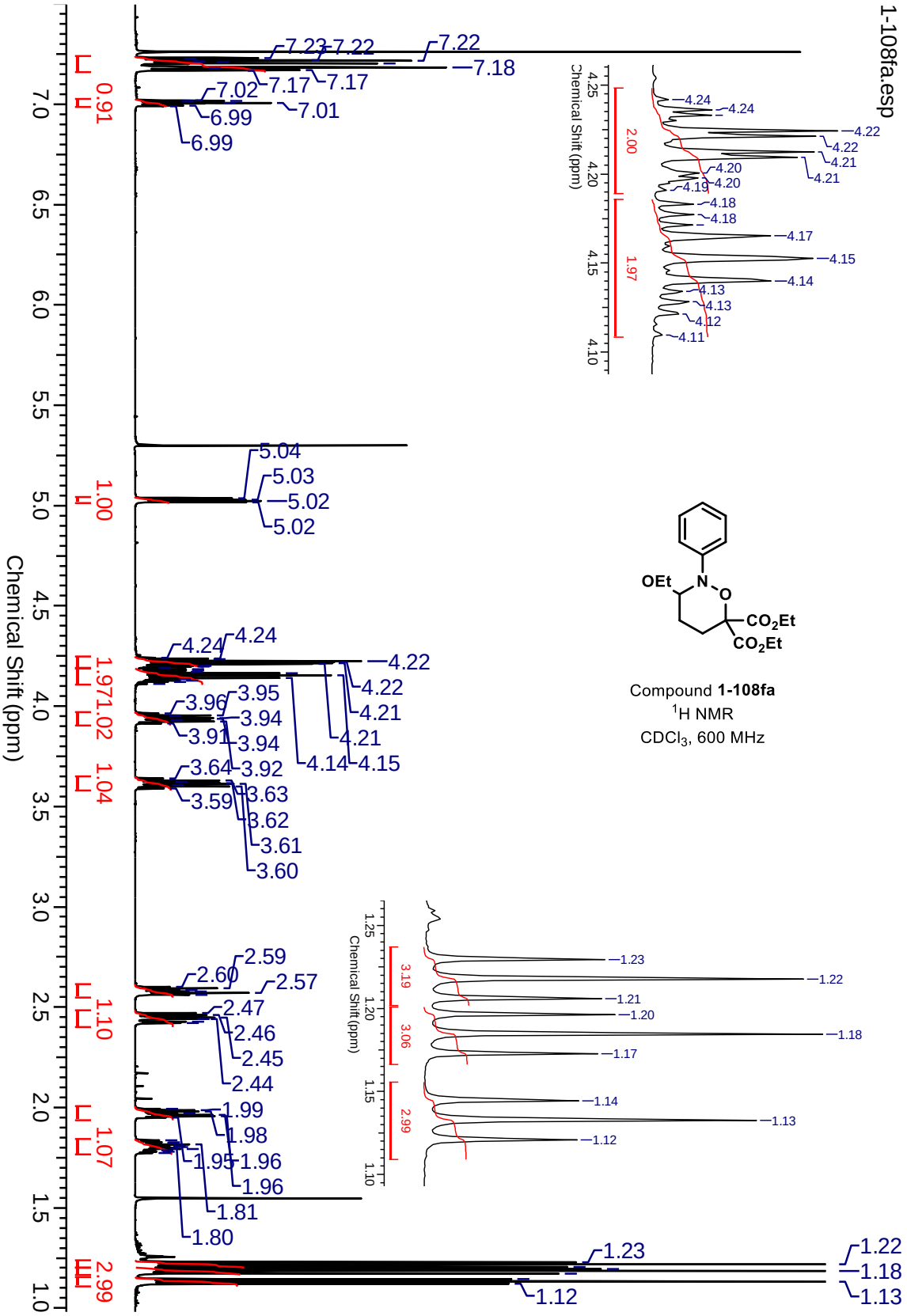


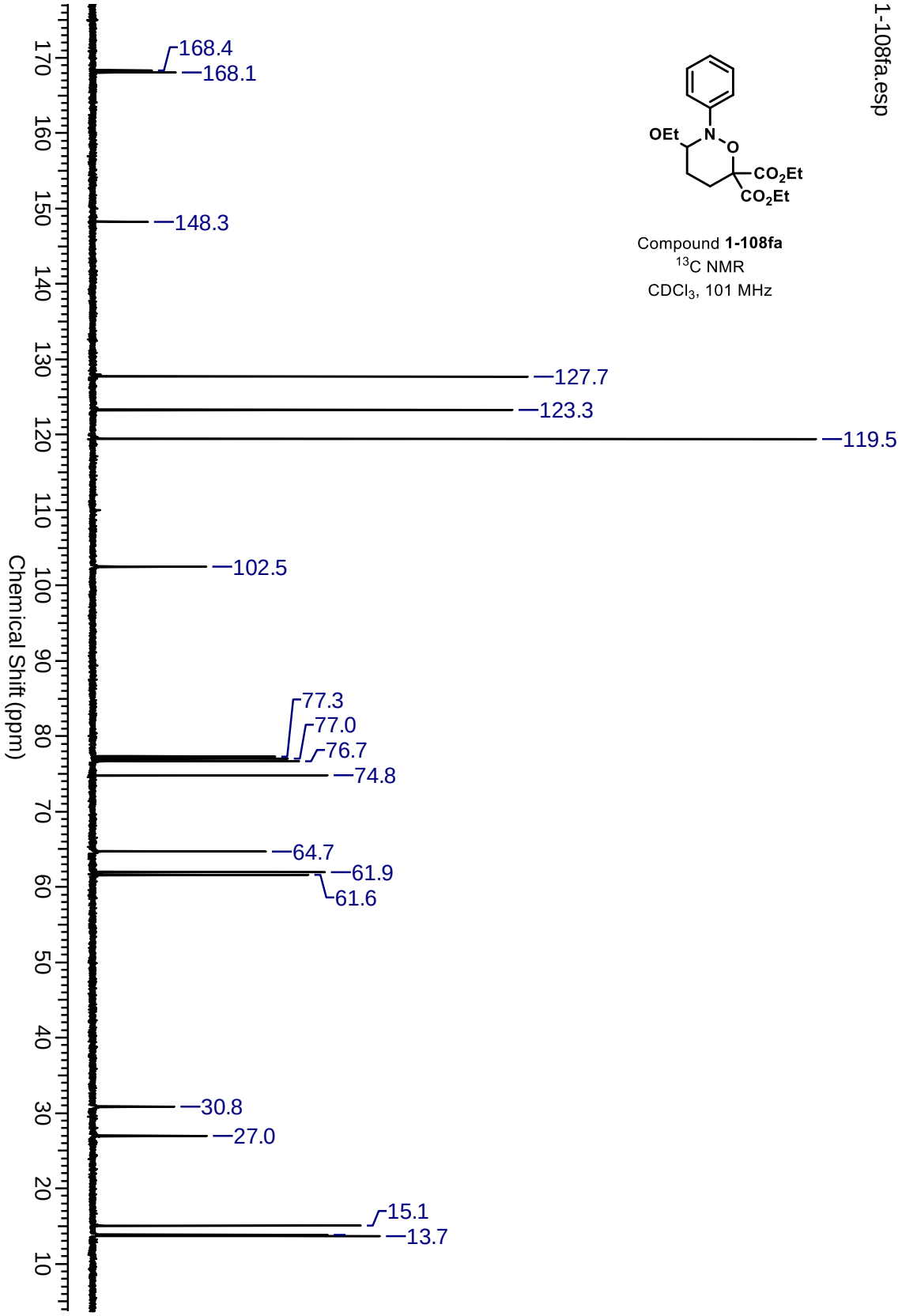


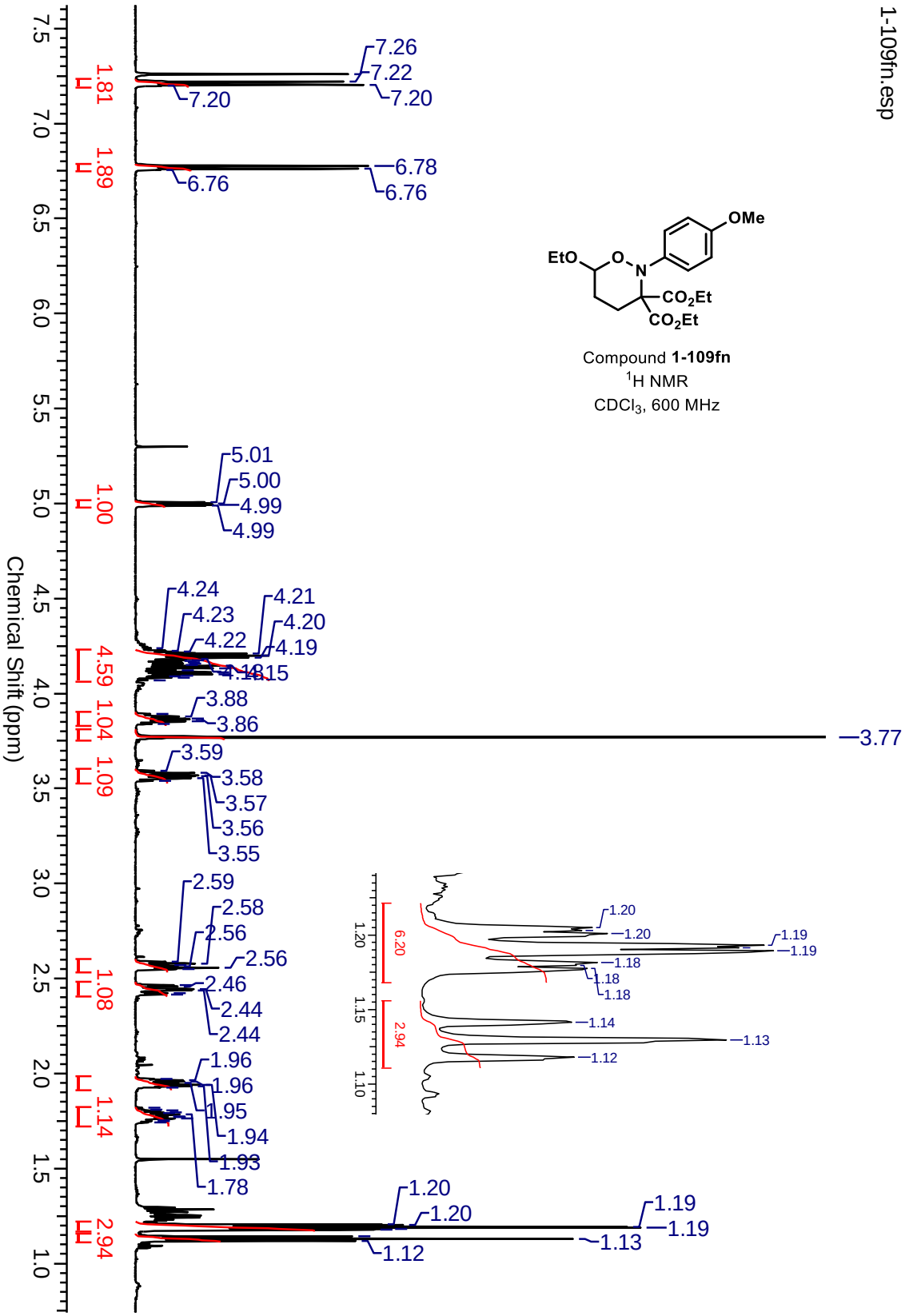


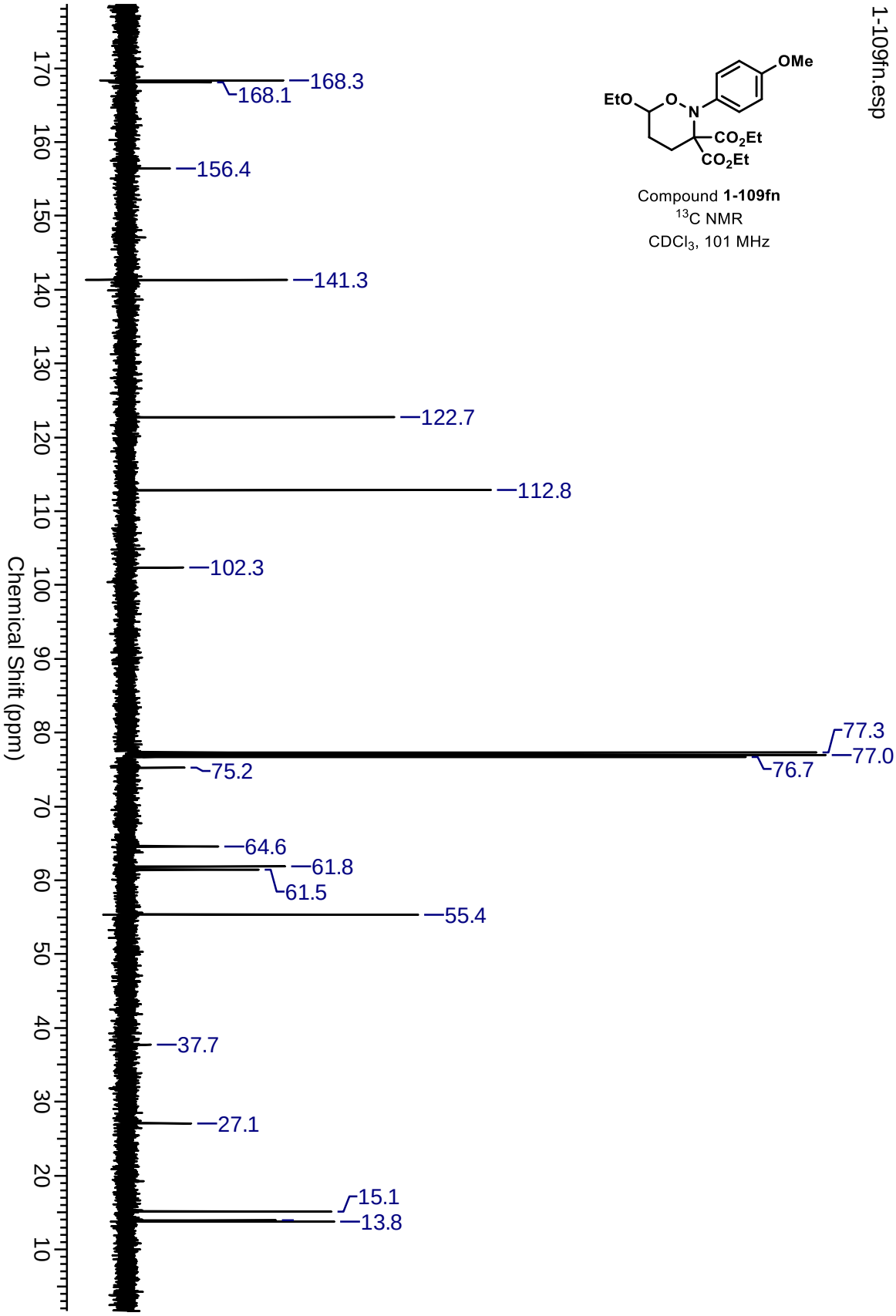




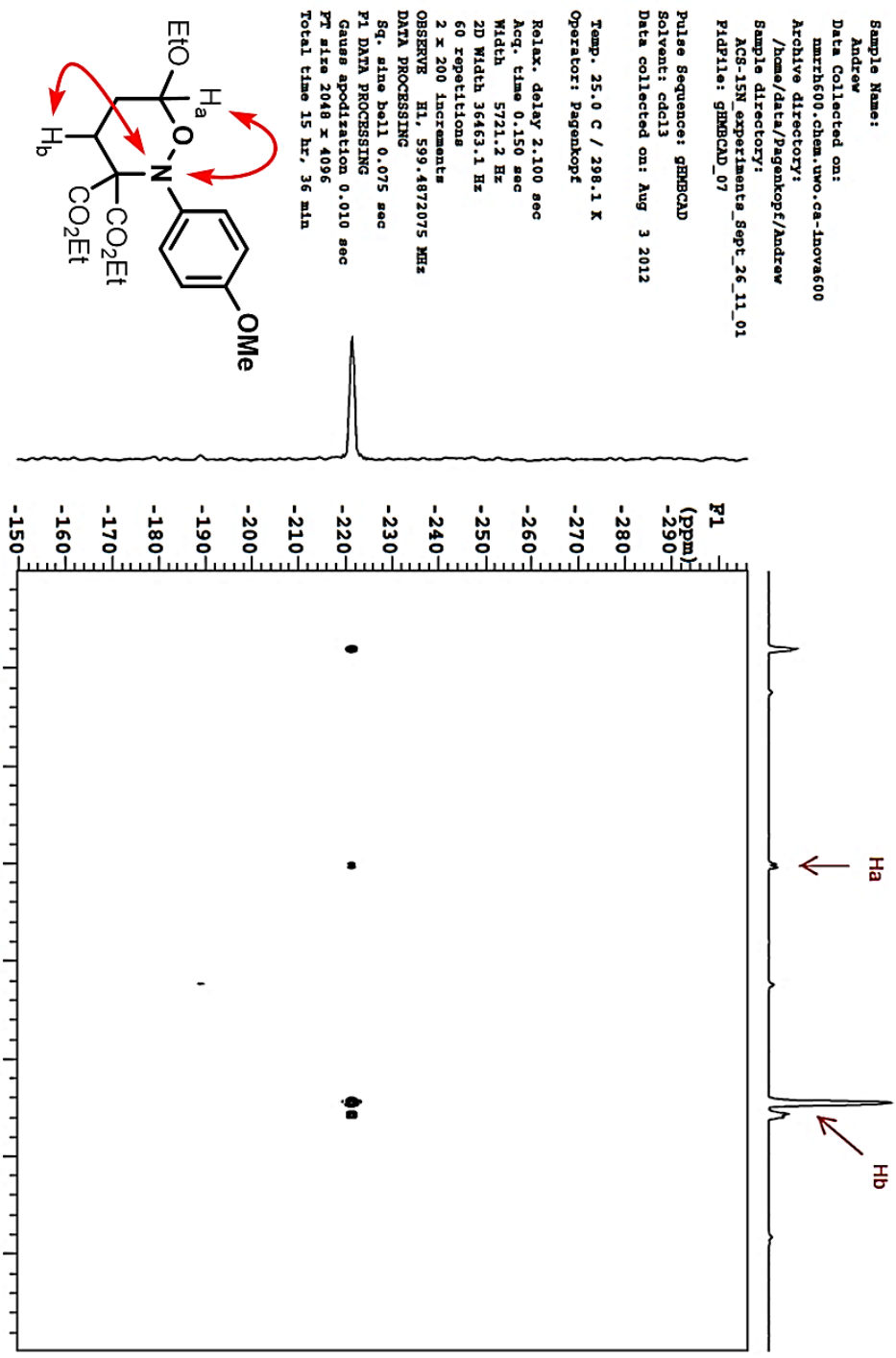


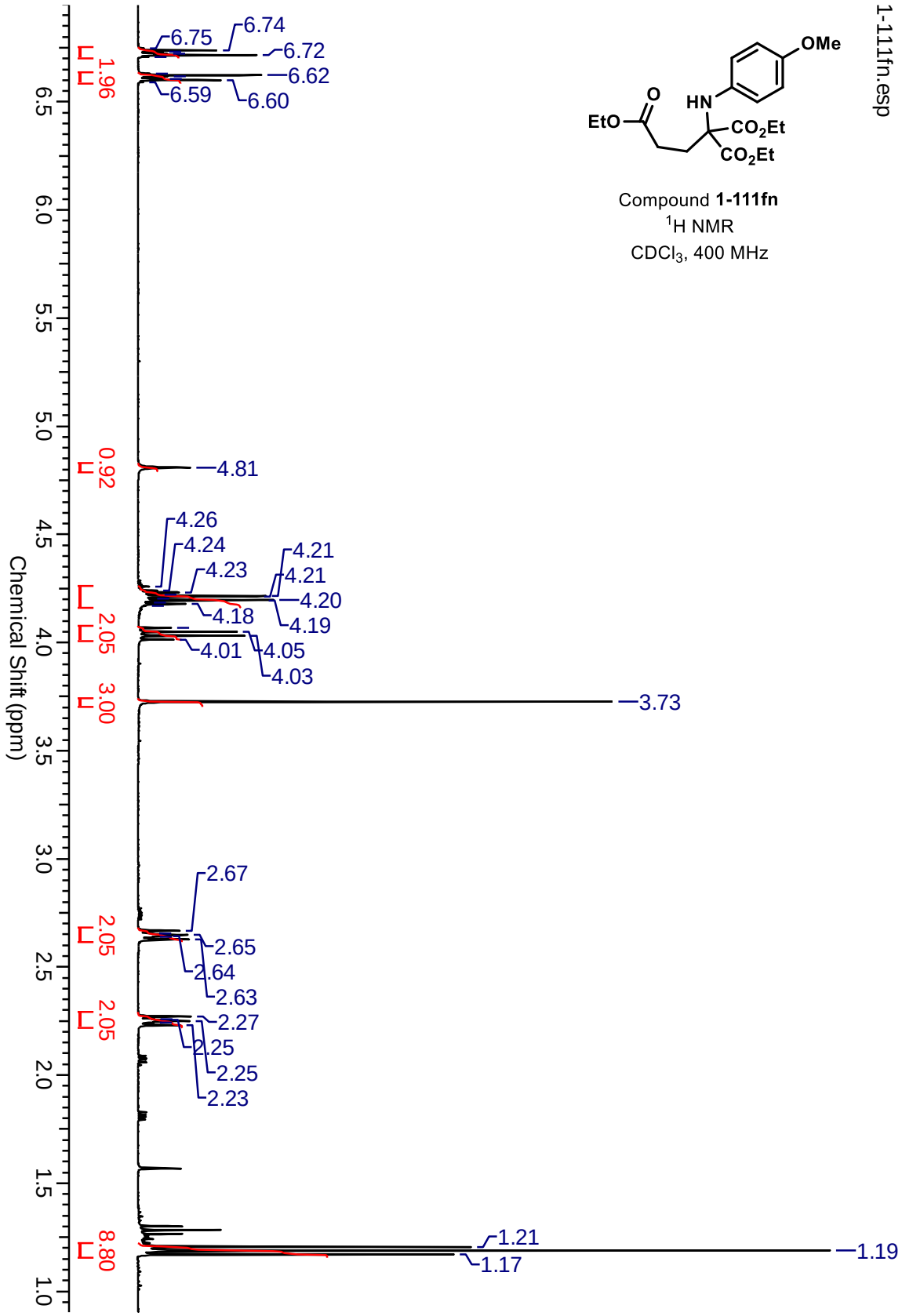


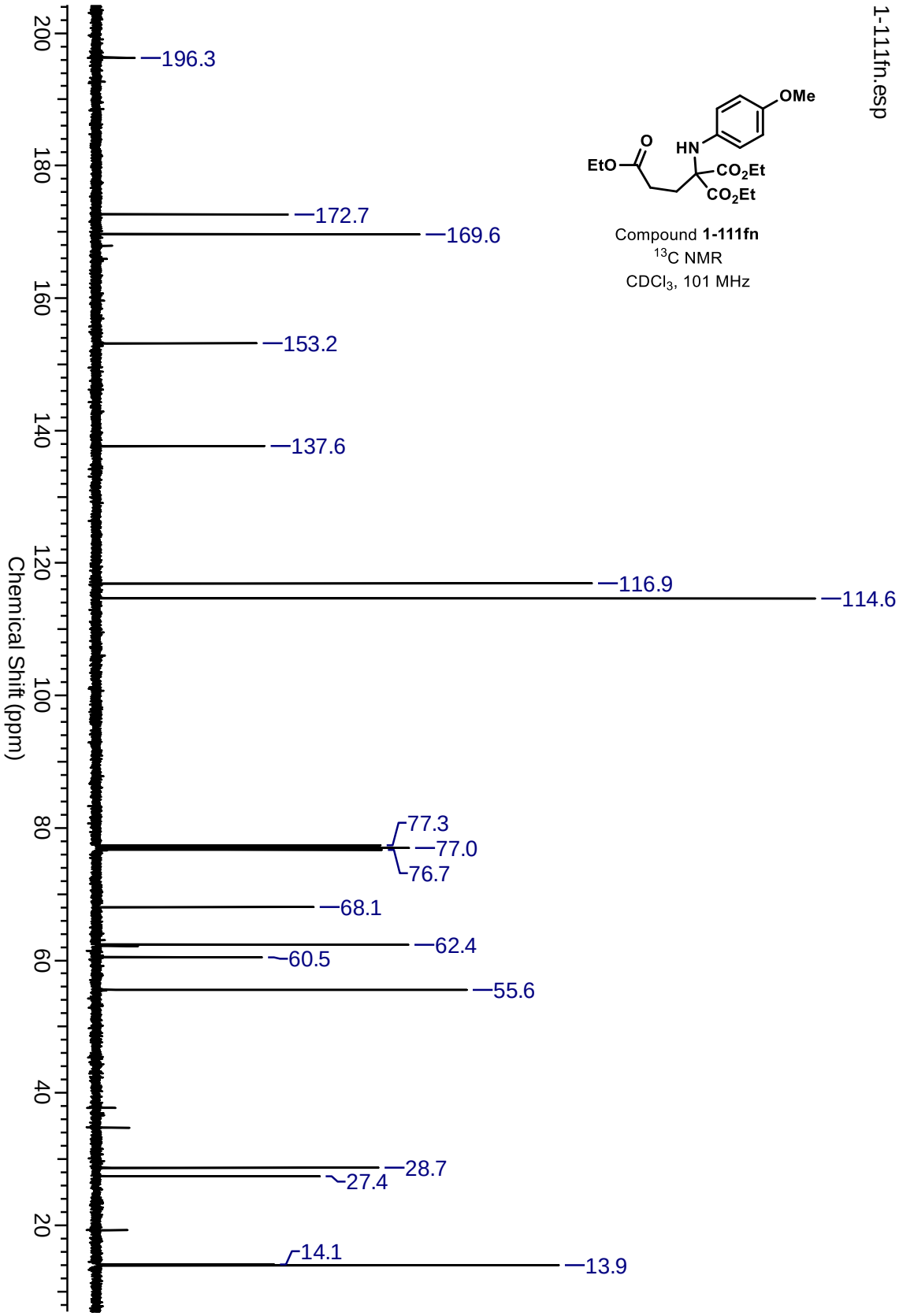


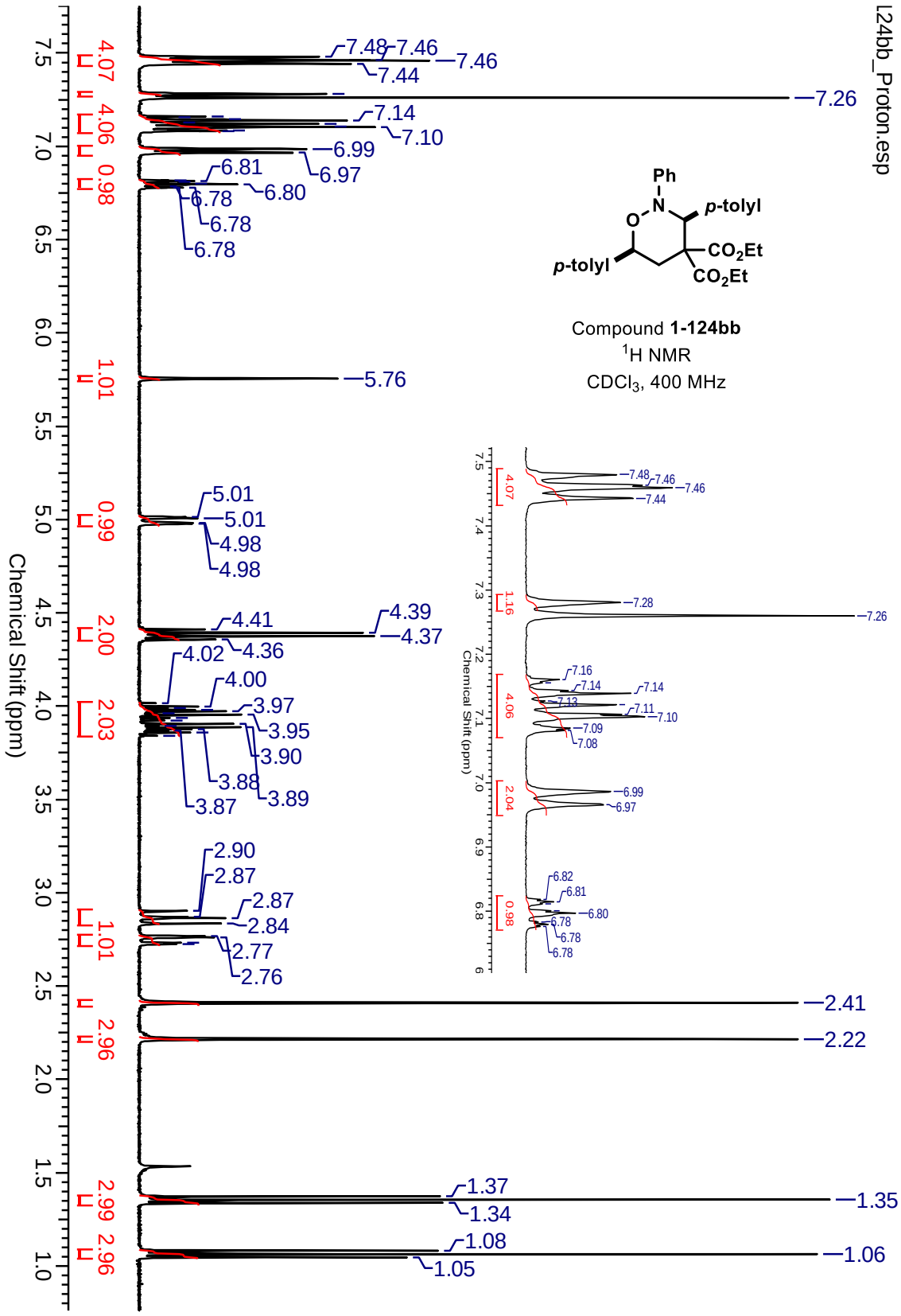


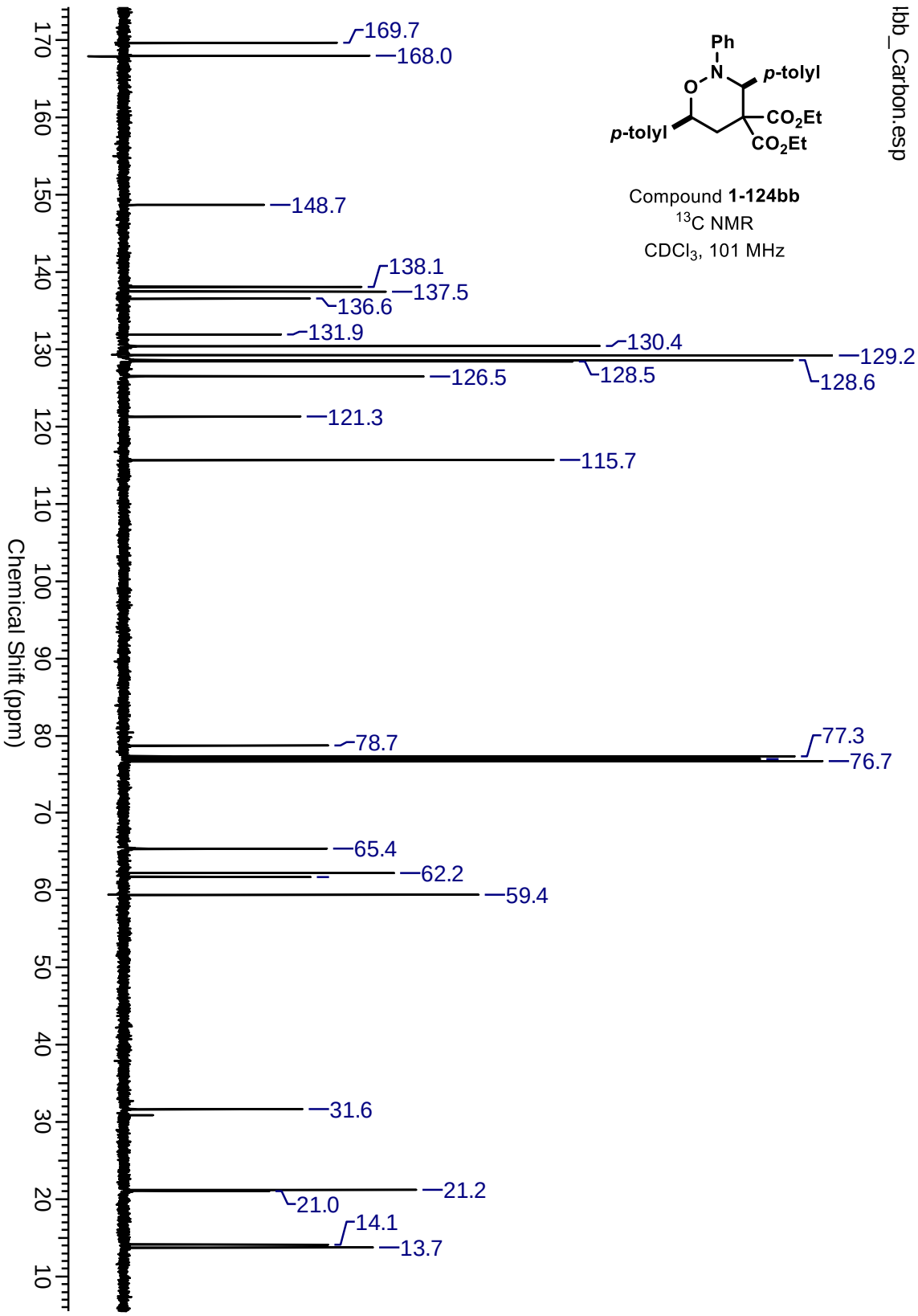
^{1}H - ^{15}N HMBC Correlations of 1-109fn

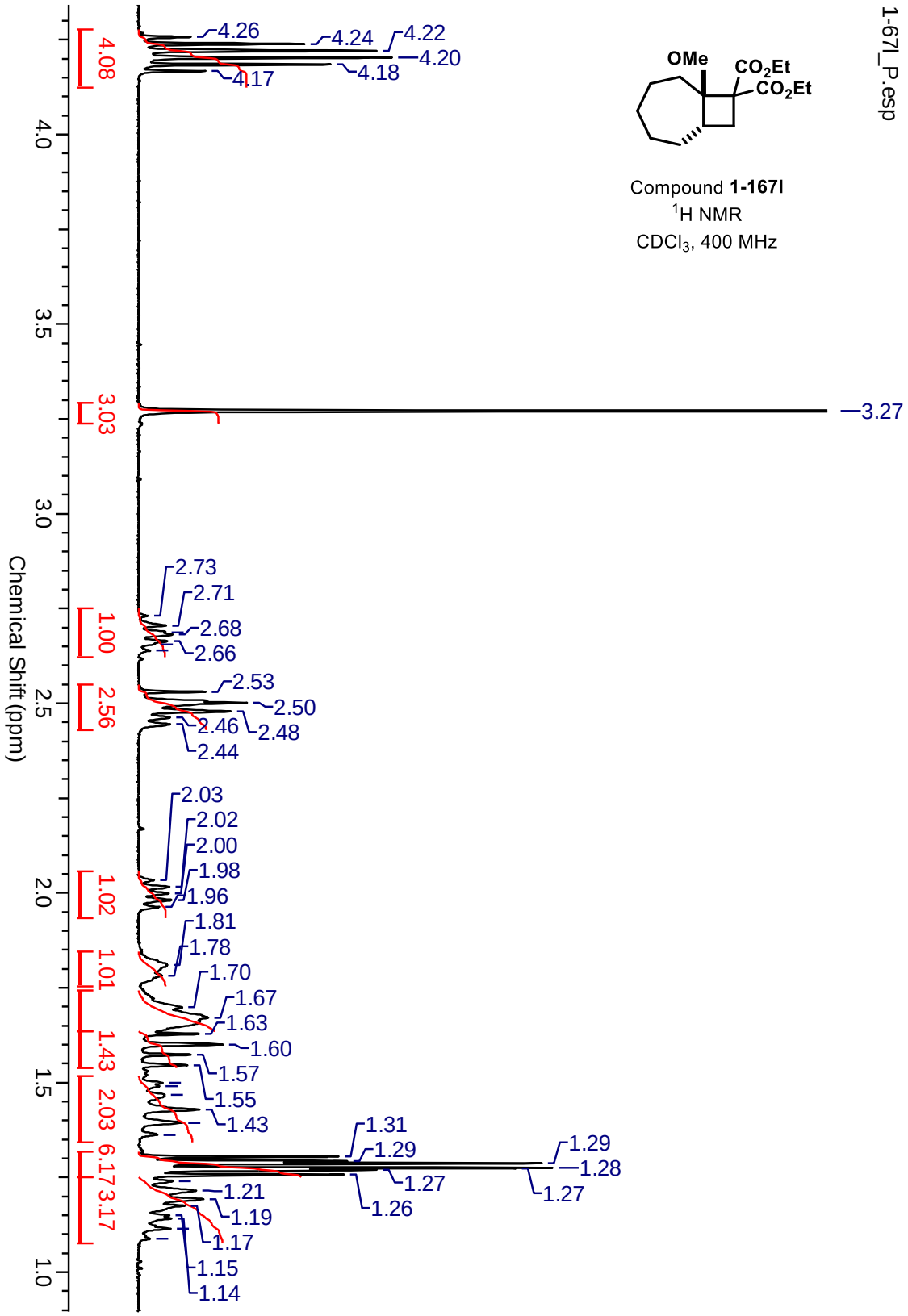


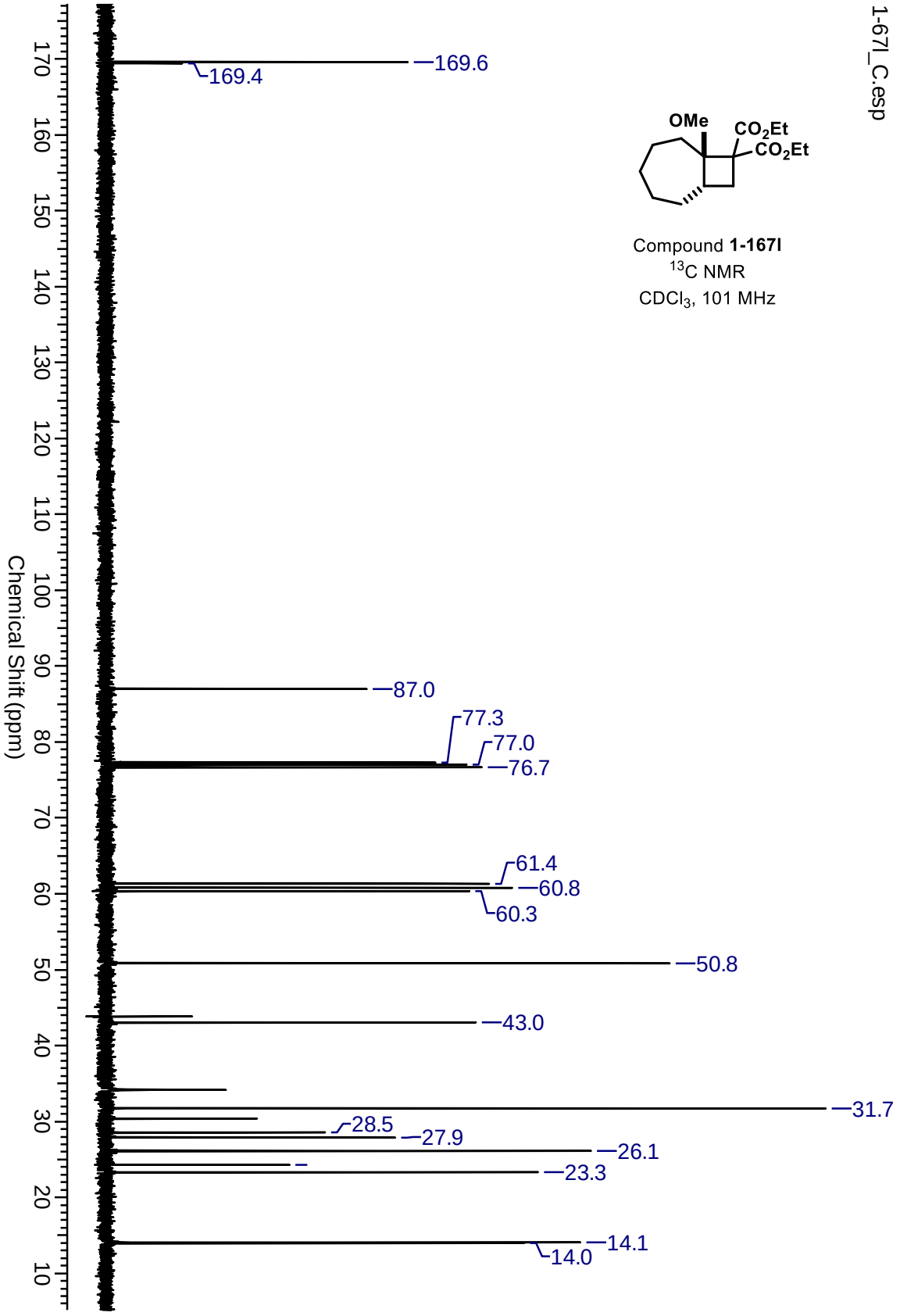


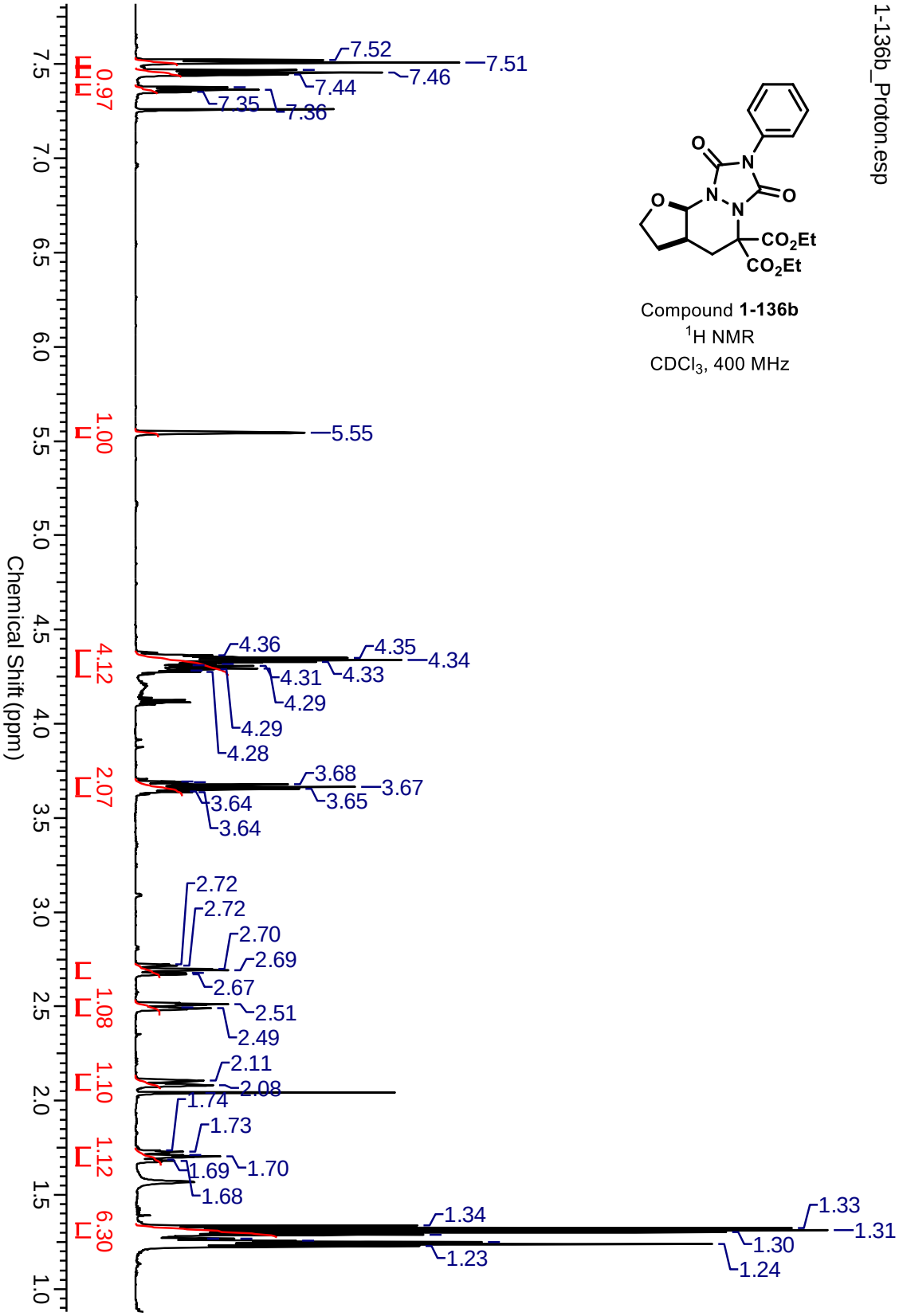


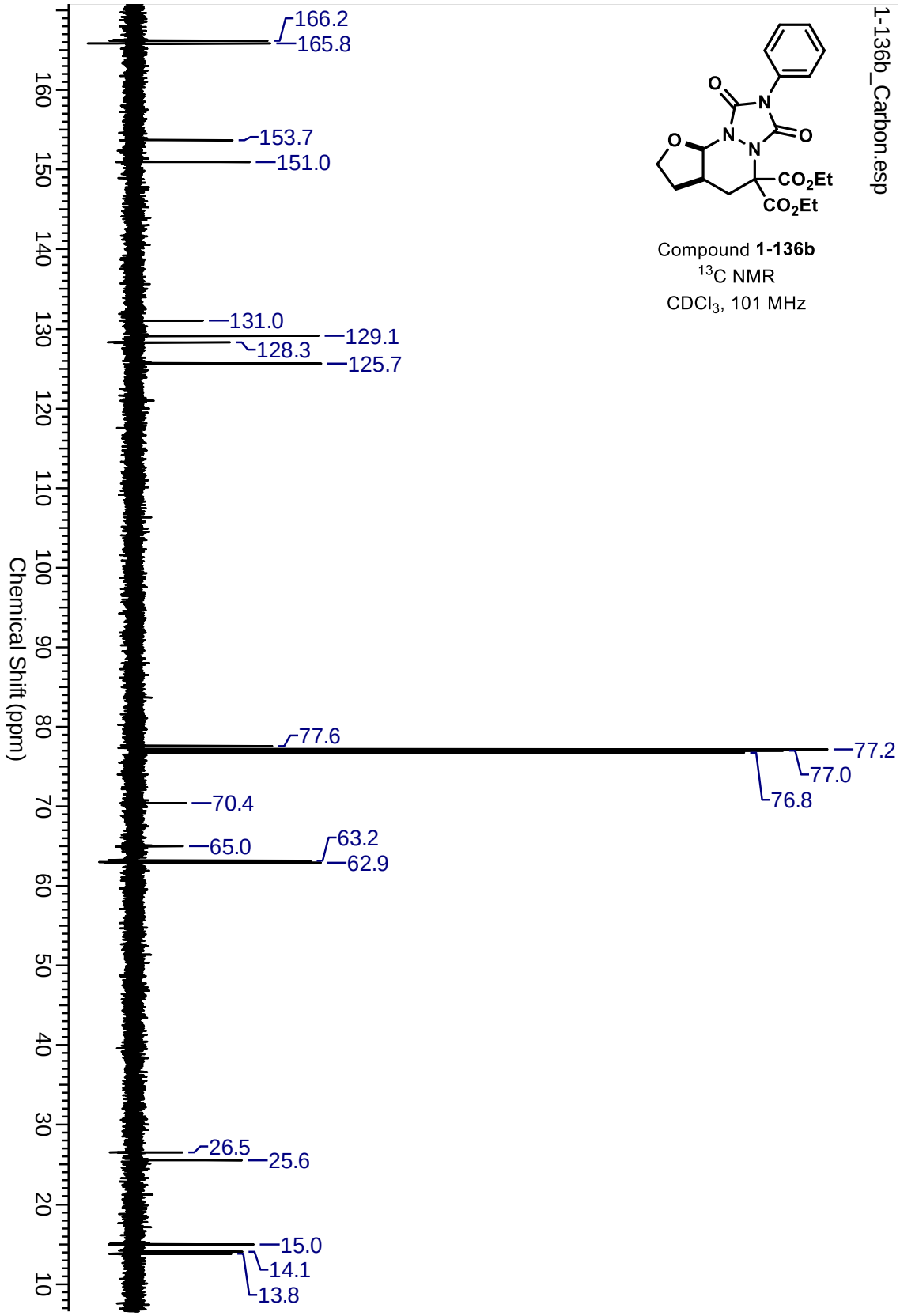


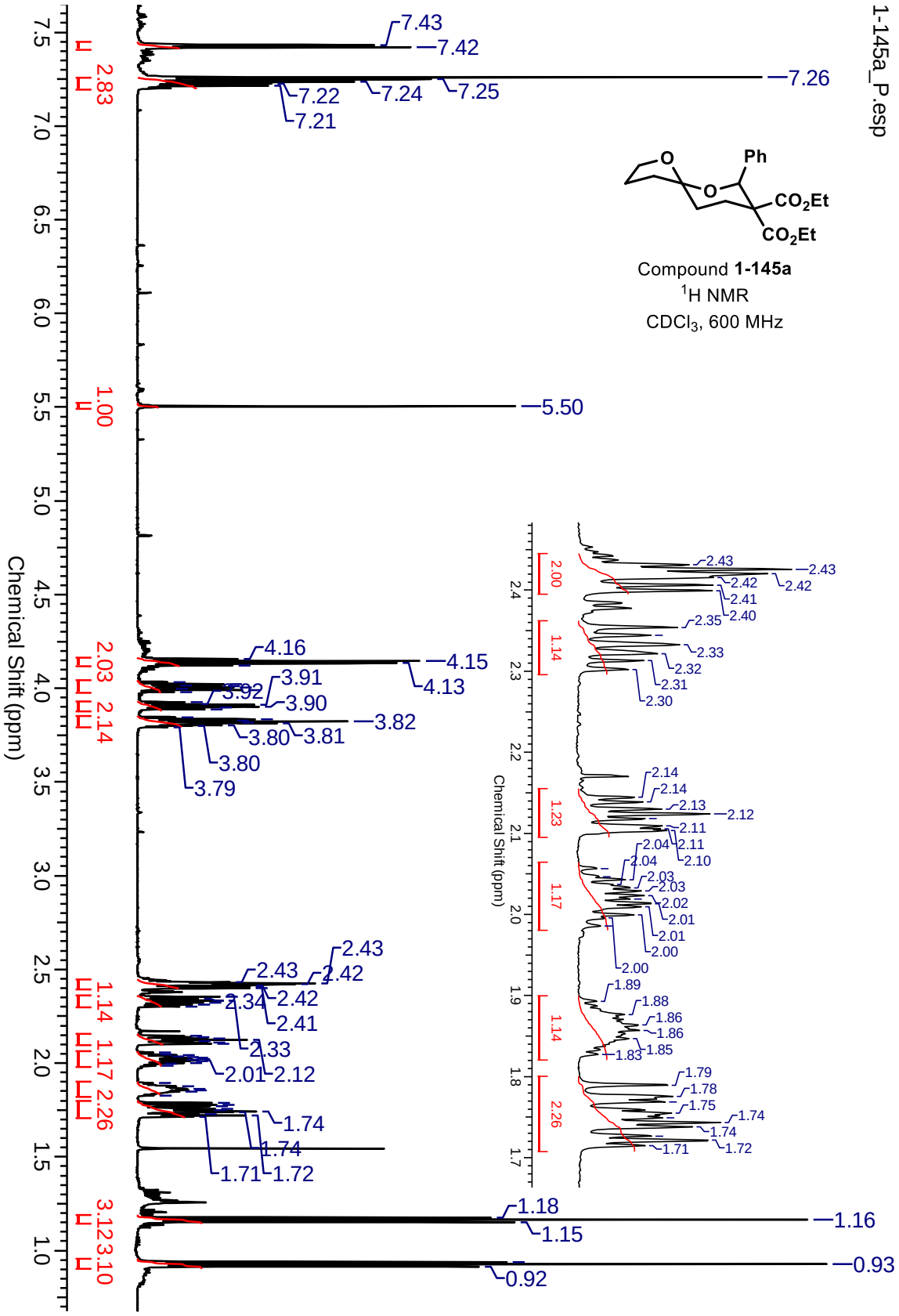


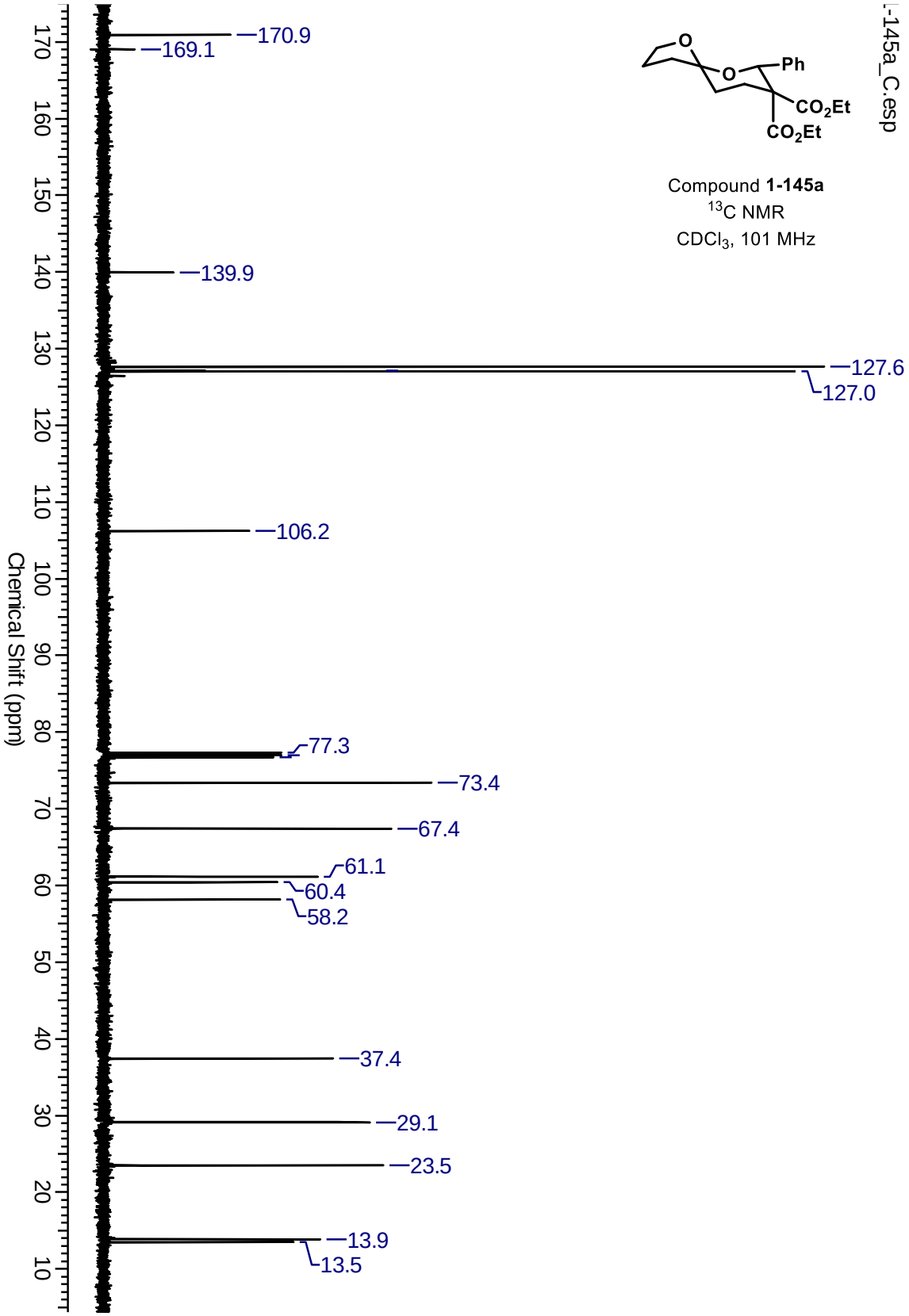


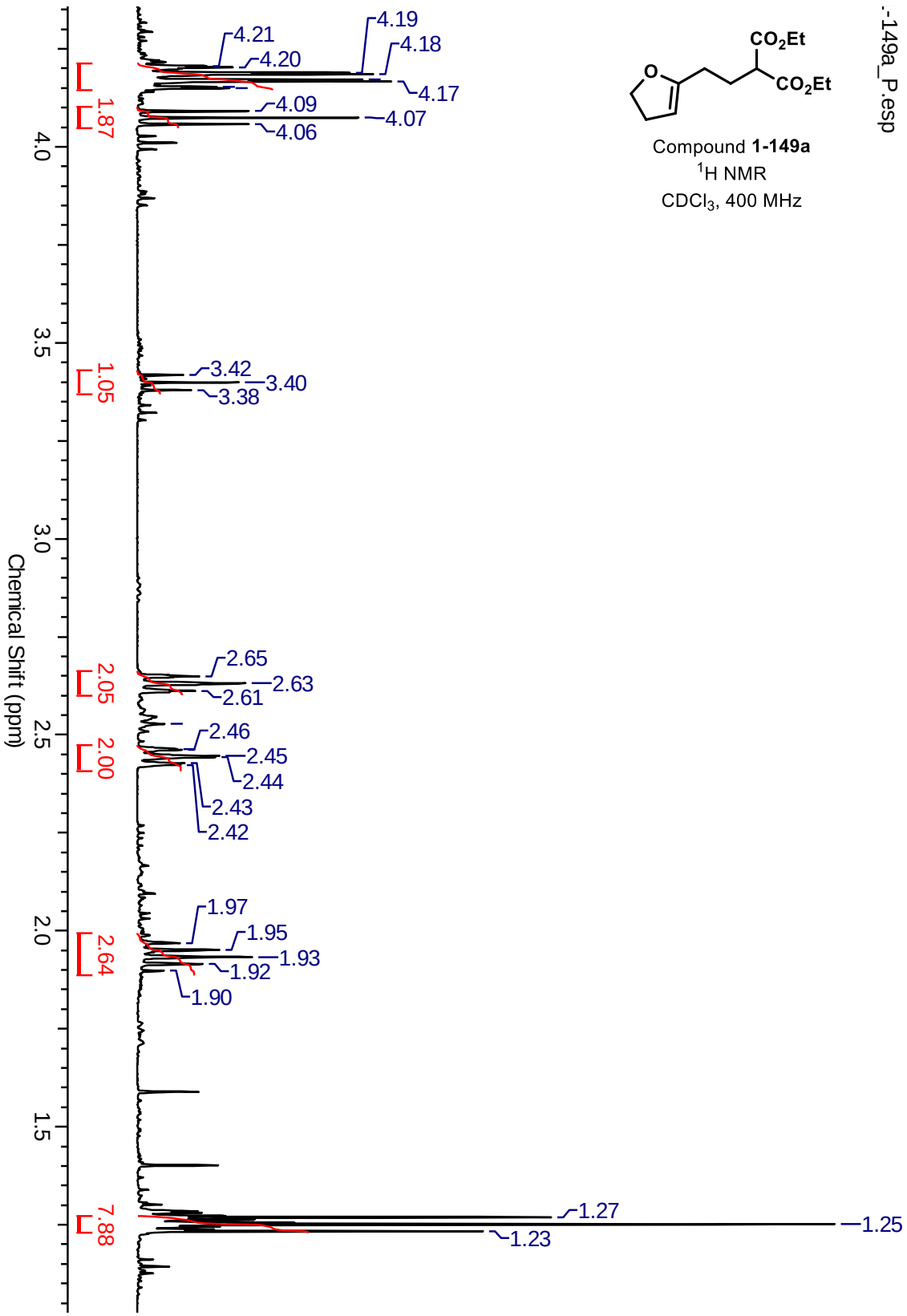


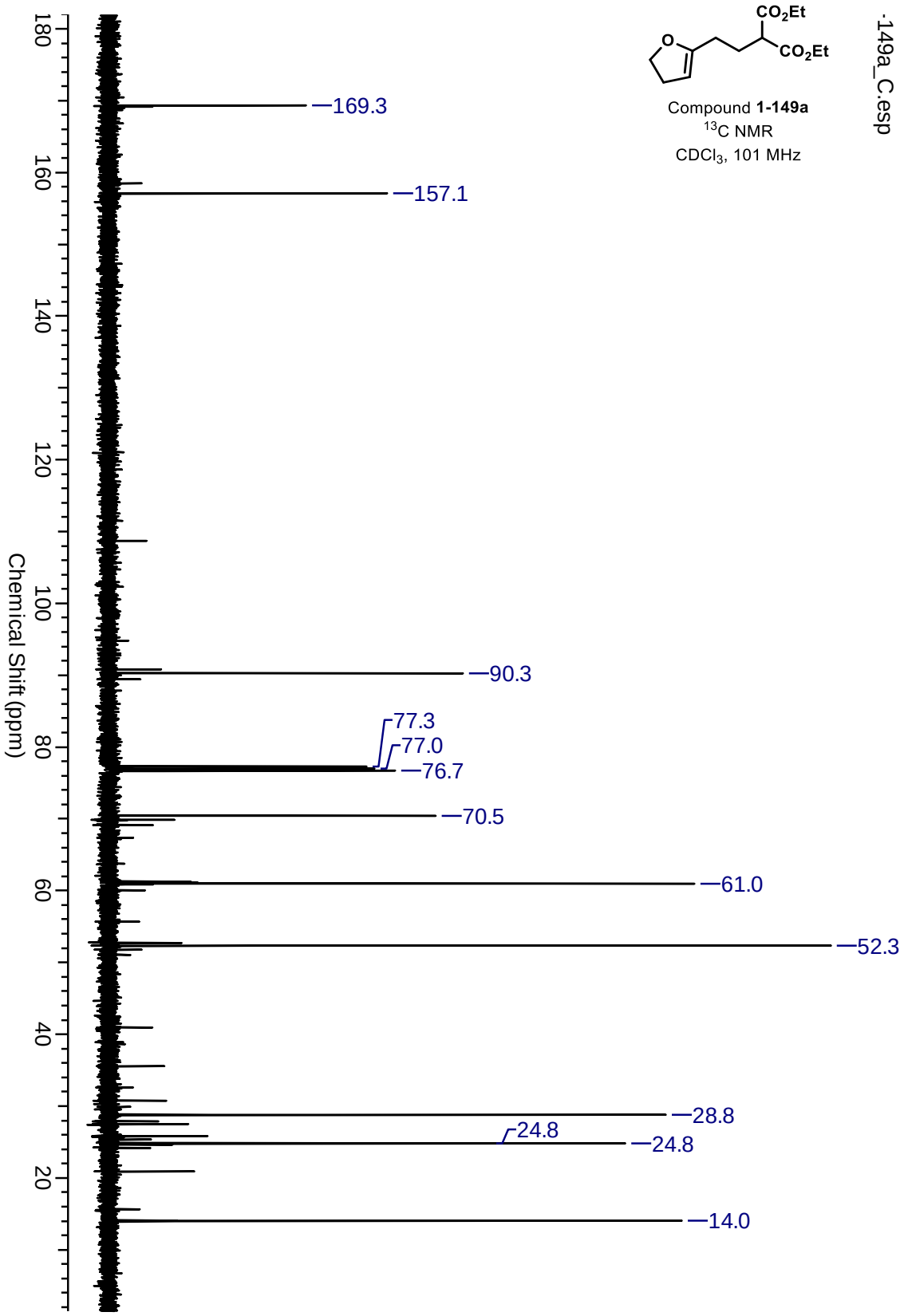




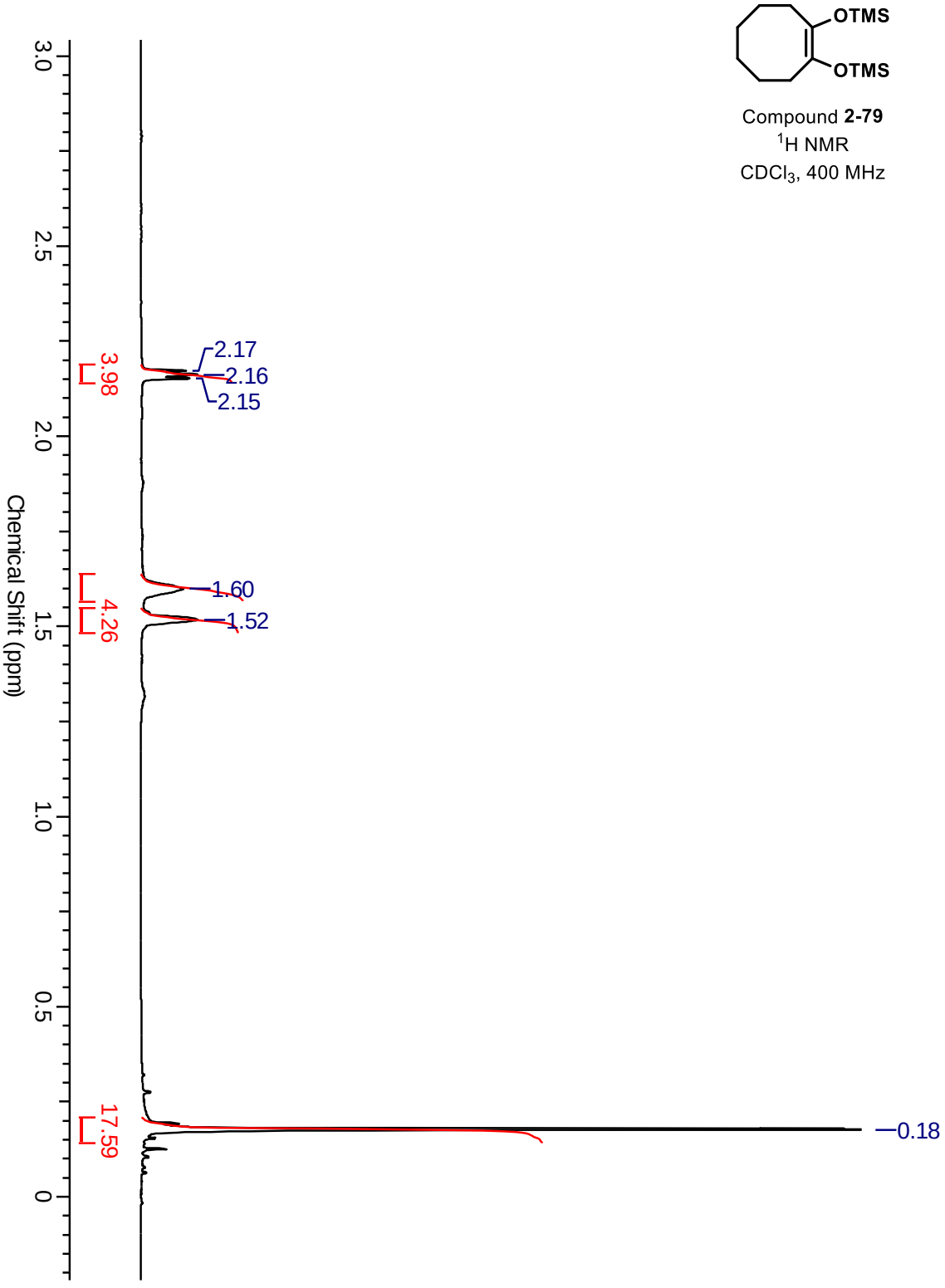


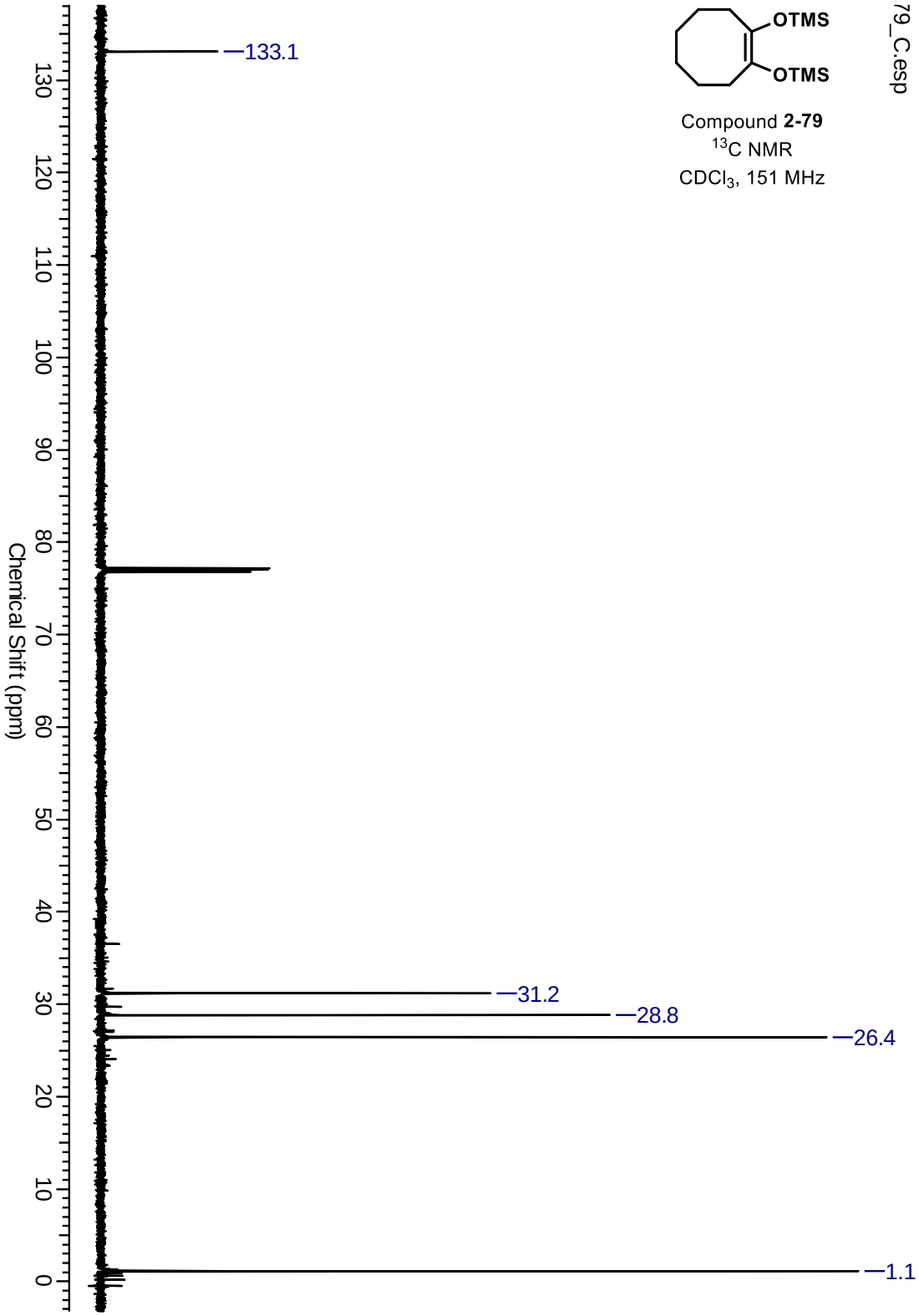


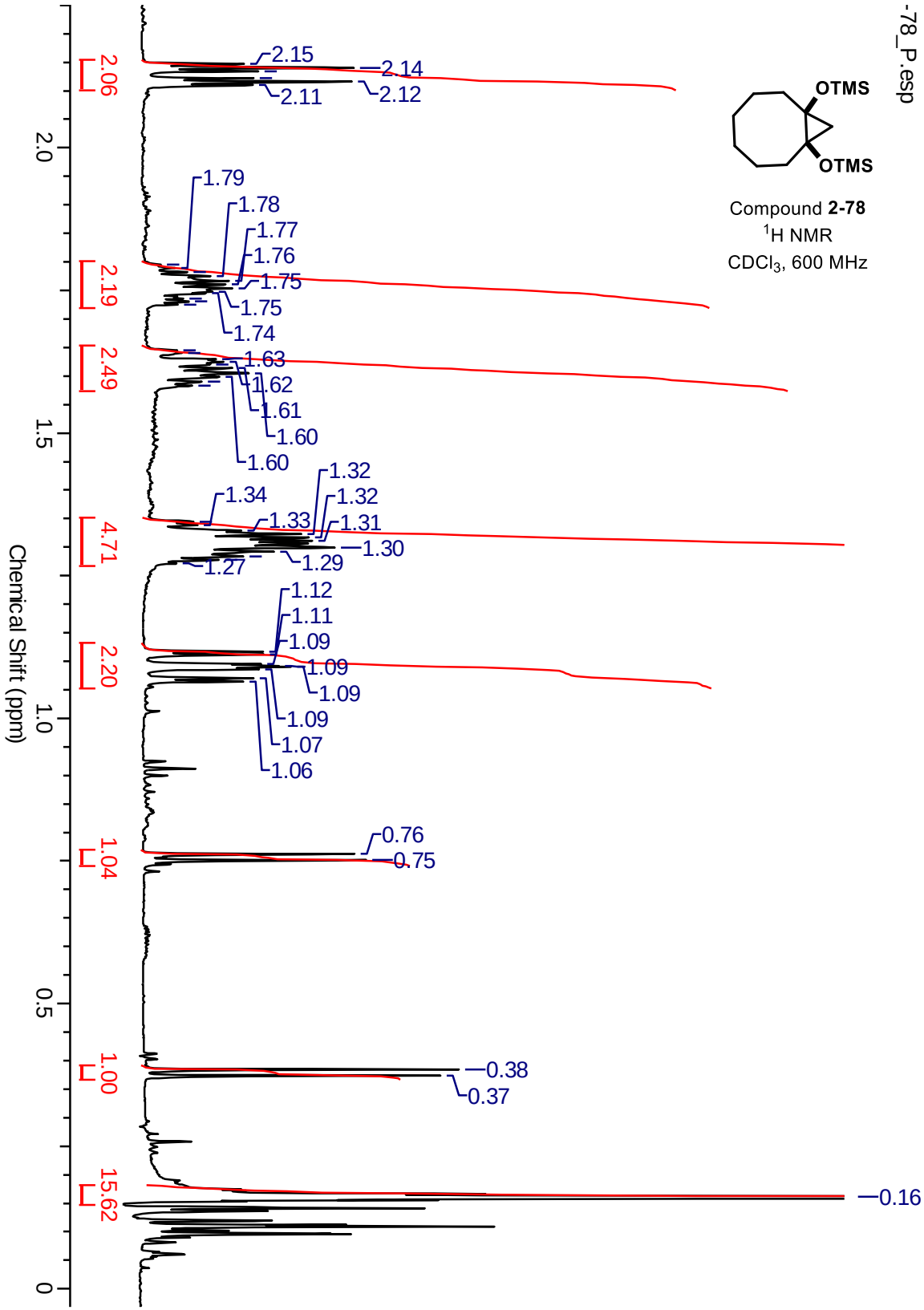


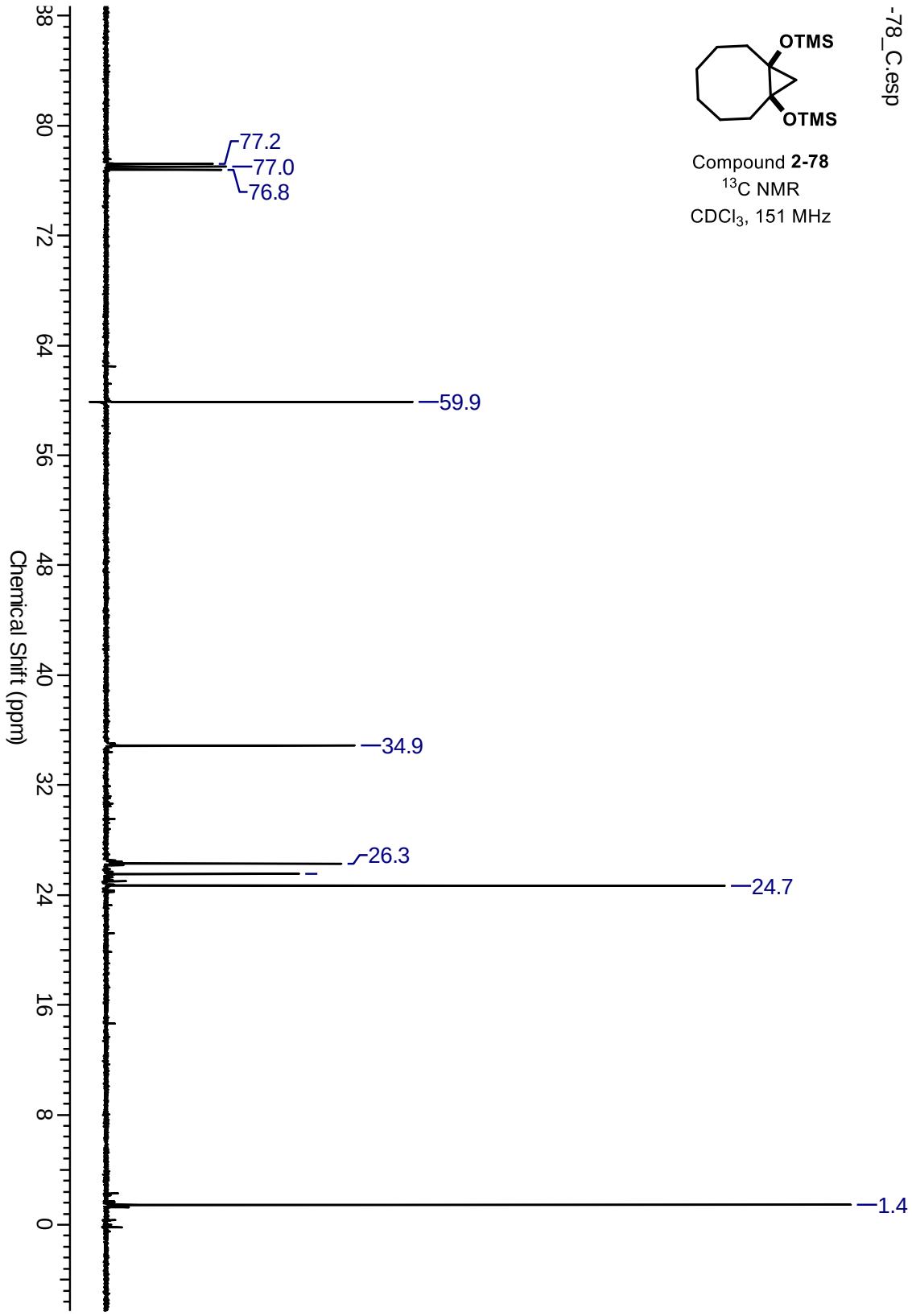


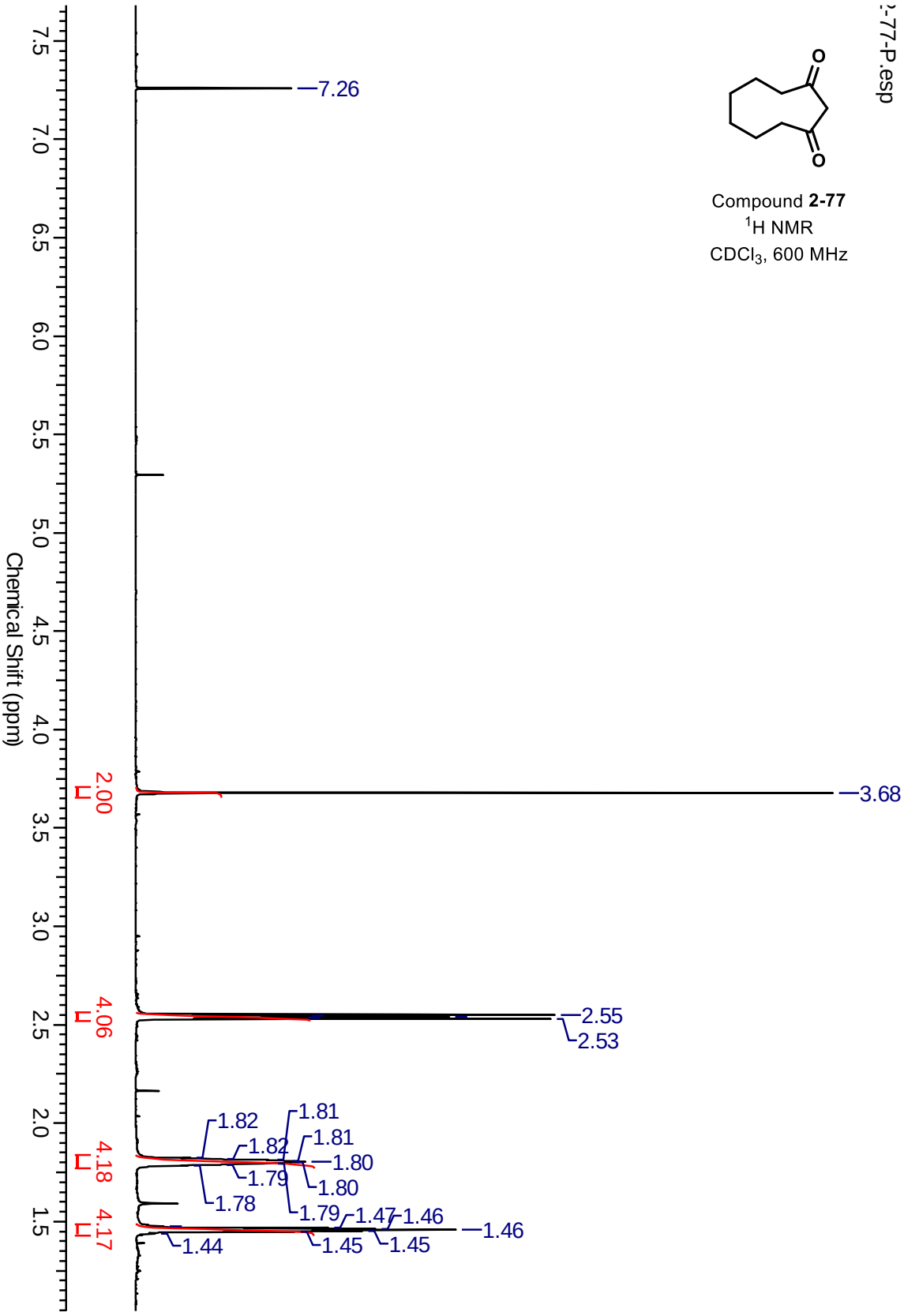
Appendix III. NMR Spectral Data of New Compounds for Chapter 2

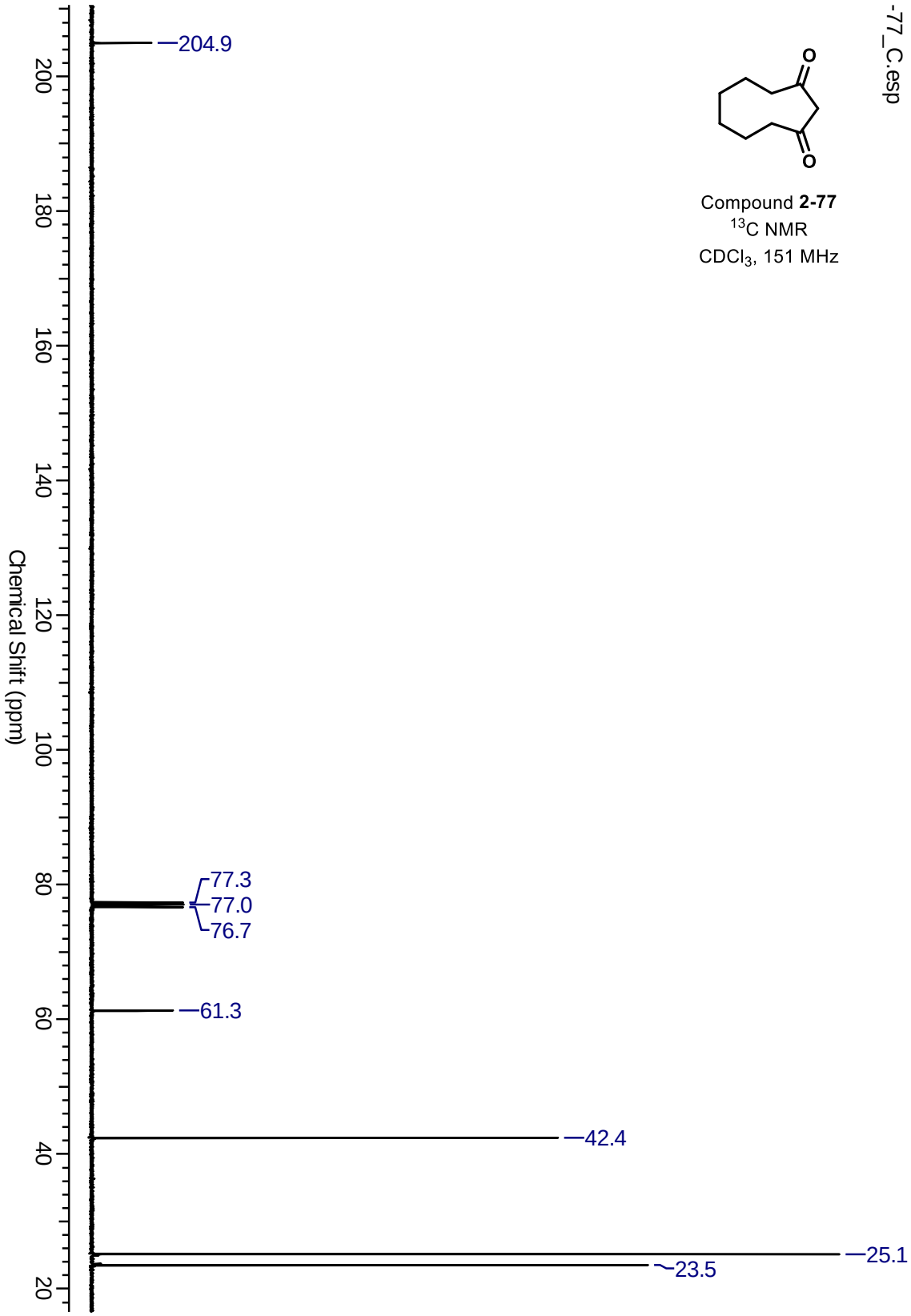


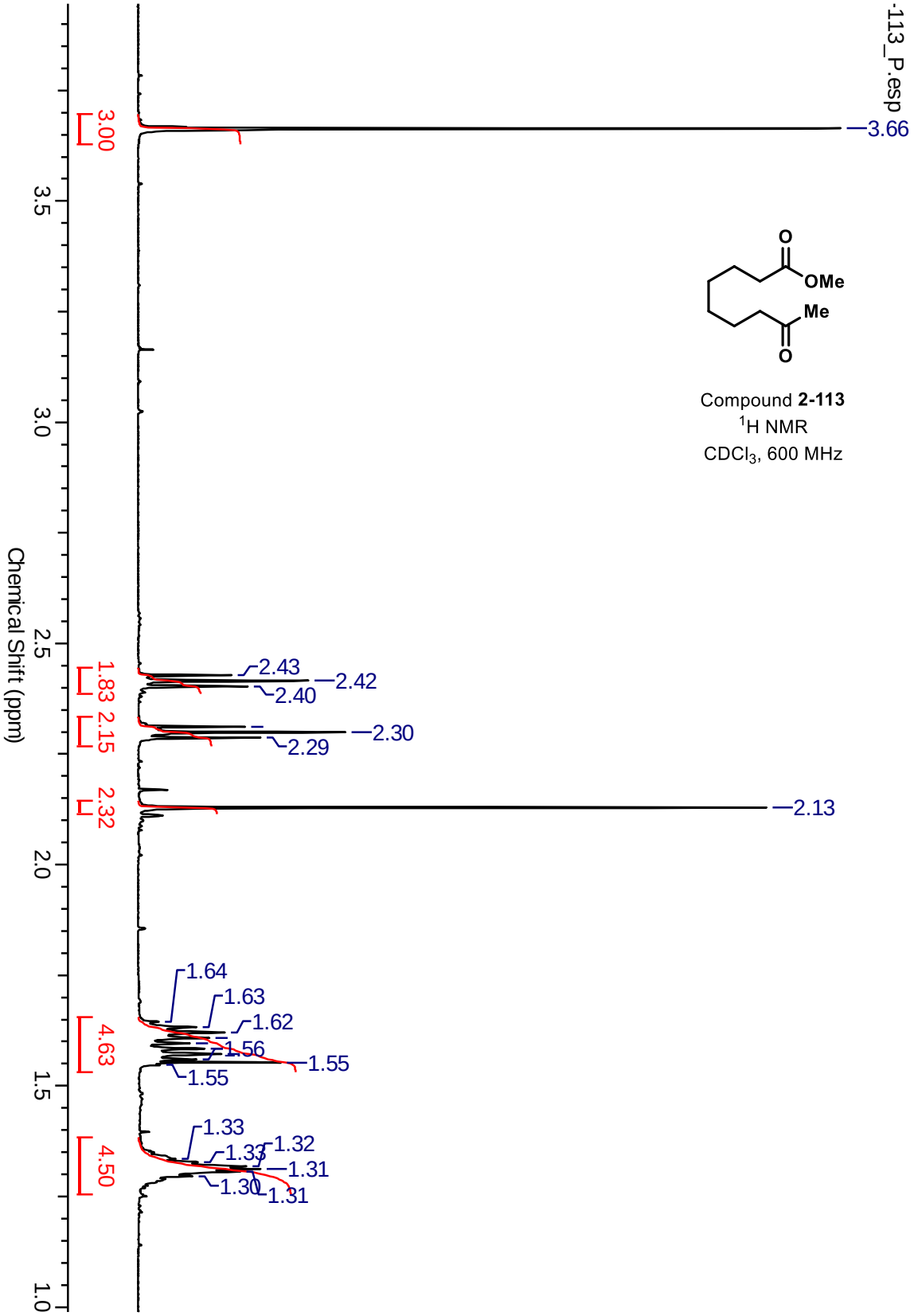


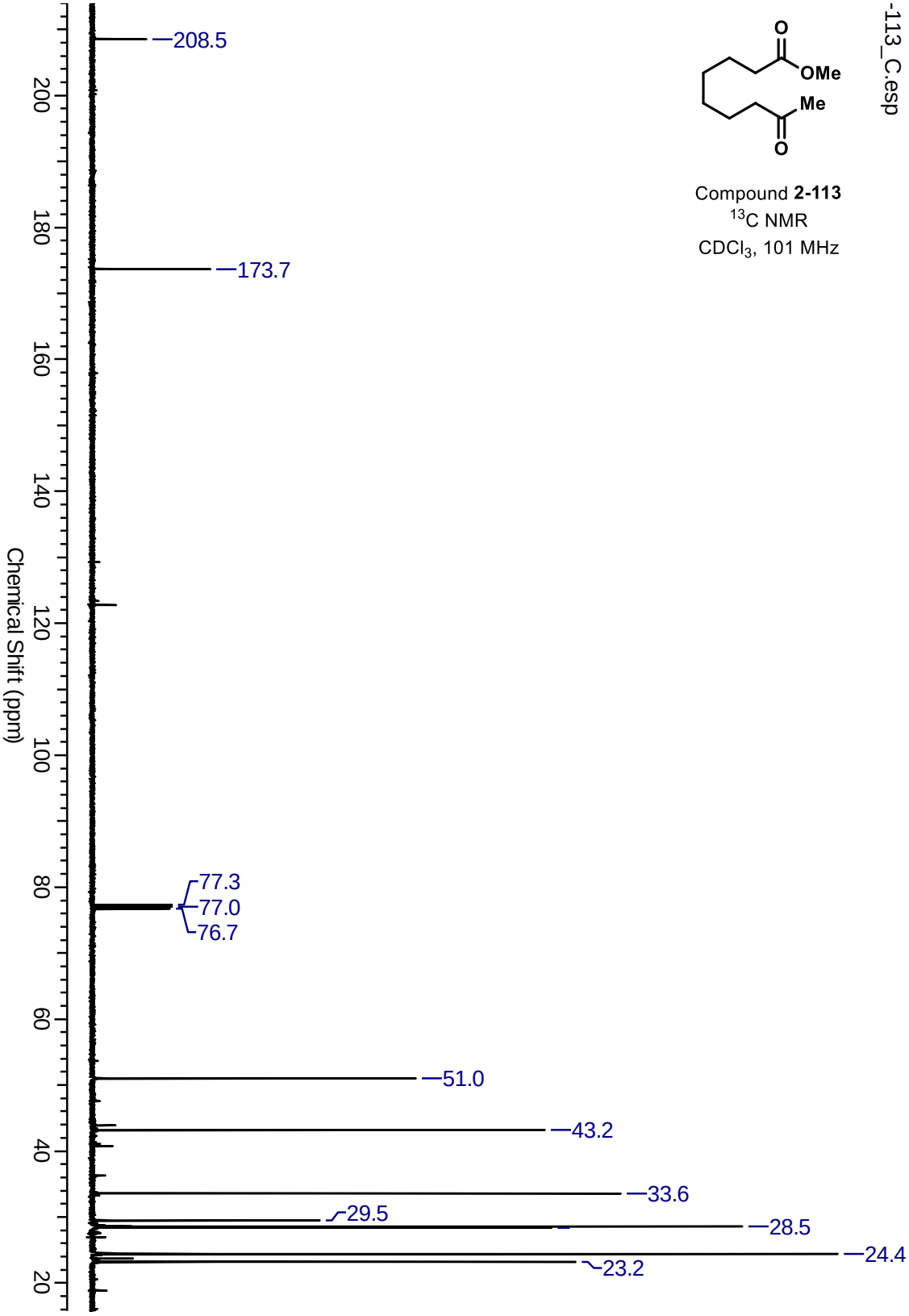


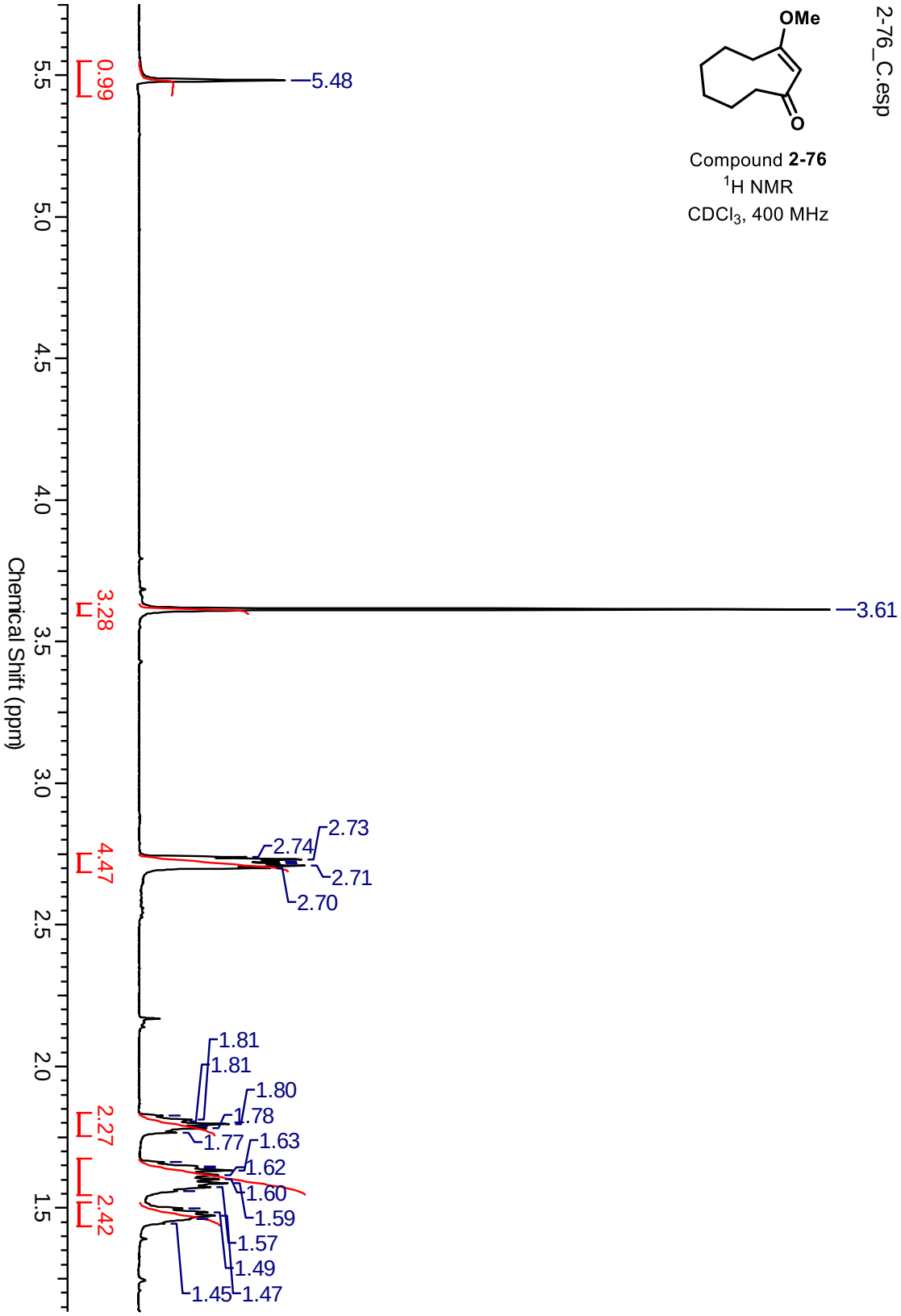


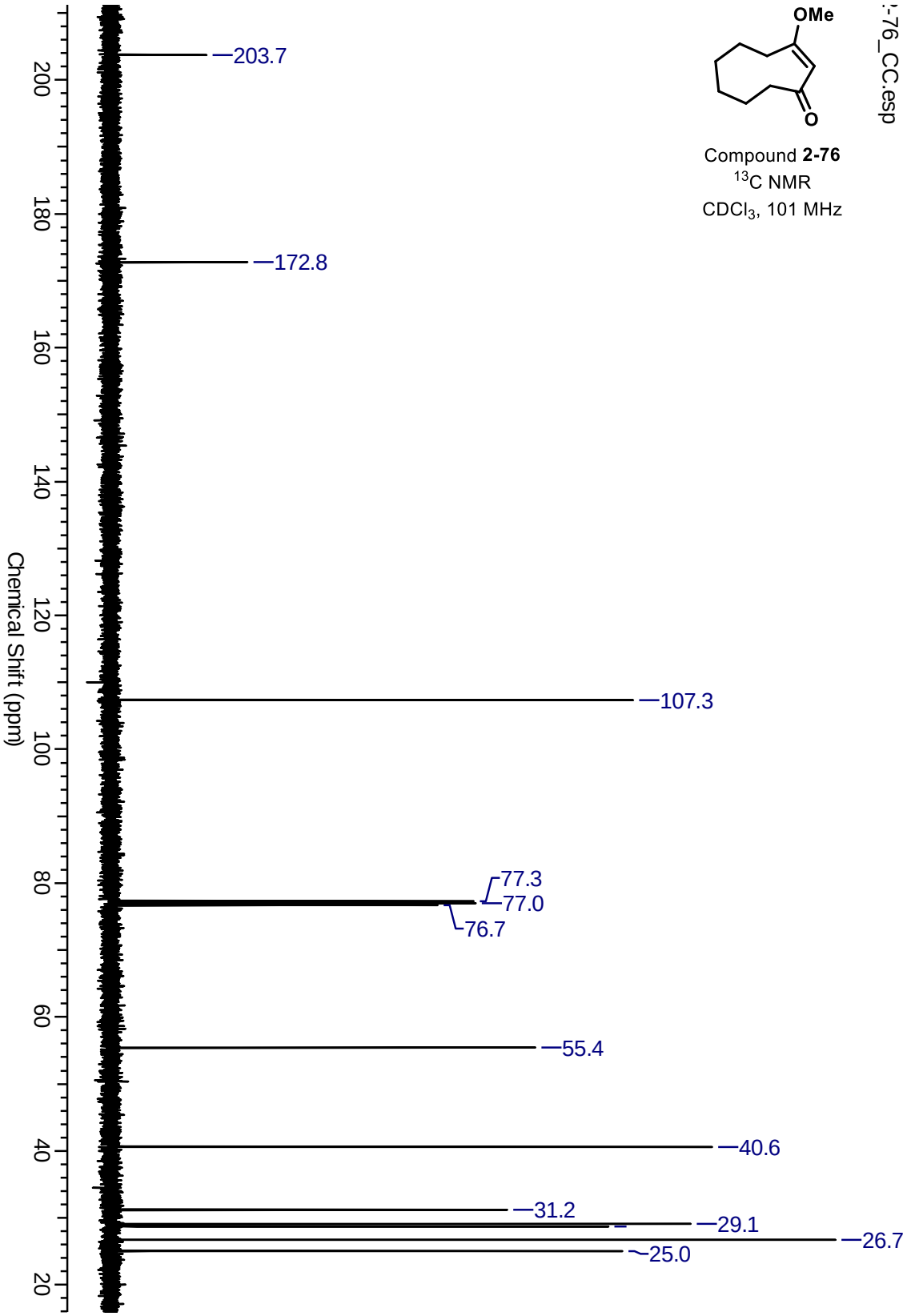


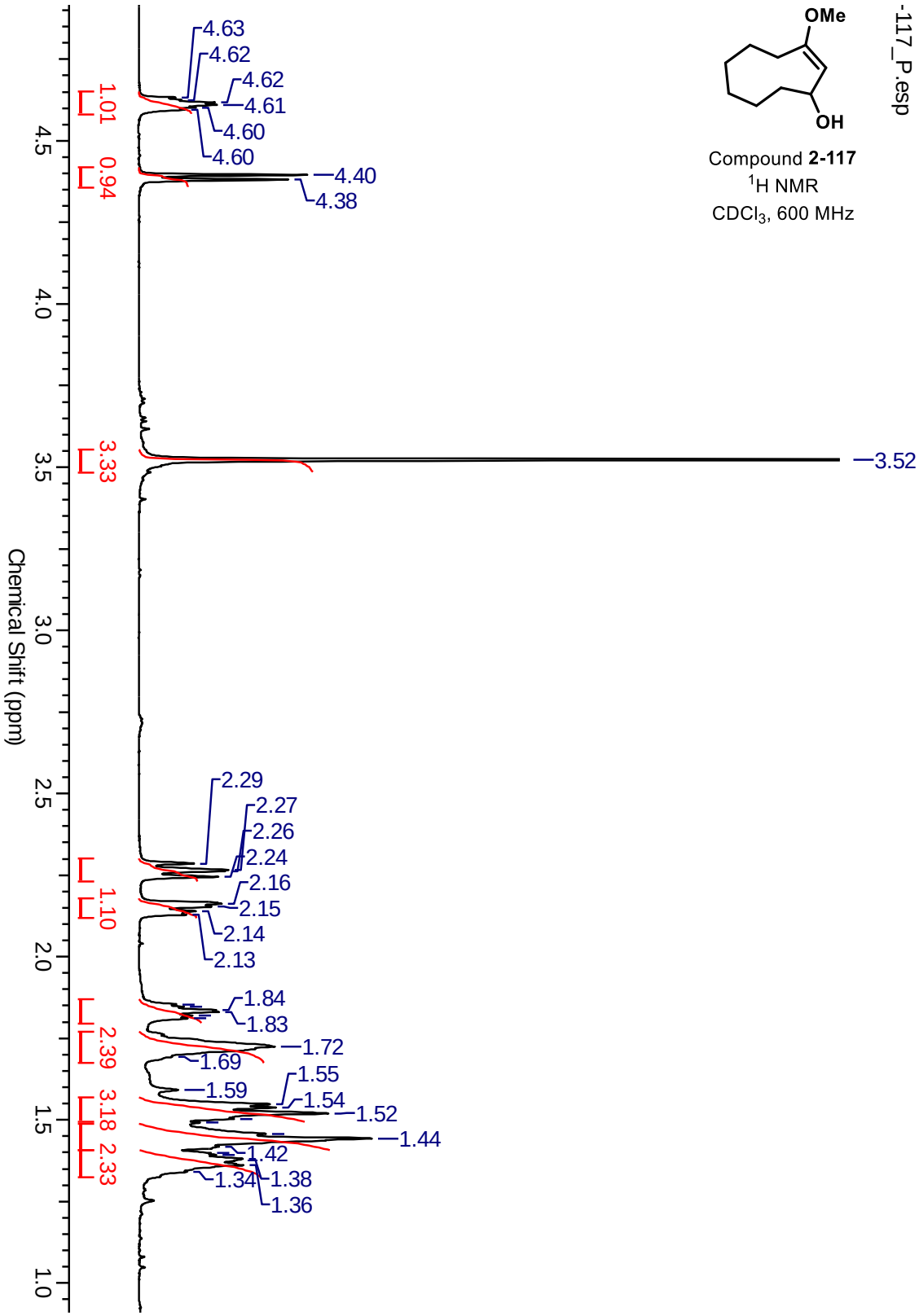


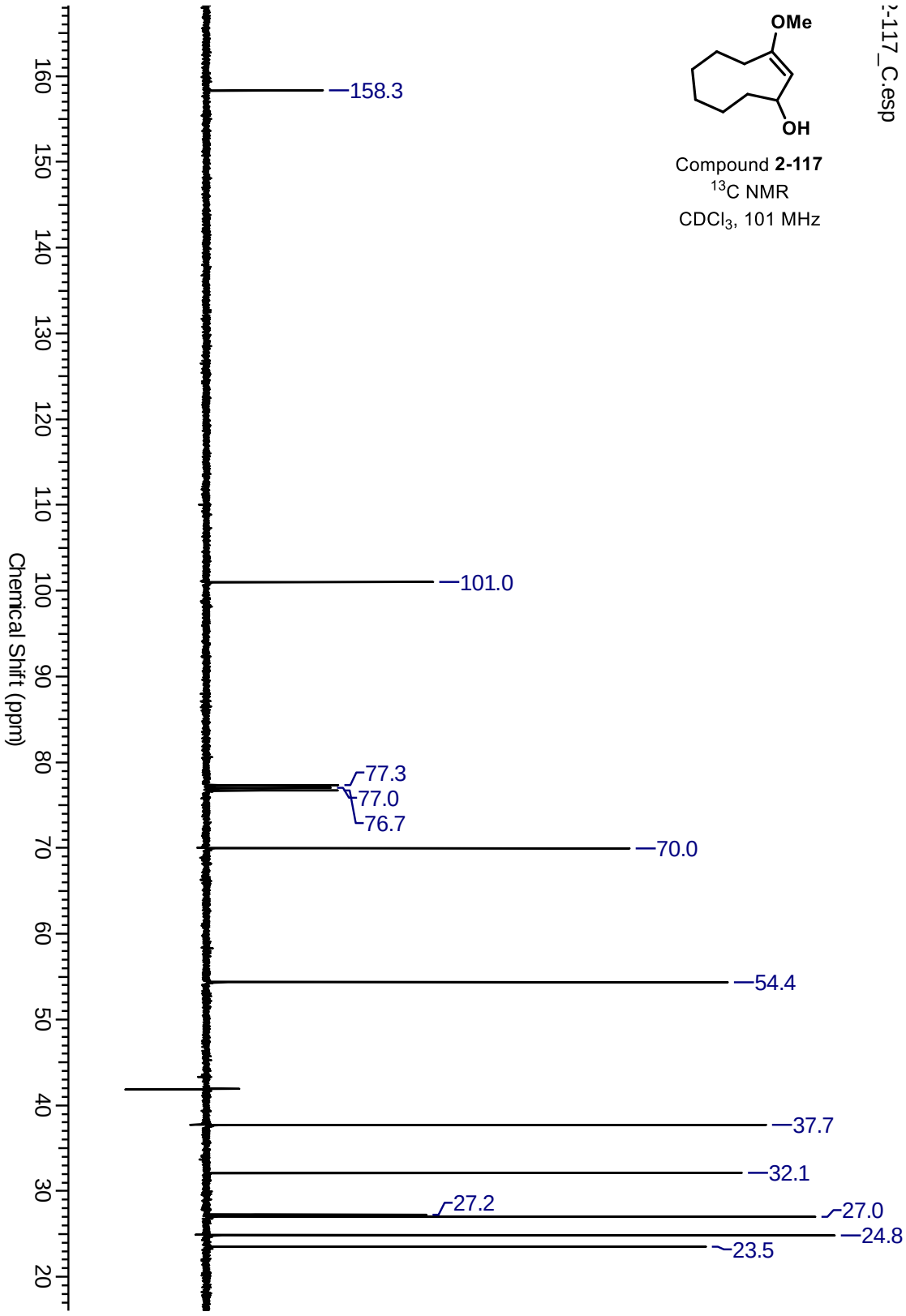


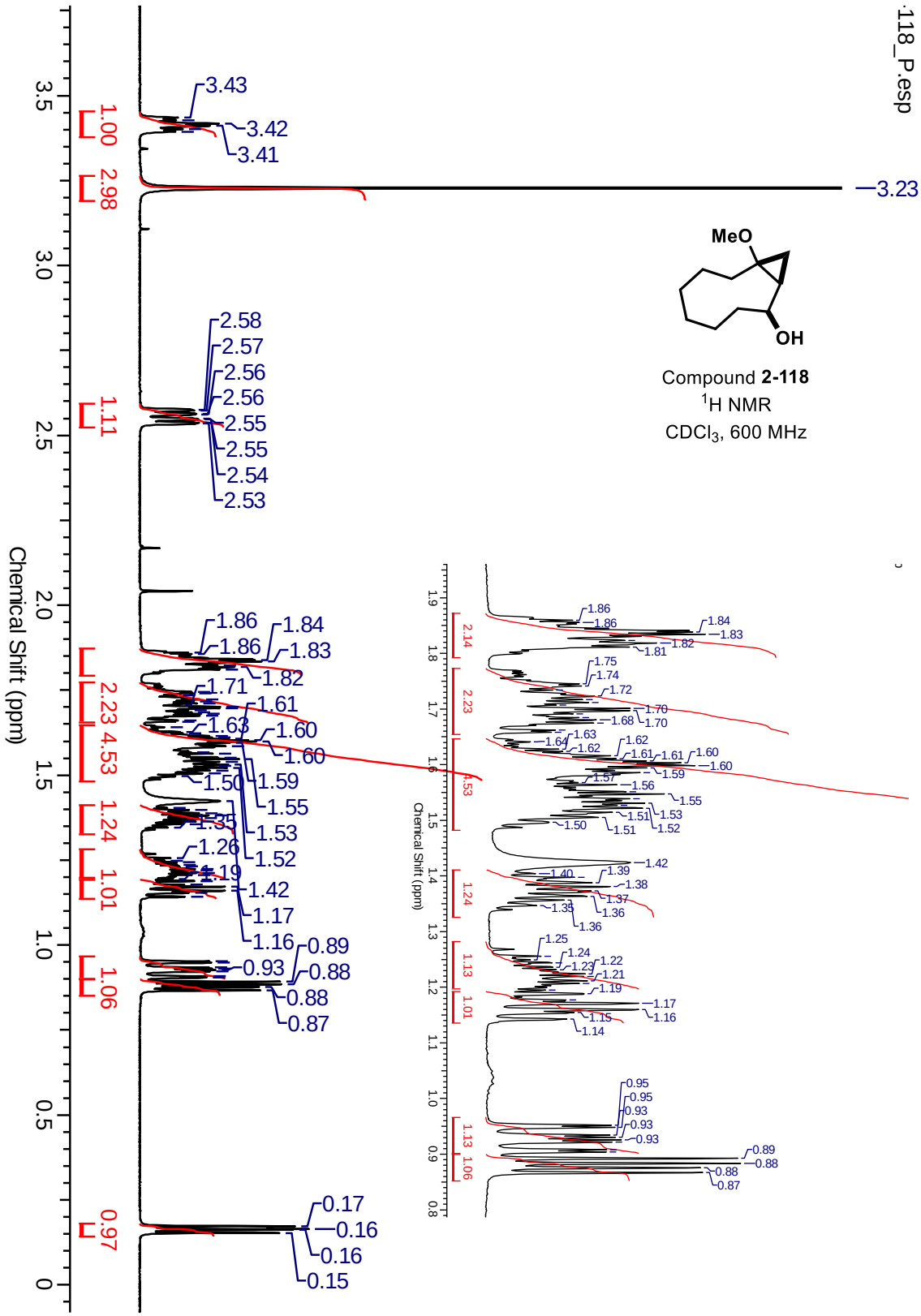


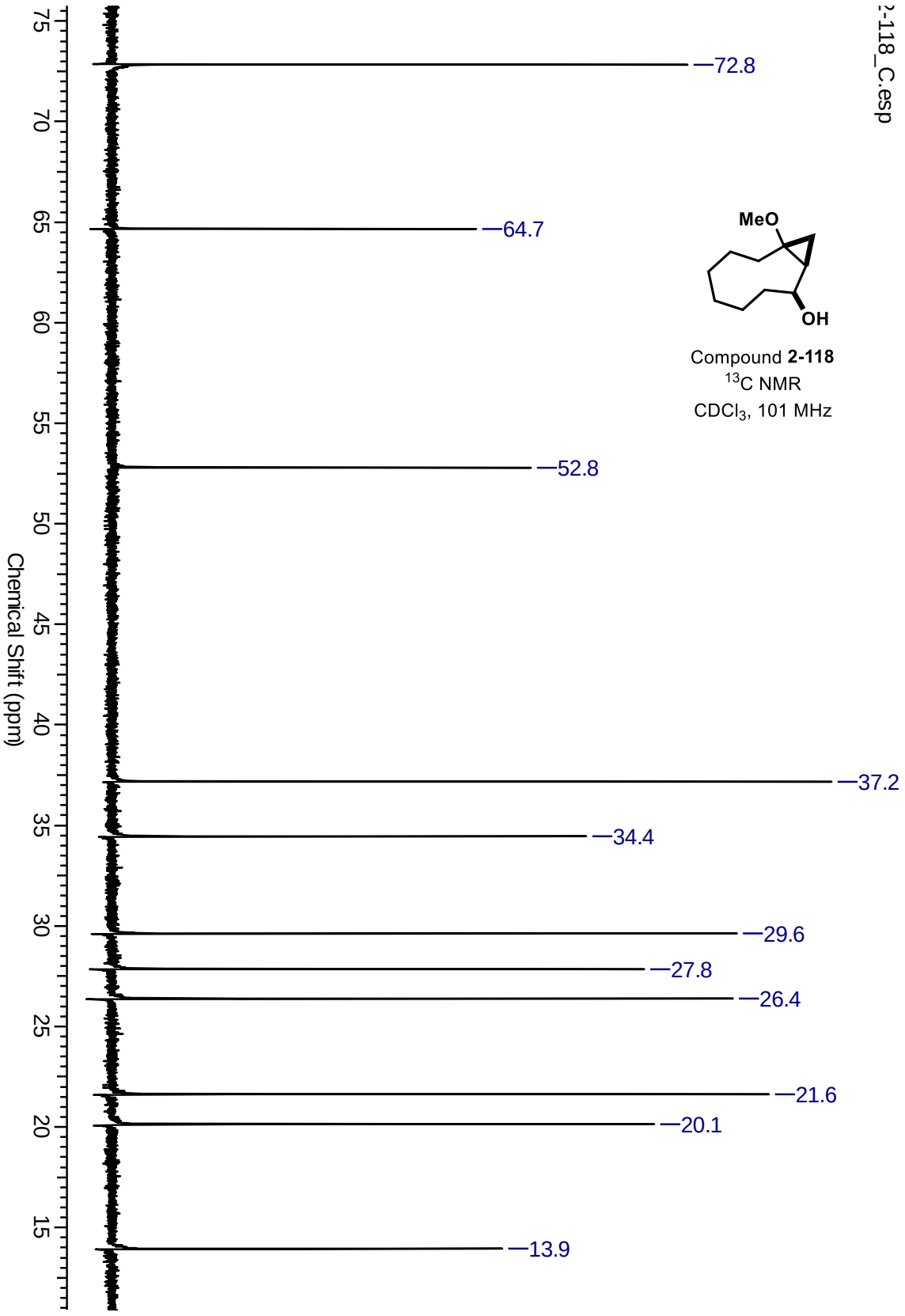


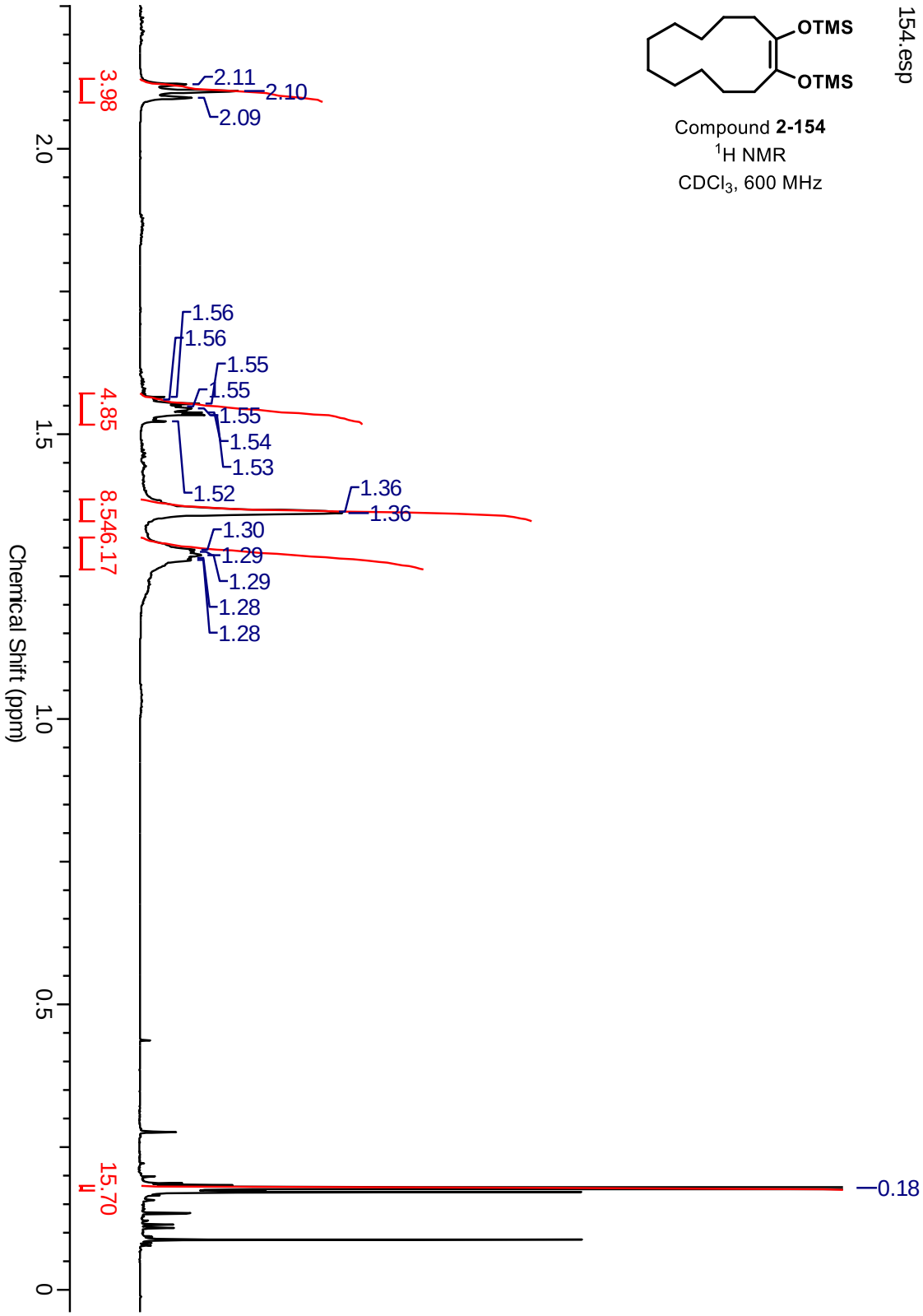


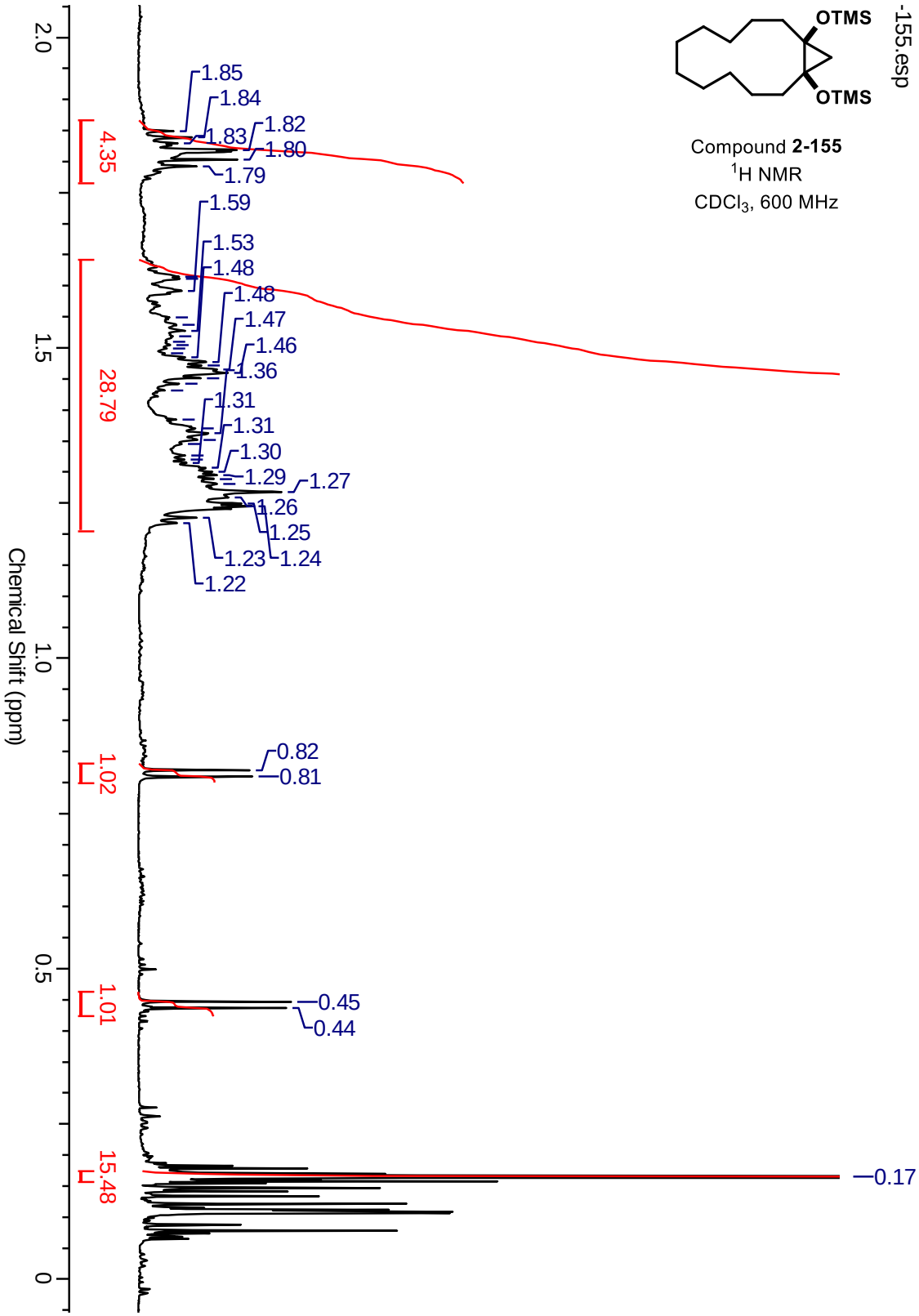


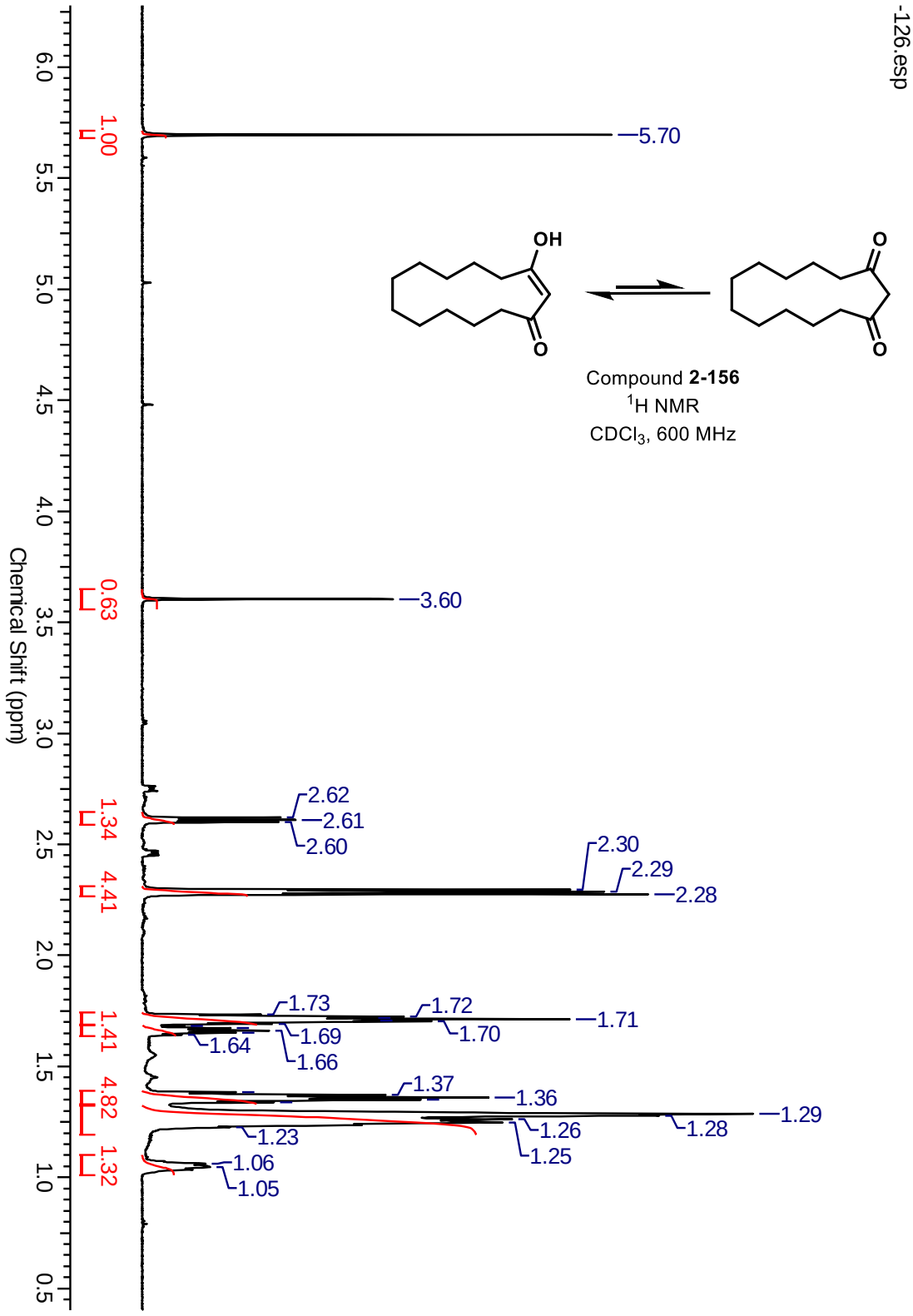


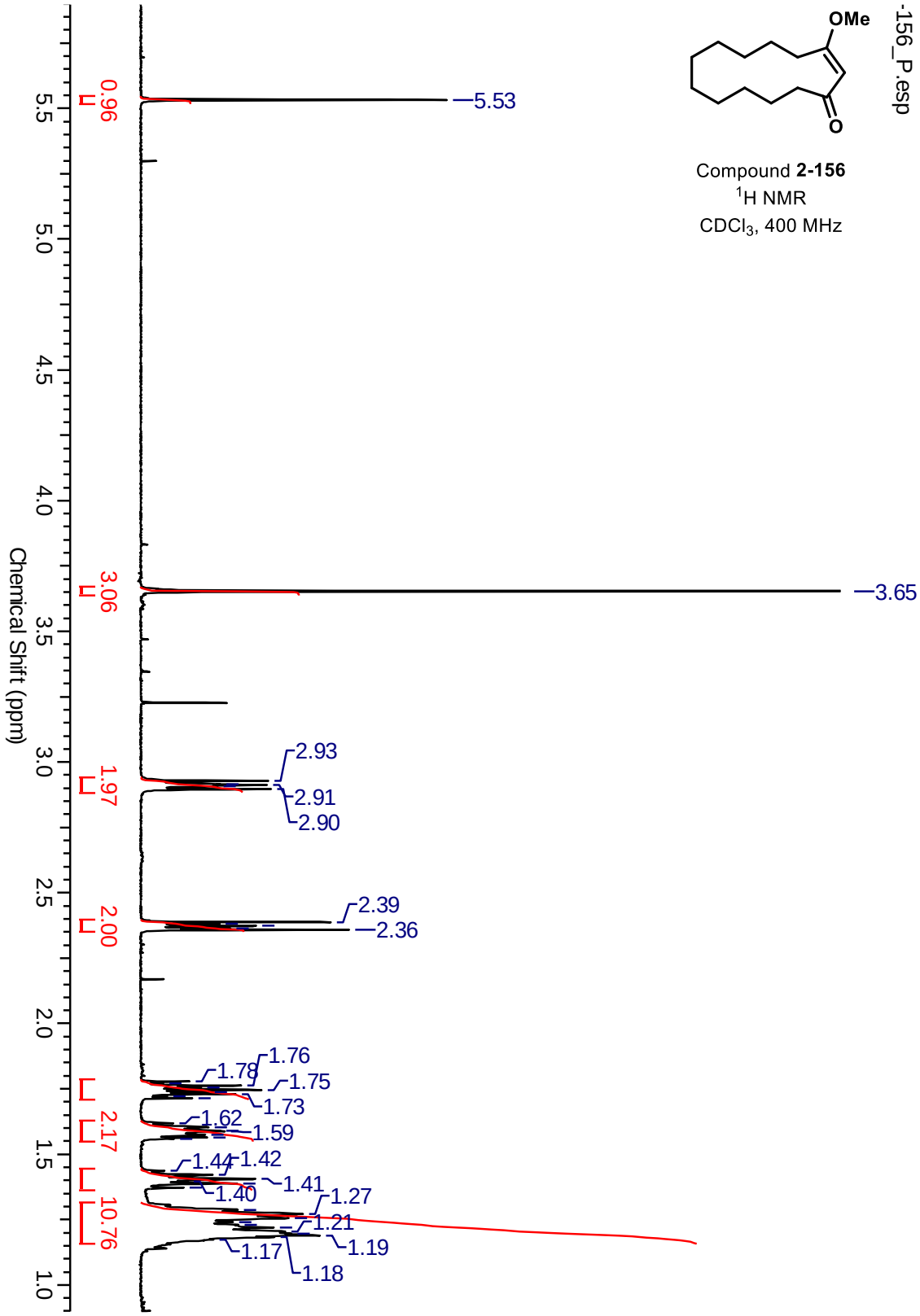


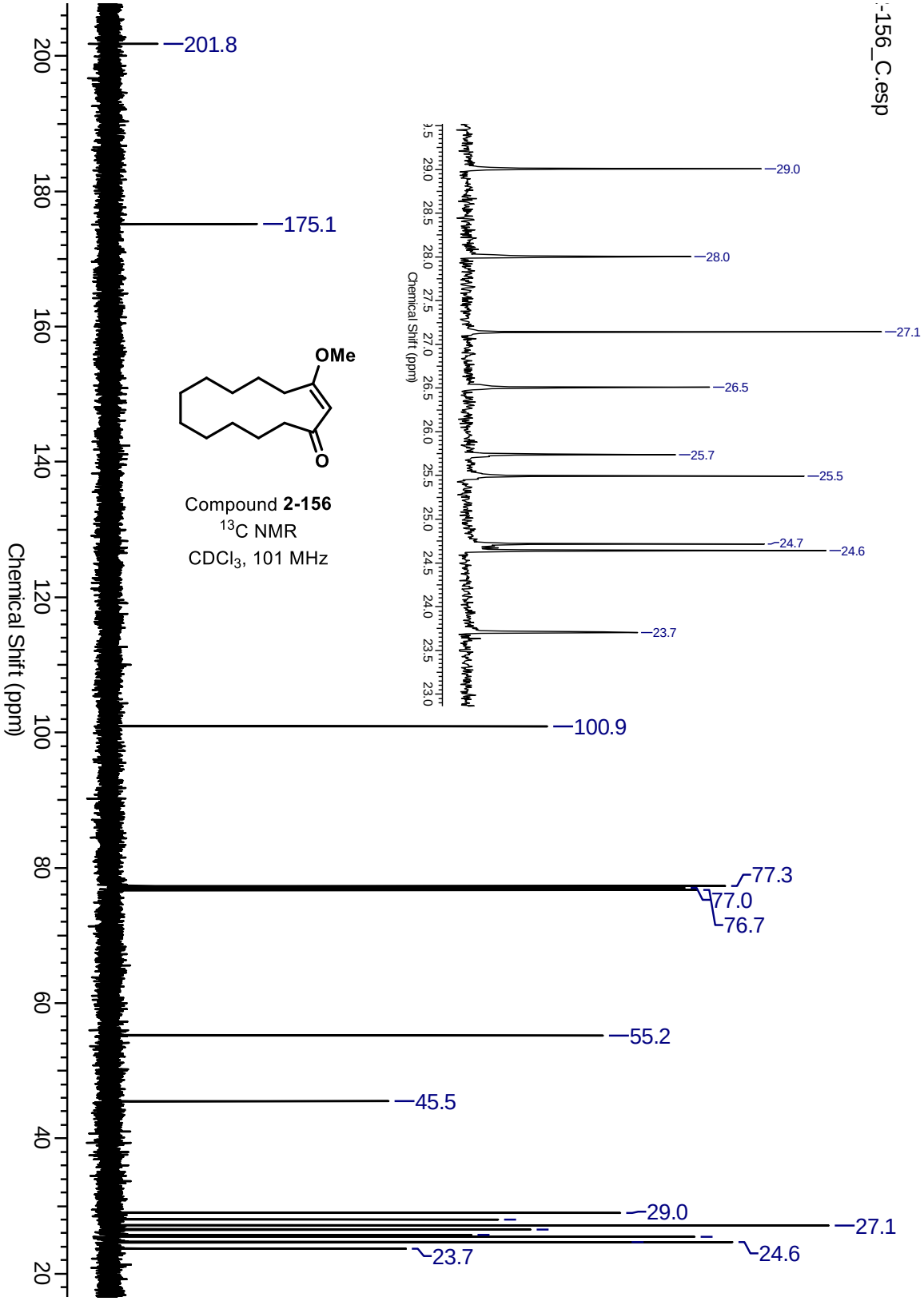


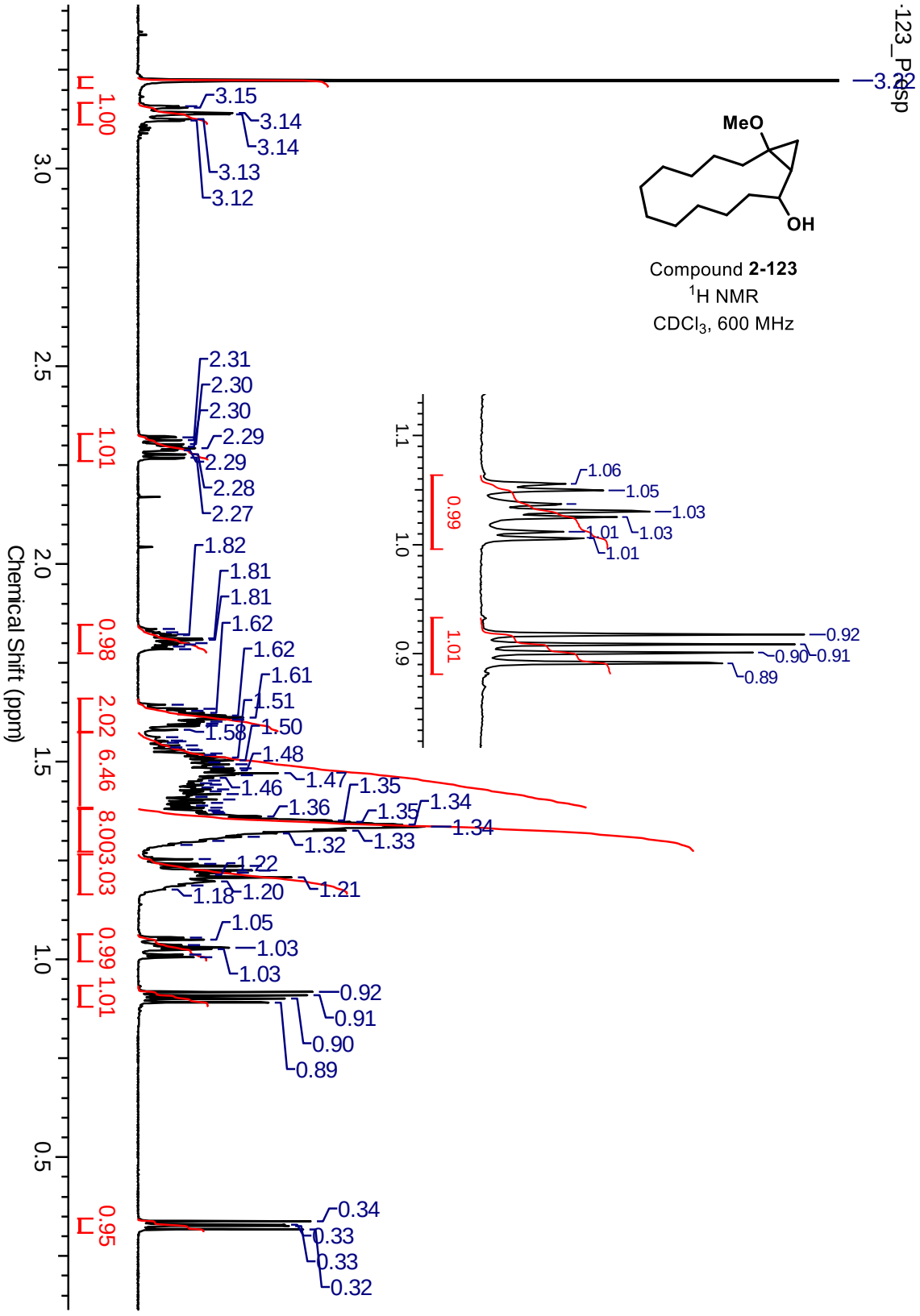


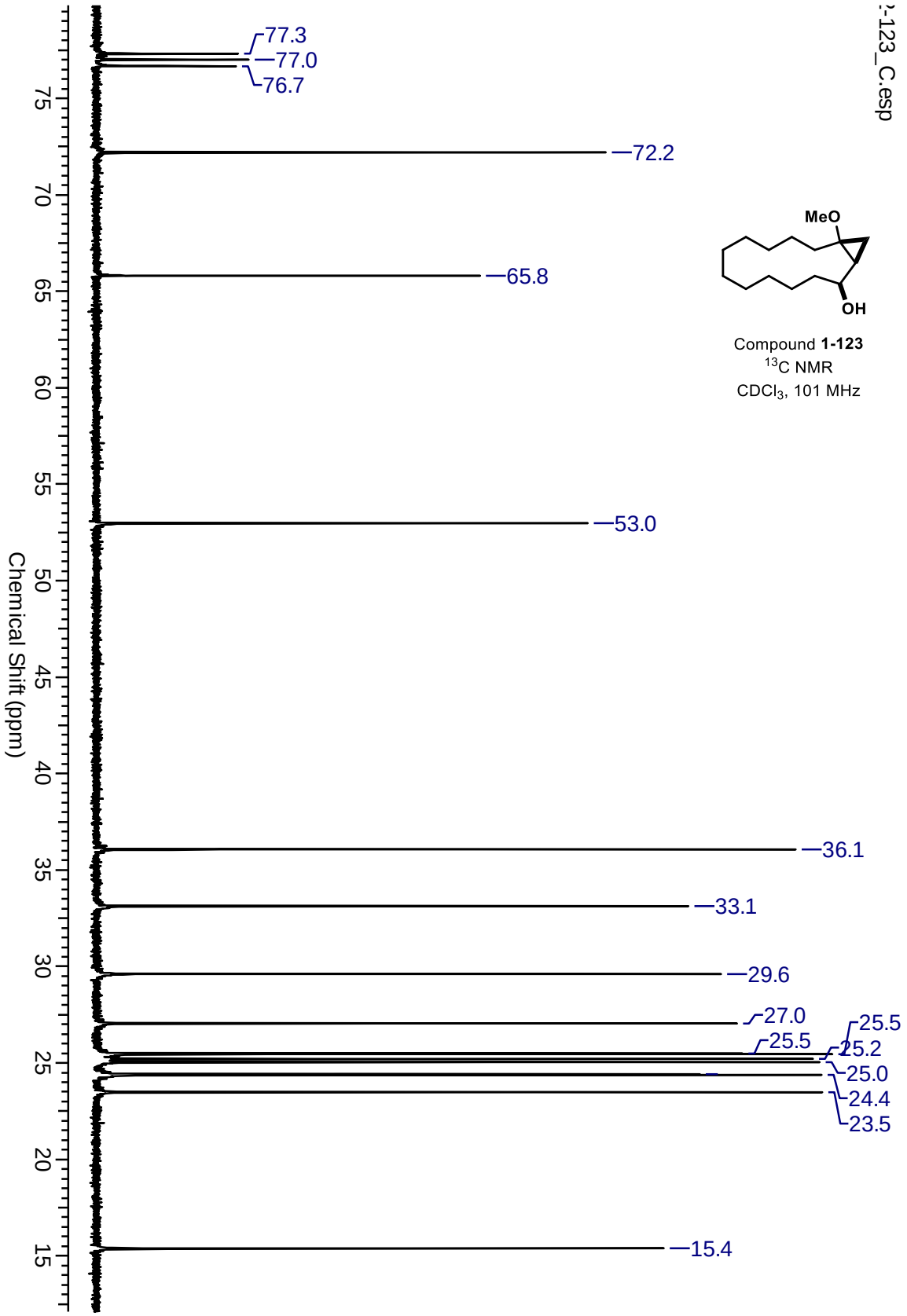


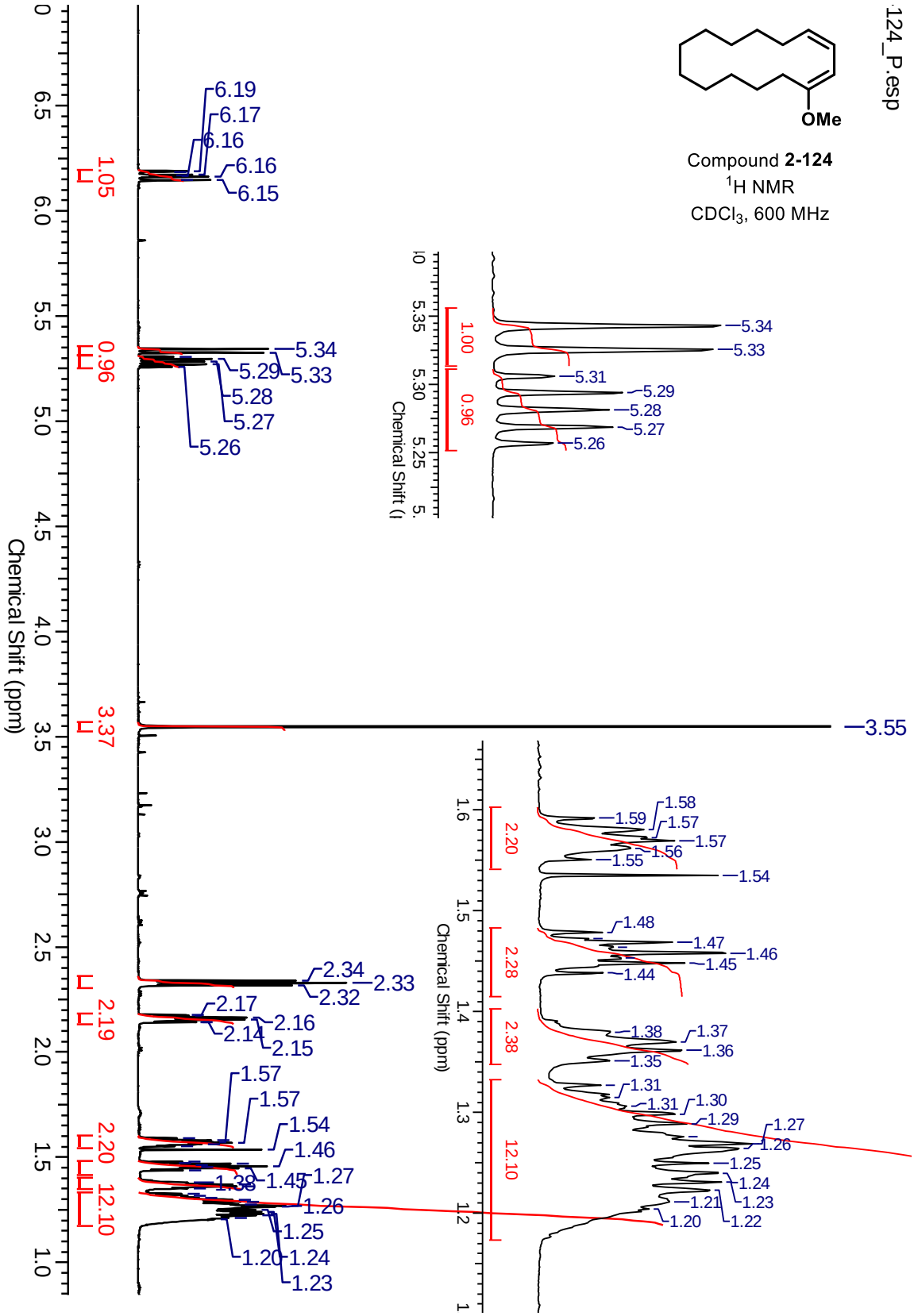


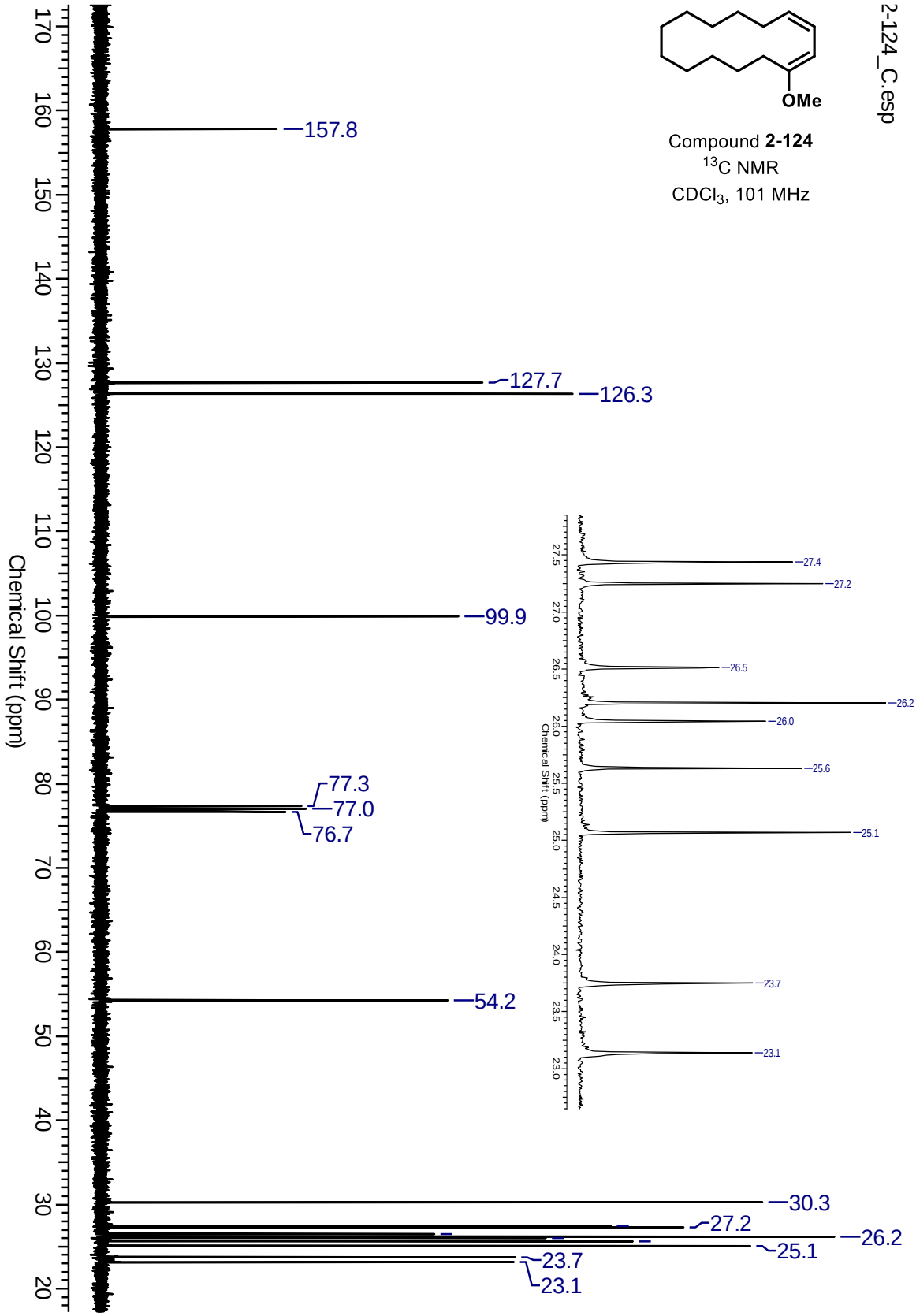


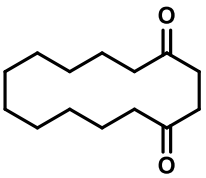




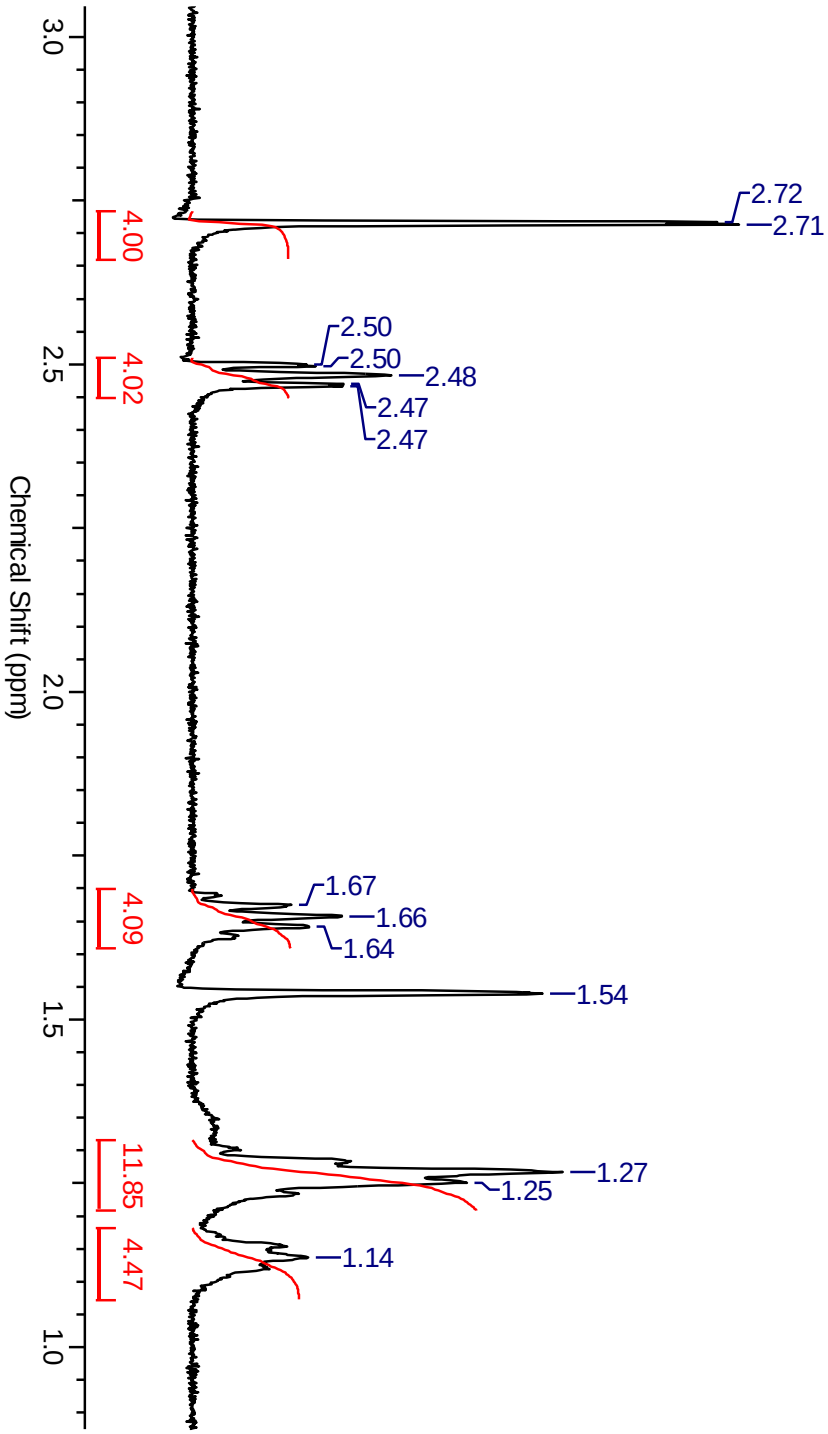


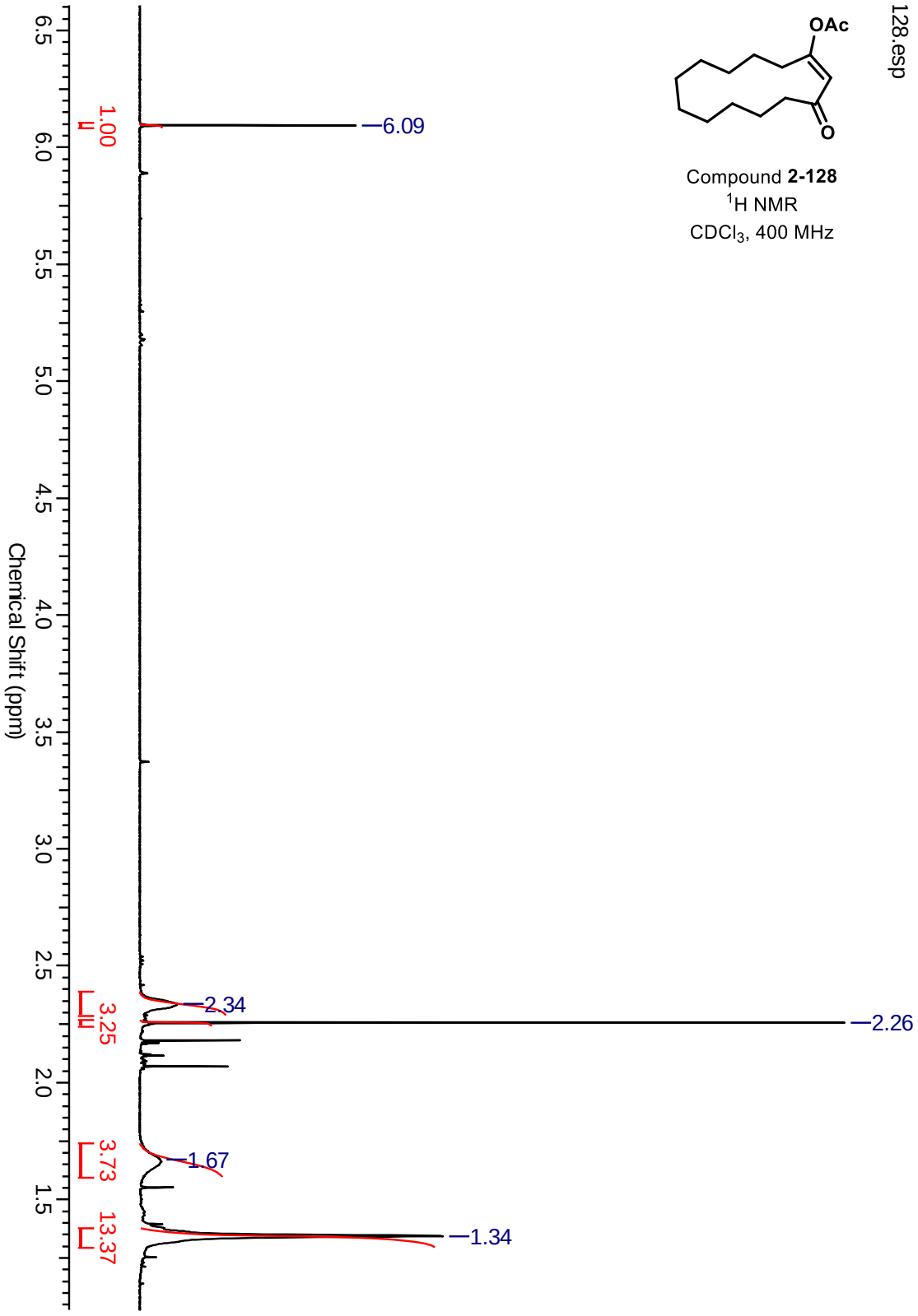


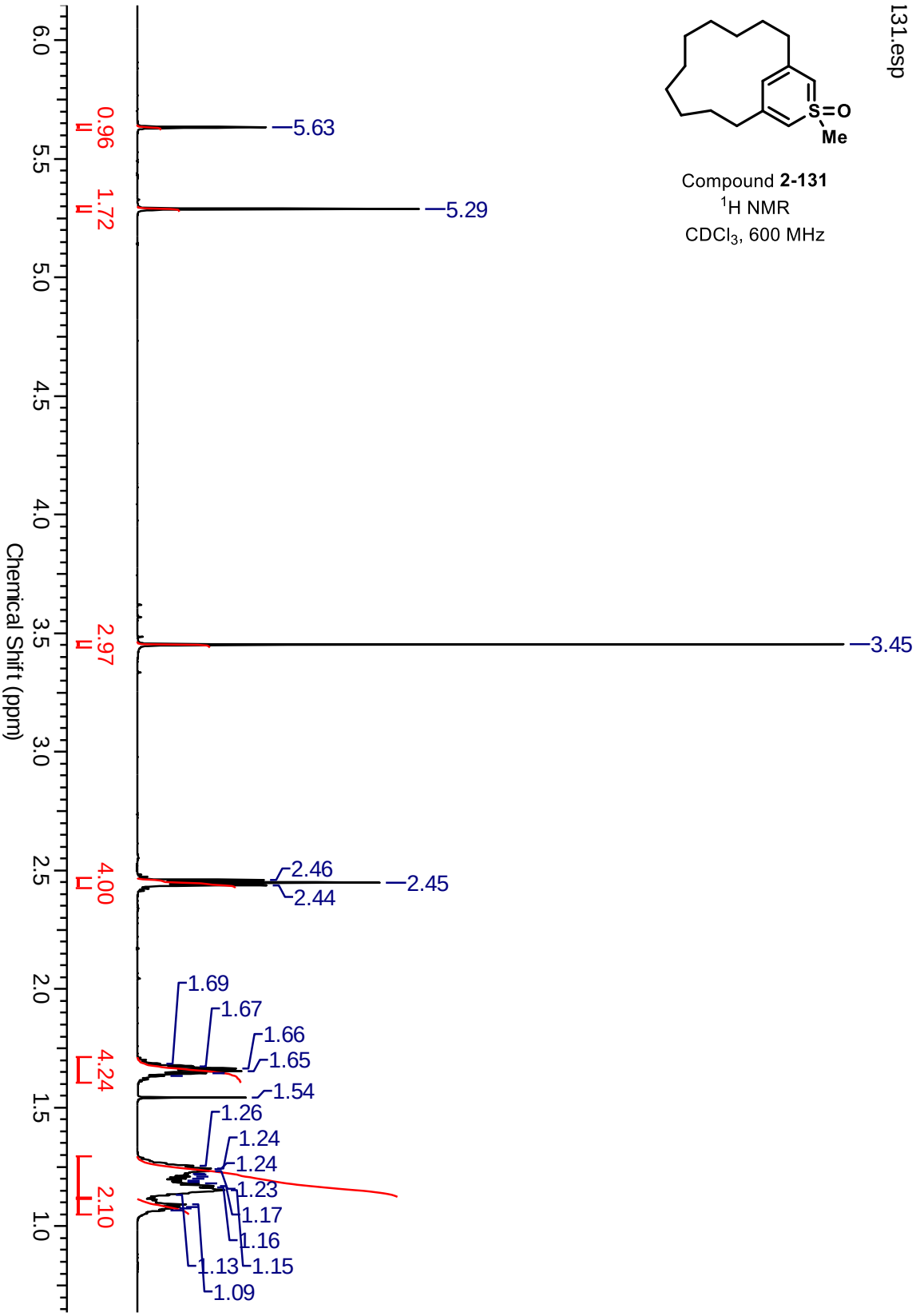


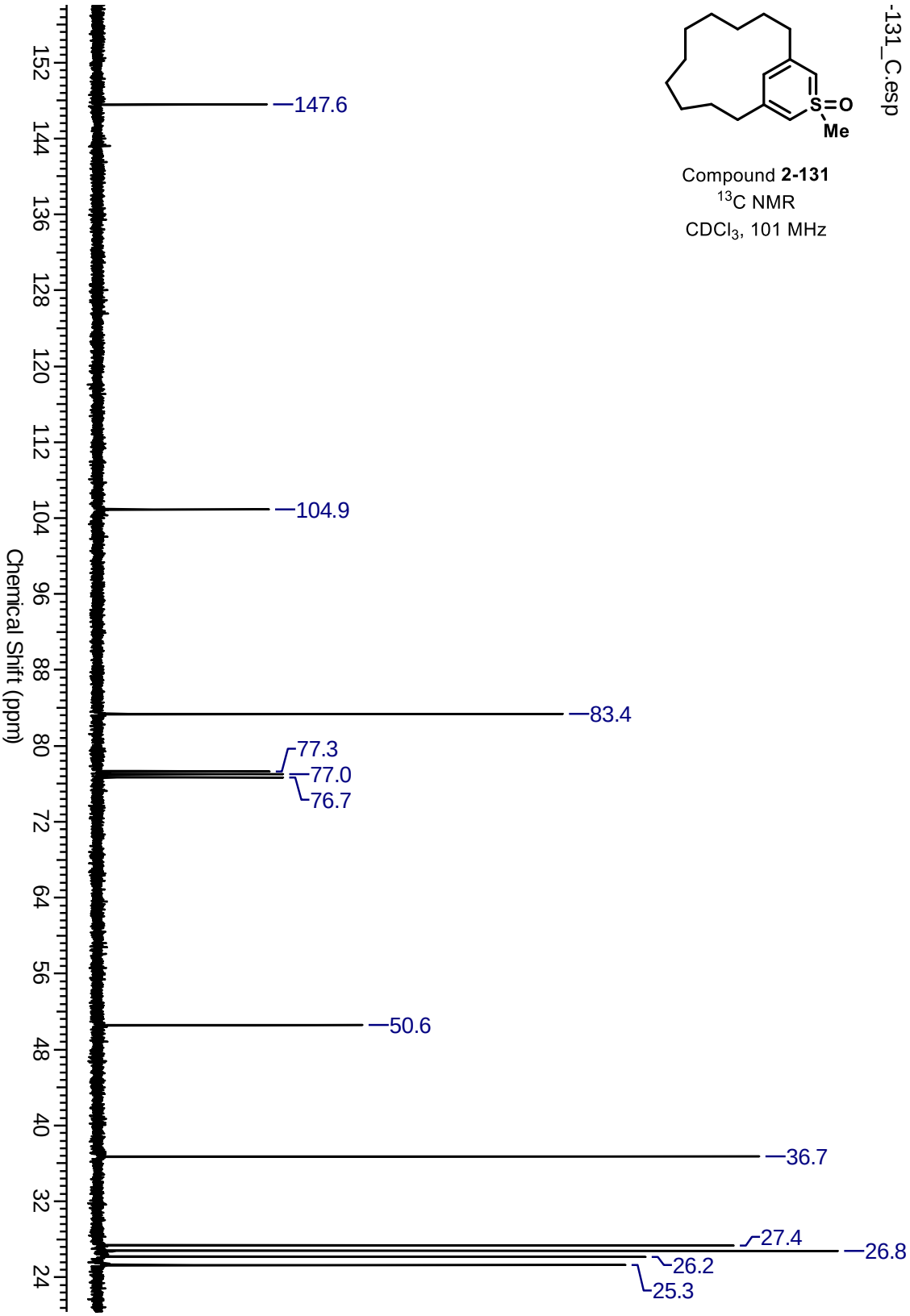


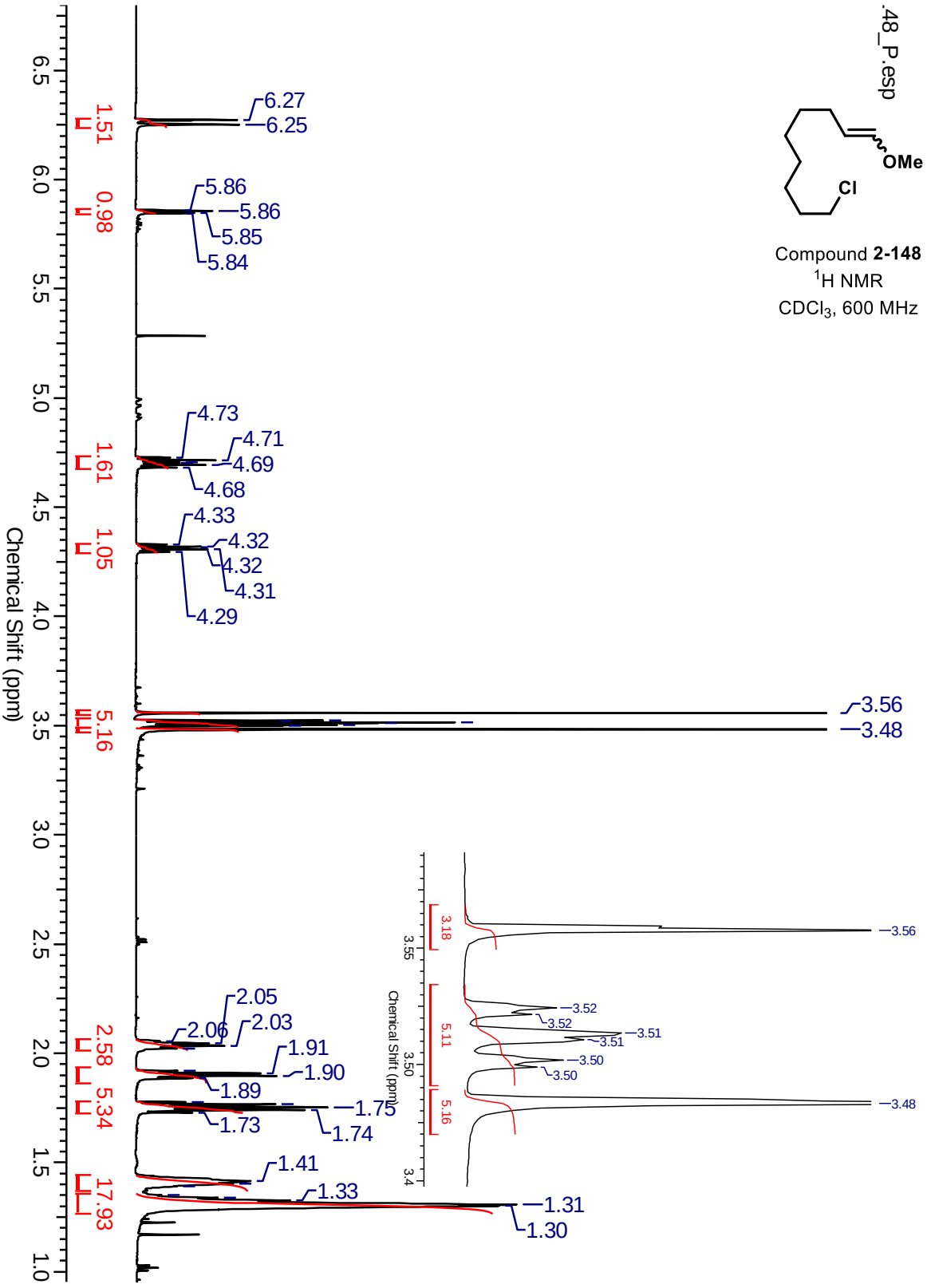
Compound **2-125**
^{1}H NMR
$CDCl_3$, 400 MHz

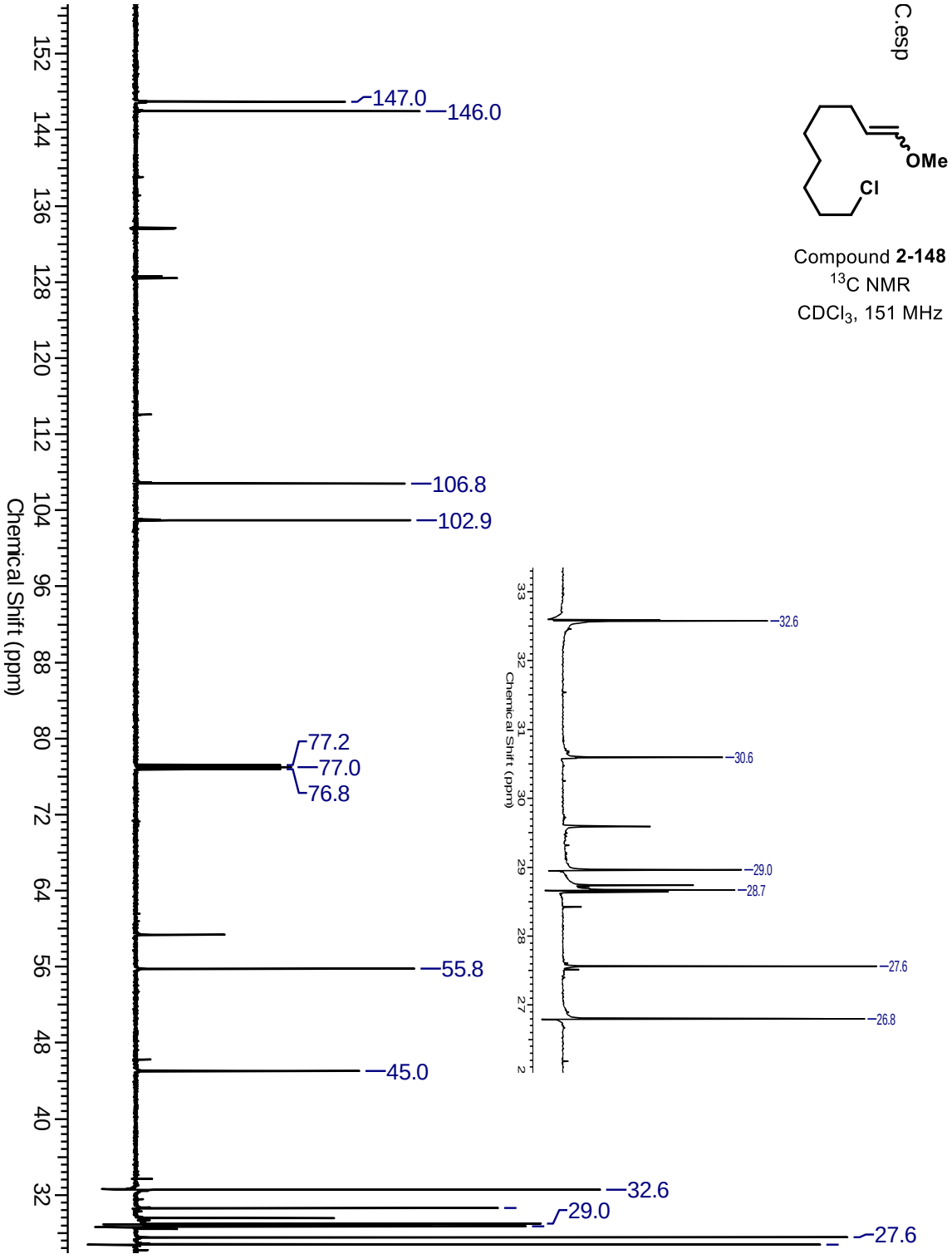


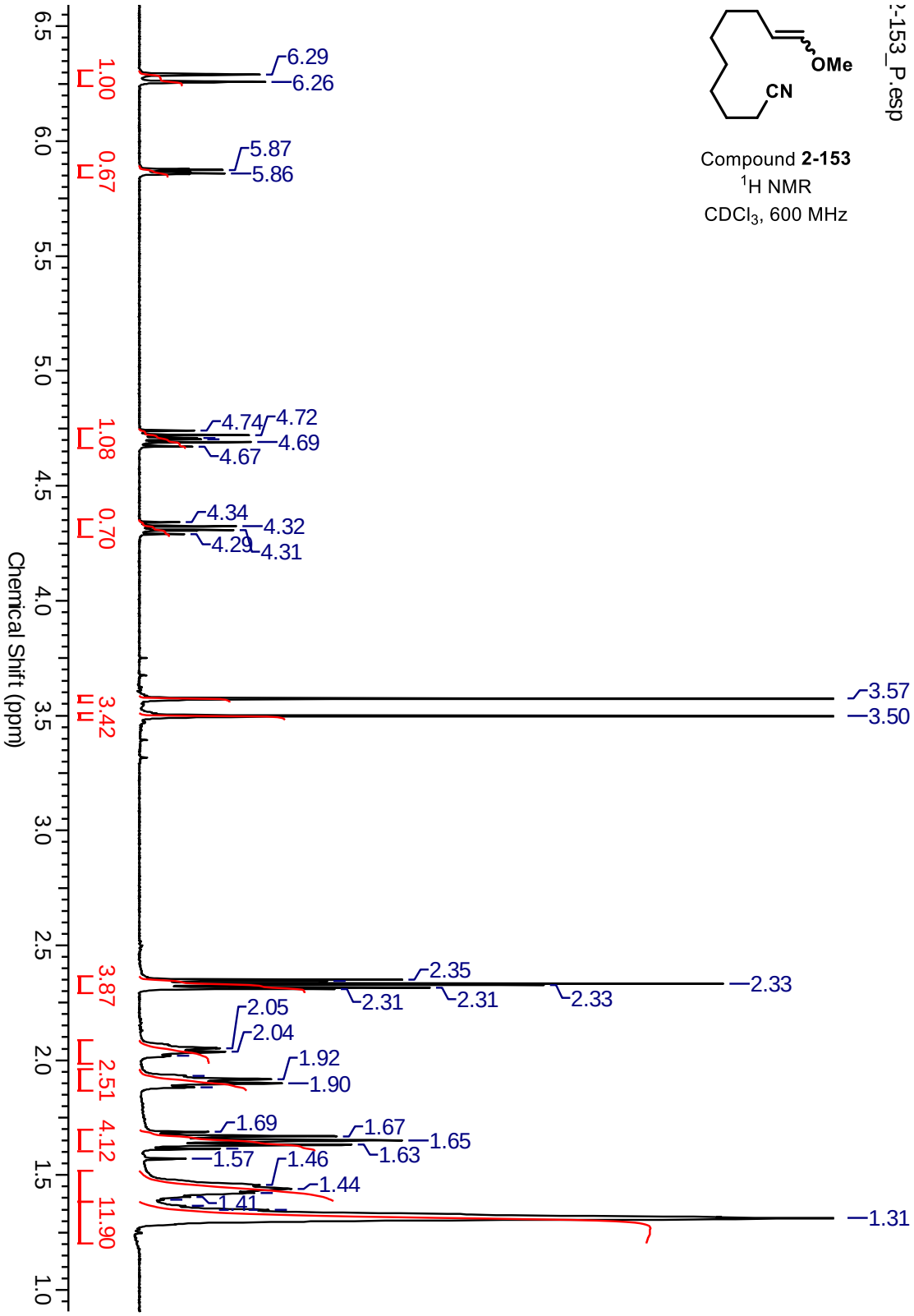


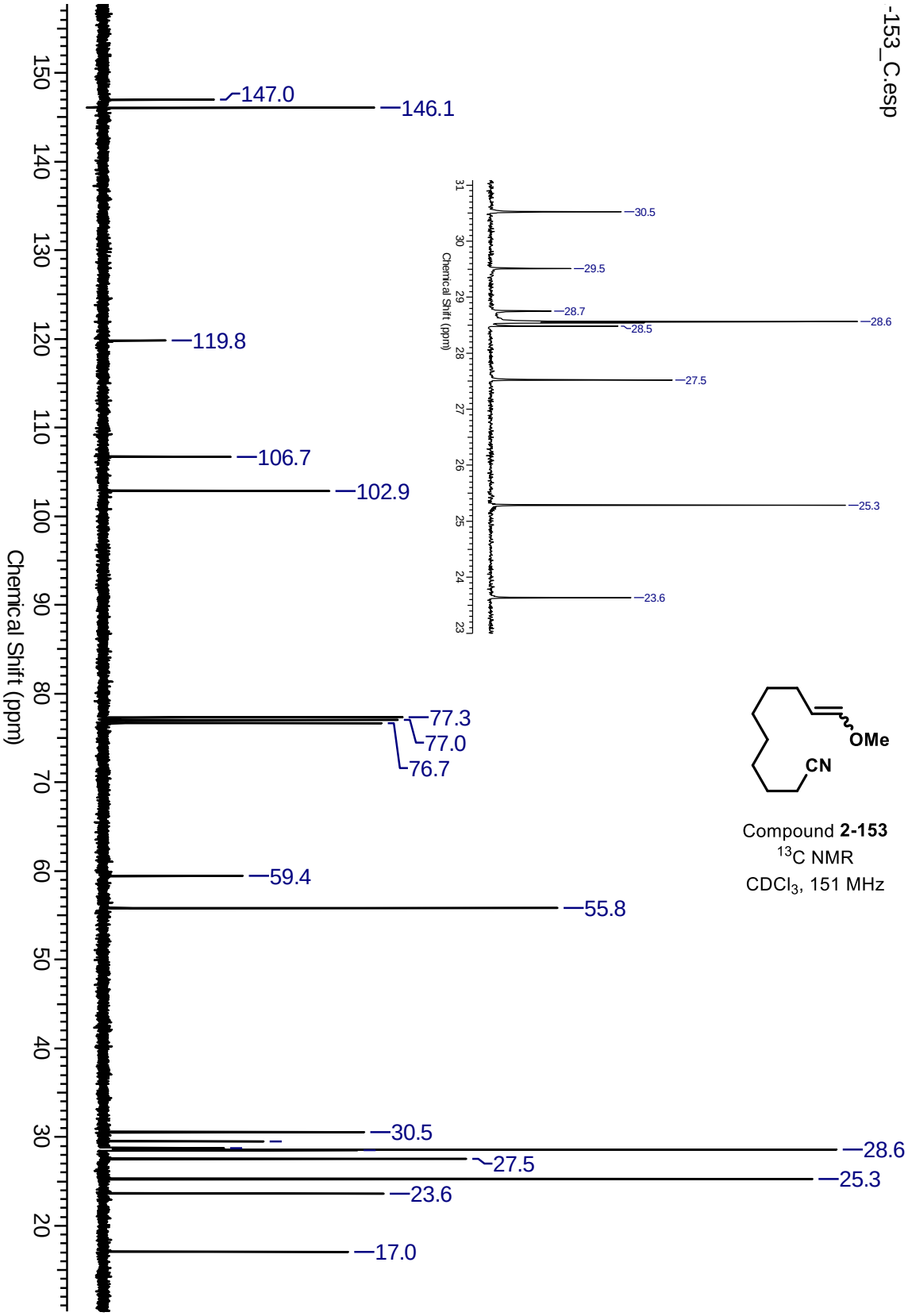












Curriculum Vitae

EDUCATION

August 2016 **Ph.D.** in Chemistry
The University *of* Western Ontario, London, ON Canada
Supervisor: Prof. Brian L. Pagenkopf

2007 **M.Sc.** Organic Chemistry
Kakatiya University, Warangal, TS India

2004 **B.Sc.** Chemistry, Botany, and Zoology
Osmania University, Hyderabad, TS India

EMPLOYEMENT HISTORY

Sep 2011 - Aug 2016 **Graduate Research/Teaching Assistant**
Department of Chemistry
T*he* University *of* Western Ontario, London, ON Canada
Supervisor: Prof. Brian L. Pagenkopf

May 2010 - Jul 2011 **Research Associate**
Discovery Research, DuPont Crop Protection
E. I. DuPont India (P) Ltd, Hyderabad, TS India

July 2007 - April 2010 **Senior Executive**
Process R&D
Dr. Reddy's Laboratories Ltd, Hyderabad, TS India

PATENTS

(2) Rangineni, S.; Duggirala, N.; Mudapaka, V. K.; Kadaboina, R.; Murki, V.; Manda, A.; Badisa, V. R.; **Vemula, N.**; Pulla, R. S. R. *"Lenalidomide solvates and processes."* PCT Int. Appl. **2010**, WO2010056384A1

(1) Devarakonda, S. N.; Yarraguntla, S. R.; Mudapaka, V. K.; Kadaboina, R.; Murki, V.; Manda, A.; Badisa, V. R.; **Vemula, N.**; Pulla, R. S. R.; Nalivela, V. *"Preparation of Lenalidomide"*. PCT Int. Appl. **2009**, WO2009114601A2

PUBLICATIONS

(7) Chidley, T.; **Vemula, N**.; Pagenkopf B. L. "The [4+2] cycloaddition of donor-acceptor cyclobutanes and *cis*-diazenes: An approach to hexahydropyridazines." **2016**. Manuscript in preparation

(6) **Vemula, N.;** Pagenkopf, B. L. "Synthesis and reactivity of alkoxy-activated cyclobutane-1,1-dicarboxylates." *Org. Chem. Front*. **2016**, Advance Article. DOI: 10.1039/C6QO00244G.

(5) Chidley, T.; **Vemula, N**.; Kerr, M. A.; Carson, C. A.; Pagenkopf B. L. "Cascade Reaction of donor-acceptor cyclopropanes: Mechanistic studies on cycloadditions with nitrosoarenes and *cis*-diazenes." *Org. Lett.* **2016**, *18*, 2922.

(4) **Vemula, N.;** Pagenkopf, B. L. "Synthesis of tetrahydro-1,2-oxazines and pyrrolidines *via* cycloadditions of donor–acceptor cyclobutanes and nitrosoarenes." *Eur. J. Org. Chem.* **2015**, *2015*, 4900.

(3) **Vemula, N.**; Stevens, A. C.; Schon, T. B.; Pagenkopf, B. L. "The [4+2] cycloaddition of donor-acceptor cyclobutanes and nitrosoarenes." *Chem. Commun.* **2014**, *50*, 1668.

(2) Raghu, N. S.; Reddy, Y. R.; **Vemula, N.**; Suryanarayana, R. V. "Separation, identification and quantitation of degradants of topotecan and its related impurities in topotecan injection by RP-HPLC and LC-MS". *J. Liq. Chromatogr. Related Technol.* **2011**, *34*, 548.

(1) Raghu, N. S.; Reddy, Y. R.; **Vemula, N.**; Suryanarayana, R. V.; Ravindranath, L. K. "Degradation studies of highly potent and life threatening human birth defect drug-lenalidomide by HPLC and LC-MS". *J. Liq. Chromatogr. Related Technol.* **2010**, *33*, 654.

SELECTED CONFERENCE PRESENTATIONS

(5) **Vemula, N**.; Chidley, T.; Pagenkopf B. L. *"Unprecedented reactivity of the donor-acceptor cyclopropanes in cycloadditions with nitrosoarenes"*, **Oral Presentation**, 250th ACS National Meeting & Exposition, Boston, MA, United States, August 16-20, **2015**

(4) **Vemula, N**.; Stevens, A. C.; Schon, T. B.; Pagenkopf, B. L. *"Divergent Synthesis of Tetrahydro-1,2-oxazines and Pyrrolidines via Cycloadditions of Donor-Acceptor Cyclobutanes and Nitrosoarenes"*, **Poster Presentation**, 24rd Quebec-Ontario Mini-Symposium on Bioorganic and Organic Chemistry (QOMSBOC) Conference, Sherbrook, QC, Canada, November 8-10, **2013**

(3) **Vemula, N**.; Pagenkopf, B. L. *"Divergent Synthesis of Tetrahydro-1,2-oxazines and Pyrrolidines via Cycloadditions of Donor-Acceptor Cyclobutanes and Nitrosoarenes"*, **Oral Presentation**, 246th ACS National Meeting & Exposition, Indianapolis, IN, United States, September 8-12, **2013**

(2) **Vemula, N**.; Pagenkopf, B. L. *"Donor-Acceptor Cyclobutanes as Synthetic Building Blocks"*, **Oral Presentation**, 23rd Quebec-Ontario Mini-Symposium on Bio-organic and Organic Chemistry (QOMSBOC) Conference, Windsor, ON, Canada, November 9-11, **2012**

(1) **Vemula, N**.; Stevens, A. C.; Schon, T. B.; Pagenkopf, B. L. "*Formal [4+2] cycloaddition of alkoxy-substituted donor-acceptor cyclobutanes and nitrosoarenes",* **Poster Presentation**, 244th ACS National Meeting & Exposition, Philadelphia, PA, United states, August 19-23, **2012**

AWARDS & AFFILIATIONS

2015	CSC 2004 Conference Travel Award
Sep 2011 - Aug 2016	Western Graduate Research Scholarship
Sep 2011 - Aug 2016	Western International Student Scholarship
Sep 2012 - present	Member of American Chemical Society
Sep 2011 - Aug 2016	Member of Western Society of Graduate Students