Study of the \textit{bldG} locus suggests that an anti-
anti-sigma factor and an anti-sigma factor may 
be involved in \textit{Streptomyces coelicolor} 
antibiotic production and sporulation

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A cloned 2.5 kb DNA fragment that can restore antibiotic production and 
sporulation to a \textit{bldG} mutant encodes a 113 aa protein showing similarity to a 
family of anti-anti-sigma factors from \textit{Bacillus} and \textit{Staphylococcus}; and the 
deduced product of a closely spaced downstream ORF, designated ORF3, shows 
similarity to cognate anti-sigma factors. The homologues in \textit{Bacillus} regulate 
the activity of sporulation- and stress-response-specific sigma factors. 
However, there is no sigma factor gene near \textit{bldG} and ORF3. \textit{bldG} is 
transcribed both as a monocistronic and a polycistronic mRNA, the latter 
including the downstream ORF3 gene. The two transcripts were present at all 
time points during growth and both were upregulated when aerial mycelium 
and pigmented antibiotics were seen. At all time points, the monocistronic 
\textit{bldG} transcript was two- to threefold more abundant than the polycistronic 
transcript. Mapping of the mRNA 5' ends indicated that \textit{bldG} transcription is 
initiated from two transcription start sites located 82 and 123 bp upstream of 
the \textit{bldG} translation start. A constructed \textit{bldG} null mutant had the same 
phenotype as previously isolated \textit{bldG} point mutations, some of which were 
shown to have potentially significant base changes within \textit{bldG}. When 
compared to the wild-type strain, the null mutant showed no differences in 
the levels of transcription from the two \textit{bldG} promoters. These results suggest 
that \textit{bldG} is not involved in autoregulation.

\textbf{Keywords:} \textit{Streptomyces}, differentiation, antibiotic production, anti-sigma factor 
antagonist, anti-sigma factor

\section*{INTRODUCTION}

Members of the genus \textit{Streptomyces} are soil bacteria 
best known for their ability to produce a wide variety of 
secondary metabolites including many of the antibiotics 
used in human and veterinary medicine. In solid-phase 
laboratory culture, the production of these compounds 
coincides with the onset of morphological differentiation 
that leads to sporulation: aerial hyphae grow from the 
older parts of the substrate mycelium, then proceed 
through a series of changes that include nucleoid 
partitioning coupled to the formation of sporulation 
septa. The end result of this complex process is the 
formation of long chains of unigenomic spores (reviewed 
is under the control of an elaborate regulatory 
system that coordinates gene-expression pathways to 
bring about the gross morphological changes in both the 
substrate and aerial hyphae. In addition, the onset of 
antibiotic production (physiological differentiation) 
is intimately associated with the onset of morphological 
differentiation, and these two processes are now known 
to share common elements in genetic regulation.

In \textit{Streptomyces coelicolor} A3(2), the genetically most-
studied streptomycete, many genes required for mor-
phological and physiological differentiation have been 
identified. As a result of such studies we know that the 
regulatory mechanisms involve both pathway-specific 
and global regulatory genes (Champness, 2000). Of
particular note are the bld (bald) genes, mutations in which often result in the failure to form both aerial hyphae and secondary metabolites. Thus the bld genes provide a key to understanding how the physiological and structural changes are initiated in the ageing substrate mycelium.

Several bld genes have been cloned, sequenced and characterized. This, together with functional analysis of several other genes, in which mutations give rise to a bald mutant phenotype but which had previously been given other gene designations (Chakraburty & Bibb, 1997; Ma & Kendall, 1994; Susstrunk et al., 1998), is beginning to paint a picture whereby the onset of physiological and morphological differentiation is governed by extracellular and metabolic signals, and is regulated at the level of transcription, translation and post-translational modification. When Nodwell et al. (1997; Ma & Kendall, 1994; Susstrunk et al., 1996) sequenced the S. coelicolor bldG gene products. To this end we have cloned and sequenced the S. coelicolor bldG gene. bldG was first identified in a study in which mutated colonies were screened for blocks in the formation of aerial hyphae and antibiotic biosynthesis (Champness, 1988). Three of the mutants identified, C103, C107 and C101J, mapped to the same region of the chromosome and defined the bldG locus. Here we show that bldG encodes a protein product showing similarity to anti-sigma factor antagonists from Bacillus and Staphylococcus. Transcriptional analyses have also revealed that bldG and the ORF immediately downstream are co-transcribed. The deduced product of the downstream ORF shows some similarity to anti-sigma factors, suggesting that it and BldG might function as a regulatory pair governing the activity of an unknown sigma factor(s).

METHODS

Strains and media. S. coelicolor strains used in this study include J1501 [hisA1 ureA1 strA1 pgI SCP1 SCP2− (Chater et al., 1982)] and its derivatives C103 [bldG103 (Champness, 1988)], C107 [bldG107 (Champness, 1988)] and C536 [bldG536; W. Champness, personal communication]; C101J [cysD18 mthB2 NF, bldG101J (Champness, 1988)] and M145 [prototrophic, SCP1 SCP2 Pgl+ (Hopwood et al., 1985) provided by M. Bibb, John Innes Centre]. C103, C107, C536 and C101J were all provided by W. Champness, Michigan State University. Streptomyces lividans 66 (John Innes strain 1326) was the host for sC31 propagation and for the transfection of protoplasts. Media, culture conditions and protoplast transformation and transfection were as described by Hopwood et al. (1985).

Escherichia coli host strains were DH5α (Gibco-BRL) and ET12567 (MacNeil et al., 1992) (a gift from D. MacNeil, Merck Sharp & Dohme Research Laboratories). Media and culture conditions were as described by Sambrook et al. (1989).

Plasmid and bacteriophage vectors. Streptomyces vector KC304 is a derivative of bacteriophage θC31 and contains the tsr (thiostrepton resistance) gene for vector selection; the rph (viomycin resistance) gene, flanked by BamHI sites, as a ‘stuffer’ fragment for replacement by up to 6 kb of insert DNA; and the att–int region to allow efficient integration at single copy number into the chromosomal att site for sC31. KC304 derivatives were manipulated as described by Hopwood et al. (1987). Cosmid H5 (Redenbach et al., 1996) was obtained from Helen Kieser, John Innes Centre, Norwich, UK. Prior to their use to transform S. coelicolor, the E. coli–Streptomyces bifunctional vectors pSET152 (Bierman et al., 1992) (NRRL B-14792) (containing a multiple-cloning site and replicon of pUC plasmids, the att–int region of sC31 and the apramycin-resistance gene for vector selection in either E. coli or Streptomyces) and pKCI218 (Bierman et al., 1992) (NRRL B-14790) (containing a multiple-cloning site and replicon of pUC plasmids, the SCP2− replicon and the apramycin-resistance gene for vector selection in either E. coli or Streptomyces) were replicated in the dam dcm host E. coli ET12567 using standard procedures (Sambrook et al., 1989). Streptomyces plasmids were maintained by selection for resistance to thiostrepton (50 µg ml−1; a gift from S. Lucania, Bristol-Myers Squib, Princeton, NJ, USA) or Apralan (50 µg ml−1 and containing 50%, w/w, apramycin; Provel [Division of Eli Lilly Canada]). E. coli plasmids pAUS (Giebelhaus et al., 1996) and pBluescript II KS/KS (Stratagene) were manipulated as described by Sambrook et al. (1989).

Isolation of a bldG103-complementing clone from an S. coelicolor phage library. A library (generously provided by R. Passantino, Instituto di Biologia dello Sviluppo del Consiglio
Phenotype. The 2 kb overlapping right-hand end of the clone was obtained by first subcloning additional DNA sequence for the region downstream of the bldG gene, were recovered from sporulating lysogens showing aerial mycelium and pigmentation typical of the bldG gene. The mutant bldG gene was amplified from the chromosome of the bldG mutant strains. S. coelicolor C103, C101J, C107 and C536 using the oligonucleotide primers BKL65 (5'-CGGCATTCGTGACGACACG-3'; spanning nt -241 to -225) or JWA5 (5'-CACGGAGGTCTGCAGTG-3'; spanning nt -160 to -144), located in the 5' flanking region of bldG, and JWA6 (5'-GGTTGCACGAGGGCATG-3'; complementary to nt 451-467), located downstream of the bldG ORF (nucleotide positions are relative to the bldG translation start; see Fig. 3). PCR amplification was carried out with 1 µg S. coelicolor genomic DNA as the template and 40 pmol each primer in 100 µl reaction volumes. Expand Taq DNA polymerase (1.25 U; Roche) was used in each reaction. The reaction mixtures were denatured at 95 °C and then subjected to 30 cycles of 95 °C for 30 s, 52 °C for 30 s and 72 °C for 1 min. The major 708 bp (BKL65 and JWA6) or 628 bp (JWA5 and JWA6) amplification product was purified from a 5% polyacrylamide gel by crushing and soaking (Sambrook et al., 1989), and sequenced directly (DNA Sequencing Service, Department of Biological Sciences, University of Alberta) using as primers the oligonucleotides BKL65 (5'-CGGCATTCGTGACGACACG-3'; spanning nt -241 to -225) or JWA5 (5'-CACGGAGGTCTGCAGTG-3'; spanning nt -160 to -144), located in the 5' flanking region of bldG, and JWA6 (5'-GGTTGCACGAGGGCATG-3'; complementary to nt 451-467), located downstream of the bldG ORF (nucleotide positions are relative to the bldG translation start; see Fig. 3). Creation of a bldG disruption mutant. The bldG disruption construct pAU68 was made as follows. First, the 1.4 kb apramycin-resistance gene was cloned as an EcoRV-BamHI fragment from pBSApR (a pBluescript derivative containing the apramycin-resistance gene cassette; a gift from S.E. Jensen, Department of Biological Sciences, University of Alberta) into similarly digested pUC119 to give pUC119ApR. The 2.5 kb HindIII fragment containing bldG (see above) was purified from pAU64 and ligated into the HindIII site of pUC119ApR. Disruption of bldG was achieved by insertion of a blunted 1 kb Bsr fragment (isolated from pAU5 using SmaI and XbaI) into the blunted BglII site located in the bldG

**Fig. 1.** Restriction map of the 2.5 kb HindIII insert in pAU63. The thin black line represents S. coelicolor M145 DNA and the thick black line represents the flanking øC31 DNA. The hatched area indicates the region of non-contiguous M145 DNA sequence. The location and orientation of bldG and the two partial ORFs (ORF1 and ORF3) are shown below the line diagram (not to scale), as are the distances between some restriction sites in kb.
coding region (see Fig. 3). The resulting recombinant plasmid was designated pAU68 and was passaged through E. coli ET12567 before being used to transform S. coelicolor J1501 and M145 protoplasts. Thiostrepton-resistant and Apralan-sensitive double-crossover mutants of each strain were selected and further tested by Southern blotting to confirm the double-crossover genotype. The S. coelicolor J1501 and M145 bldG disruption strains were designated S. coelicolor C3b (bldG3b) and S. coelicolor C1a (bldG1a), respectively.

**Complementation of bldG mutants.** A 917 bp fragment containing the bldG ORF and upstream promoter was generated by PCR using pAU64 as template and the oligonucleotides DBG12 (5'–GCCGCAAATCTGCTC/GGGAGTGGC-GACGCA/3'); nt −450 to −434 and containing a non-homologous tail (underlined) with an EcoRI site] and DBG3 (5'–GCCGCTCTAGATGTCAGGCTTGGCGGATG-3'); complementary to nt 451–467 and containing a non-homologous tail (underlined) with an XbaI site] as primers (nucleotide positions are relative to the bldG translation start). The amplified DNA was gel purified by the trough-purification method (Zhen & Swank, 1993), digested with EcoRI/XbaI and ligated into EcoRI/XbaI-digested pSET152. The resulting recombinant plasmid, designated pAU69, was isolated after transformation of E. coli DH5α and selection for Apralan resistance. After passage through E. coli ET12567, pAU69 was introduced into protoplasts of S. coelicolor bldG mutants CS36, C107, C101J and C3b by protoplast transformation. Apralan-resistant transformants were scored for their morphological and pigmentation phenotype.

**RNA isolation.** Streptomyces cultures were grown on cellophane discs (75 mm, 325 discs; Courtaulds Films) on the surface of R2YE agar as previously described (Leskiw et al., 1993). RNA was extracted essentially as described elsewhere (Hopwood et al., 1985) except that mycelia were scraped directly from the cellophane discs into modified Kirby mix. The RNA was isolated at various time points as described in Results.

**Northern blot analysis.** This was performed according to Williams & Mason (1985). RNA (40 μg) was denatured with glyoxal and DMSO, and size fractionated by electrophoresis at 4 V cm⁻¹ on a 1·25% agarose gel using a 10 mM NaHPO₄/NaH₂PO₄ (pH 7·0) recirculating buffer system. DNA molecular mass marker III (625 ng; Boehringer), treated in the same way, served as the size marker. Capillary transfer to nylon-bond-N (Amersham) membrane was as described by Sambrook et al. (1989). For detection of bldG transcripts, the probe was an [α³²P]dCTP random-primer-labelled 207 bp PCR product internal to bldG (the probe was generated by PCR using primers BKL63, 5'–GTGAGGCGGCTGTAGATCCG-3', and BKL64, 5'–GCCAAGCTGCGTGCAGC-3'). For detection of transcripts extending through the intergenic region and into the ORF located downstream of bldG, the probe was an [α³²P]dCTP random-primer-labelled 428 bp PCR product internal to the downstream ORF [the probe was generated by PCR using primers DBG8, 5'–GCCGAAAGCTTGGTTG-CGGCCCGTGCT-3', and BKL83, 5'–GCCGAAAGCTTGGGT-GAAATGGCGCGGTCT-3', both containing 10 nt non-homologous extensions (underlined)]. Hybridization was performed overnight at 65 °C in a solution containing 50% formamide (Hopwood et al., 1985) and 8 × 10⁺⁶ c.p.m. probe. After hybridization, the nylon filter was washed at the same temperature for 2 × 30 min in a solution containing 2 × SSC (0·3 M NaCl, 0·03 M sodium citrate), 0·1% SDS and then 2 × 30 min in 0·2 × SSC, 0·1% SDS. The signals were detected using a PhosphorImager (Molecular Dynamics model 445 SI). The molecular mass marker was visualized by hybridizing [α³²P]dCTP random-primer-labelled marker DNA to the filter at 44 °C. As a control for RNA loading levels, a probe for 16S rRNA was hybridized to the same blot. The 16S RNA probe was an oligonucleotide, 5'–CCGCGCTTGCCACCGGTTG-3', corresponding to a conserved region in Streptomyces 16S rRNA sequences. Hybridization and washing were performed at 55 °C without formamide according to Procedure B described by Hopwood et al. (1985).

**S1 nuclease mapping of the bldG transcription-start site.** The probe for S1 nuclease mapping of bldG was generated by PCR amplification of a 264 bp fragment using pAU64 as the template. The primers were an 18-mer synthetic oligonucleotide, DBG14 (5'–CTGCAATTTGCGCCACCGA-3'), corresponding to a sequence internal to the bldG ORF and a 27-mer synthetic oligonucleotide, JWA20 (5'–GGCGAACGGTTGGGATCGGCTCGG-3', corresponding to a region 194 nt upstream of the bldG start codon and containing a 10 nt non-homologous extension (underlined)). The probes for S1 nuclease protection of the intergenic region between bldG and the downstream ORF were generated by PCR amplification of a 401 bp fragment using pAU64 as template. The primers were a 17-mer synthetic oligonucleotide, JWA17 (5'–GTGACCGGTCGTGACG-3'), corresponding to a sequence internal to the downstream ORF, and either a 27-mer synthetic oligonucleotide, JWA18 (5'–GGCGAACGGTTGGGATCGGCTCGG-3') or a 27-mer oligonucleotide, BK181 (5'–GGCGGAAATTCGGTCG-AGCTGTGACG-3'), corresponding to regions 121 nt and 350 nt upstream of the start codon for the downstream ORF and containing 10 nt non-homologous extensions (underlined). The amplified DNA was purified from a 2% agarose gel by the trough-purification method (Zhen & Swank, 1993). The 5' ends of the amplified DNA (about 2 pmol) were labelled with [γ³²P]ATP using T4 polynucleotide kinase. The probes, labelled at both ends, were used without treatment since the non-homologous extensions would be removed by the S1 nuclease treatment and would not result in the appearance of labelled, protected fragments (Leskiw et al., 1993). The sequencing ladders for the bldG and intergenic region S1 nuclease mapping were generated by the dideoxy chain-termination method (Sanger et al., 1977) using DBG14 and JWA17 as primers, and pAU64 as the template. For each S1 nuclease protection reaction, 40 μg RNA was hybridized to 5000 Cerenkov c.p.m. probe in formamide buffer as described by Hopwood et al. (1985) except that glycinogen (Roche) replaced the carrier tRNA. To control for RNA loading levels, the RNA samples were first subjected to Northern blot analysis using the 16S rRNA probe (see above) and aliquots showing equivalent signals were subsequently used for S1 nuclease mapping. The samples were run under standard conditions on a 6% polyacrylamide sequencing gel.

**Primer-extension mapping of the bldG transcription-start site.** The primer was a 17-mer synthetic oligonucleotide, DBG15 (5'–GTCGACGGGACAGGTC-3'), that was designed to hybridize immediately downstream from the bldG start codon and approximately 100 bp away from the proposed transcription-start point. Primer (50 pmol) was end-labelled with [γ³²P]ATP as described above. Approximately 5 pmol of [γ³²P]-labelled primer and 40 μg RNA were dissolved in 1×SB buffer (60 mM NH₄Cl, 10 mM Tris-acetate, pH 7·4; 6 mM 2-mercaptoethanol) (Hartz et al., 1988), denatured by heating to 90 °C for 5 min and annealed by transferring to 75 °C, slow cooling to 55 °C and then incubating at 55 °C for 1 h. The primer-annealed RNA was ethanol precipitated, washed with 80% ethanol and air-dried for 10 min. Extension of the primer was performed at 45 °C for 1 h in a solution of...
1×SB buffer, 15 mM magnesium acetate, 3 mM dNTPs, 17.5 U RNAGuard (Amersham) and 12.5 U AMV reverse transcriptase (Roche). Loading dye (98% deionized formamide, 10 mM EDTA, pH 8.0, 0.025% xylene cyanol, 0.025% bromophenol blue) was added and the reaction was evaporated at 80°C for 20 min. The entire reaction mixture was loaded onto a 6% polyacrylamide sequencing gel. A sequencing ladder was generated as described above using the same oligonucleotide as for the primer-extension reactions.

**Computer-assisted sequence analysis.** General raw sequence handling was done using the GeneTool 1.0 program (BioTools). A version of the frame (Bibb et al., 1984) program modified to run on an Apple Macintosh (obtained from S. E. Jensen, University of Alberta, Canada) was used to detect putative ORFs. Similarities between deduced protein products and known proteins in the databases were detected using BLAST at the internet site http://ncbi.nlm.nih.gov. Multiple sequence alignments were generated using the PILEUP program of the Genetics Computer Group. Potential RNA secondary structure was done using the Prosite ProfileScan server (Kalman et al., 1990; Dufour & Haldenwang, 1994; Duncan et al., 1996). Since ORF2 was the only complete ORF present on the subcloned 2.5 kb DNA fragment that was able to complement the bldG103 mutation, this ORF was designated bldG (GenBank accession no. AF134889). Since genes encoding anti-anti-sigma factors are typically encoded as the first gene in an operon also encoding a cognate anti-sigma factor and sigma factor (Kalman et al., 1990), the remainder of the ORF3 sequence, as well as an additional ~1 kb of downstream sequence was determined. Comparison with sequences in the databases revealed that the ORF3 protein product resembles anti-sigma factor proteins of B. subtilis, including SpoIIB (Duncan & Losick, 1993; Min et al., 1993) and RsbW (Benson & Haldenwang, 1993a); anti-sigma F and anti-sigma B proteins, respectively. Surprisingly, a sigma factor was not encoded in the sequence downstream of the putative anti-sigma factor. Instead, a partial ORF showing similarity to pyrophosphate synthases was located 339 nt downstream of the putative anti-sigma factor. The sequences with the existence downstream of the ORF3 stop codon of a sequence capable of forming, in RNA, a stable stem–loop structure \([AG = −21.3 \text{ kcal mol}^{-1} (−89 \text{ kJ mol}^{-1})]\) that might serve as a transcription-termination signal, suggested that the putative pyrophosphate synthase gene is not part of a bldG operon. The partial sequence of the divergently expressed ORF1 suggests that the protein product belongs to a group of bacterial RNA helicases. The sequences for bldG and the surrounding ORFs on cosmid H5 have been determined as part of the S. coelicolor genome sequencing project (http://www.sanger.ac.uk/Projects/S._coelicolor/) and have been deposited under accession no. AL036636. It is clear from the sequence analysis that the 2.5 kb HindIII fragment present in our clone does not arise from contiguous chromosomal sequences and has come from the ligation of two non-contiguous Sau3AI fragments during library preparation. The non-contiguous DNA is shown as a hatched box in Fig. 1.

**RESULTS**

**Cloning of the bldG gene**

Before the S. coelicolor genome project (see http://www.sanger.ac.uk/Projects/S._coelicolor/) began, we had cloned bldG by complementation of the S. coelicolor bldG103 mutation. bldG-containing recombinant KC304 phage derivatives were identified from a library of S. coelicolor M145 DNA fragments by their ability to restore antibiotic production and aerial hyphae formation to the S. coelicolor C103 mutant strain. The phage library was introduced into the bldG mutant, and two thiostrepton-resistant lysogens that were able to sporulate and produce the pigmented antibiotics actinorhodin and undecylenoprodiosin were selected for further study out of ~4000 colonies screened. The phages released from the lysogens were spotted on a S. coelicolor C103 lawn to verify that the cloned DNA was responsible for restoring antibiotic production and sporulation. It was not determined whether the production of calcium-dependent antibiotic, the other antibiotic produced by S. coelicolor J1501, was restored. Both lysogens appeared to have identical inserts and therefore only one, designated KC741, was chosen for further study.

**Sequencing and analysis of ORFs**

The ~5.5 kb DNA fragment containing bldG was subcloned from KC741 as a 6.5 kb EcoRV fragment containing 1 kb of flanking oC31 vector DNA. The fragment was introduced into pSET152, which integrates site specifically into the S. coelicolor chromosome at the oC31 attB site, generating pAU61. Further sequencing of a 2.5 kb HindIII fragment from pAU61 into pKC1218, a low-copy-number E. coli–Streptomyces shuttle vector, generated pAU63. Introduction of pAU63 into the S. coelicolor C103 mutant restored apparently wild-type levels of both pigmented-antibiotic production and aerial-mycelium formation. Nucleotide sequencing of the 2.5 kb HindIII fragment revealed two partial (ORF1 and ORF3) and one complete ORF (ORF2) (Fig. 1). BLAST analysis indicated that the predicted product of ORF2 resembles a group of anti-anti-sigma factor proteins that include RsbV from Staphylococcus aureus (Wu et al., 1996) and SpoIIAA and RsbV of Bacillus subtilis (Kalman et al., 1990; Dufour & Haldenwang, 1994; Duncan et al., 1996). Since ORF2 was the only complete ORF present on the subcloned 2.5 kb DNA fragment that was able to complement the bldG103 mutation, this ORF was designated bldG (GenBank accession no. AF134889).

**Alignment of BldG and the ORF3 protein products with known proteins from the databases**

The bldG gene encodes a 113 aa protein with end-to-end similarity to a number of anti-anti-sigma factors that regulate the activity of sigma factors responsible for
stress-induced or growth-stage-specific transcription. BldG is most closely related to the 
*Sta. aureus* and *B. subtilis* SpoIIA proteins (38% and 40% identity, and 61% and 60% similarity, respectively), and to *B. subtilis* SpoIIA (26% identity, 56% similarity). Alignment of BldG with RsbV and SpoIIA proteins (Fig. 2a) reveals a highly conserved region of sequence surrounding the serine residue known to be phosphorylated on the *B. subtilis* SpoIIA (Najafi et al., 1995). Likewise, alignment of the ORF3 product with other anti-sigma factors revealed about the same degree of similarity to RsbW from *B. subtilis* and *Listeria monocytogenes* (28% identity, 43% similarity and 25% identity, 44% similarity, respectively), and to SpoIIA from *B. subtilis* (26% identity, 42% similarity). These anti-sigma factors are encoded along with, and interact directly with, RsbV and SpoIIA, respectively. Since both RsbW and SpoIIA in *B. subtilis* have been shown to have kinase activity that regulates their interaction with either their cognate sigma factor or anti-anti-sigma factor by phosphorylation of the anti-sigma factor antagonist (Dufour & Haldenwang, 1994; Min et al., 1993), the ORF3 amino acid sequence was aligned with RsbW and SpoIIA sequences to look for conserved kinase domains. As shown in Fig. 2b, the ORF3 protein product contains only two of the five conserved amino acid residues that are thought to be important for ATP and magnesium binding (Kang et al., 1996) and in bacterial histidine kinases in general (Stock et al., 1995). Also, analysis of the ORF3 protein sequence using the Prosite ProfileScan Server did not reveal any conserved histidine kinase domains within the sequence. These findings suggest that the ORF3 protein product lacks the kinase activity...
Fig. 3. Nucleotide sequence of the *bldG* promoter and coding region. The deduced amino acid sequence of *bldG* and the partial amino acid sequences of ORF1 and ORF3 are shown below in single letter code. Nucleotide positions are indicated relative to the first nucleotide of the *bldG* start codon (designated +1). The proposed transcription start sites (P1, P2; ○−) and putative −10 and −35 sequences for *bldG* are shown, as well as potential ribosome-binding sites (RBS) for *bldG* and ORF3. The two inverted repeats at the end of the *bldG* coding region are indicated by the arrows. Point mutations identified in the *bldG* mutant strains are shown in bold, with the base changes indicated above. Oligonucleotide primers used for sequencing of the *bldG* mutations are indicated by (‗) above the sequence. The unique *BglII* site used to construct the *bldG* disruption vector is underlined.

A constructed *bldG* null mutant has the same phenotype as the strains with *bldG* point mutations

A *bldG* null mutant allele was constructed by inserting the thiostrepton-resistance gene (*tsr*) at a unique *BglII* restriction site internal to *bldG* (Fig. 3). The mutant allele was used to replace the wild-type allele in the chromosomes of *S. coelicolor* J1501 and M145 as described in Methods. Disruption of *bldG* in the chromosome of representative J1501 and M145 *bldG* mutants was confirmed by Southern blotting (data not shown) and the strains were designated *S. coelicolor* C3b (*bldG3b*) and *S. coelicolor* C1a (*bldG1a*), respectively. Both phenotypically resembled the *bldG* mutants of Champness (1988) in being devoid of blue or red pigments and failing to make detectable aerial mycelium on R2YE or MM › glucose (but sporulating aerial mycelium was formed, as with other *bldG* mutants, on MM + mannitol). The M145 *bldG* mutant was not studied further.

To confirm that the constructed J1501 *bldG* null mutant did not contain any other defects, pAU69, a pSET152-derivative containing a copy of *bldG* together with its promoter region, was introduced into *bldG3b*. The same complementation plasmid was also introduced into the *bldG* point mutants used in this study. pAU69 restored the wild-type phenotype to *bldG3b* as well as the C103, C107 and C536 strains; however, introduction of the plasmid had no effect on the phenotype of C101J.

Sequencing of *bldG* mutations

To map the location of the *bldG* mutation in C103, C107 and C536, as well as to confirm the absence of a mutation in the *bldG* coding region of C101J, the *bldG* ORF from the four *bldG* mutants was amplified by PCR and the resulting products were sequenced. As expected on the basis of the complementation studies, *bldG101J* did not have a mutation in the *bldG* coding or promoter region. Since the mutation in this strain maps to the same region of the chromosome as the mutations in C103, C107 and C536, it may reside in one of the nearby ORFs. Alternatively, the C101J strain may be a double mutant, making the genetic mapping data difficult to interpret and possibly misleading. As shown in Fig. 3, the *bldG103* and *bldG536* mutations both involve an A–T substitution at the same base, introducing a stop codon that would generate a truncated 87 aa BldG protein. The *bldG107* mutation, the substitution of an adjacent CT for AG, leads to an amino acid change of aspartate to glutamate at position 56, and of a serine to alanine at position 57 of BldG. The latter residue corresponds to one known to be phosphorylated in SpoIIAA by the SpoIAB protein kinase. These data suggest that the C-terminal 26 aa of BldG, as well as the conserved region corresponding to the phosphorylation site that has been shown in *B. subtilis* to be important for the regulation of anti-anti-sigma factor and anti-sigma factor interactions.
Fig. 4. Northern blot analysis of bldG and ORF3 transcripts. RNA (40 µg) was isolated from S. coelicolor J1501 and the bldG disruption mutant, bldG3b, at various times post-inoculation (h) as indicated. The probe for bldG was a random-primer-labelled 207 bp PCR product internal to bldG, and a 428 bp random-primer-labelled PCR product was used to probe for ORF3 transcripts. Molecular mass marker III (Boehringer) was used for size determination. RNA integrity and loading levels were controlled by hybridizing the same blots with an oligonucleotide probe specific for 16S rRNA.

Although some bldG transcripts are monocistronic, some also include ORF3

Northern blotting was performed using RNA isolated from S. coelicolor J1501 to determine the size of the bldG transcript as well as the timing of expression. The experiments were performed at least twice using RNA from three different time courses, and representative results are shown in Fig. 4. The probe, a 207 bp fragment internal to bldG, hybridized to two RNA species with sizes of 600–700 nt and 1100–1200 nt. The size of the smaller transcript is consistent with a monocistronic bldG transcript terminating in the intergenic region between bldG and the start of ORF3, whereas the larger transcript has a size comparable to that expected for a monocistronic transcript including both bldG and the downstream ORF3 gene. When a second blot, prepared at the same time and in the same manner as the first, was probed with a PCR-amplified probe internal to the putative anti-sigma factor-encoding ORF3 (Fig. 4), only a band corresponding to the larger transcript was observed, and the same results were observed when a single blot was first hybridized with the bldG-specific probe, stripped and reprobed with the ORF3-specific probe (data not shown). The two transcripts were present at low levels during vegetative growth and at higher levels from 24 h post-inoculation, the time point corresponding to the appearance of aerial hyphae and pigmented antibiotics. Quantitative analysis of the two bands indicated that the smaller transcript is present at a two- to three-fold higher concentration than the larger transcript.

The putative anti-sigma factor encoded downstream of bldG does not have its own promoter

To further investigate whether the putative anti-sigma factor gene is co-transcribed with bldG rather than being transcribed from its own promoter, S1 nuclease protection studies were performed using a probe corresponding to the intergenic region between the two ORFs. RNA samples isolated from three independent time courses were tested and representative results are shown in Fig. 5. The major S1 product observed at all the time points tested has a size of 172 nt, which is equivalent to the size of the full-length probe excluding the 10 nt non-homologous extension. Full-length protection was also observed with a 401 bp probe generated using the same anti-sigma factor gene-specific internal primer (JWA17) and the oligonucleotide BKL81 (corresponding to nt 102–118 relative to the bldG start codon), which anneals to a region within the bldG ORF (data not shown). These data confirm that an anti-sigma factor gene-specific promoter is not located either in the intergenic region or within 3’ sequence of the BldG

Fig. 5. High resolution S1 nuclease mapping of the intergenic region between bldG and ORF3. RNA (40 µg) was isolated from surface-grown S. coelicolor J1501 at 24 and 36 h post-inoculation. The probe was an end-labelled 182 bp PCR product containing a non-homologous extension to distinguish between probe reannealing and full-length protection. The sequencing ladder was generated with the oligonucleotide (JWA17) used to synthesize the probe. Probe + S1, control lane containing probe that went through the S1 procedure; Probe – S1, control lane containing probe that did not go through the S1 procedure.
coding region. In the light of these data, the question was raised as to why disruption of bldG did not lead to polar effects on expression of the downstream gene. Analysis of the sequence of the disruption plasmid revealed that tsr was transcribed in the same direction as bldG and ORF3. Since the tsr terminator was not present on the cloned tsr-containing fragment, it is possible that ORF3 could be expressed by readthrough transcription from either the bldG promoter (located upstream of the inserted tsr gene) or from the tsr gene promoter. Both the ability to complement the bldG3b strain with a plasmid containing only the bldG ORF, as well as a Northern blot analysis using an ORF3-specific probe, confirmed the existence of such transcripts (Fig. 4).

S1 nuclease mapping and primer-extension analysis reveal two bldG mRNA 5’ ends

To determine the transcription-initiation site for the bldG transcripts, high-resolution S1 nuclease mapping studies were performed using a 264 bp PCR-amplified probe labelled at the 5’ ends. As above, RNA samples isolated from three independent time courses were tested and representative results are shown in Fig. 6.

Interestingly, two major S1 nuclease-protected products of 152 nt and 193 nt were detected when the hybridization was carried out at 5 °C and at 12 °C (not shown) above the predicted probe melting temperature. If these products correspond to transcription-start points, the +1 positions would be situated 82 and 123 nt upstream of the bldG translation-start codon. The same mRNA 5’ ends were identified by primer-extension analysis of the same RNA samples using an end-labelled 17 nt oligonucleotide primer (Fig. 6), showing that the shorter protected species (see Fig. 3) was not an artefact caused by an S1 nuclease hypersensitive site. The transcription-start site proximal to the translation-start codon is located just downstream of a putative −10 sequence similar to those found in E. coli-like Streptomyces promoters (Strohl, 1992). At an atypically short spacing of 16 bp, a −35-like sequence was also present in this region. Similarly, a putative −10 sequence was found upstream of the distal transcription-start point. In this case, it was not possible to identify appropriately spaced −35 sequences. As was seen in the Northern analysis, both transcripts are expressed at low levels during vegetative growth and are upregulated when aerial mycelium and pigmented antibiotics become visible. The relative intensities of the signals for transcripts initiating at both promoters correlate well with the relative intensities of the long and short transcripts seen by Northern analysis. These results may suggest that initiation from the distal promoter gives rise to the monocistronic transcript and that transcription initiation at the proximal promoter gives rise to the polycistronic transcript. However, the low resolution of the Northern blots did not permit us to address this directly.

The bldG gene product does not appear to be involved in an autoregulatory circuit

The well-studied bldG homologue spoIIA plays an indirect part in its own transcriptional regulation. Like bldG, spoIIA is transcribed from two promoters. One of these is dependent on the σF factor encoded by spoIIC, the third gene in the spoIIA operon. Inactivation of spoIIA leaves σF locked in a complex with SpoIAB, preventing use of the σF-dependent promoter (Schuch & Piggot, 1994). To find out whether bldG is likewise important for transcription of one or both of its promoters, S1 nuclease protection studies using RNA samples isolated from the constructed bldG null mutant, bldG3b, were performed (Fig. 6). The same two mRNA 5’ ends that were identified in bldG+ strain were detected at comparable relative abundance in the mutant, indicating that the loss of bldG activity has no effect on bldG transcript initiation.

DISCUSSION

The simplest interpretation of the extracellular-signalling model for regulation of differentiation in S. coelicolor is that all of the bld genes might directly
encode the intercellular signals, or the components for sensing or uptake of those signals. On the basis of what we know about the bld gene products characterized to date, this simple interpretation is not supported. So far, only bldK and bldJ appear to encode direct components of the hierarchical signalling cascade (Nodwell et al., 1996) and all of the other bld genes appear to encode products that must have indirect roles in signal synthesis, sensing or uptake. bldA encodes a leucyl tRNA that is the only means for efficient translation of rare UUA codons (Leskiw et al., 1991, 1993) found, for example, in the messages for the pathway-specific activators of pigmented-antibiotic production (Fernández-Moreno et al., 1991; White & Bibb, 1997); bldD encodes a small transcription factor that appears to regulate gene expression by its DNA-binding ability (Elliot et al., 1998; Elliot & Leskiw, 1999); bldB encodes a small protein with some similarity to BldD in that it also contains a putative DNA-binding helix–turn–helix motif near its C terminus (Harasym et al., 1990; Pope et al., 1998); and now here we propose that bldG encodes a putative anti-sigma factor that might control developmentally regulated transcription by regulating the activity of a specific sigma factor(s).

Despite the sequence similarities between BldG and the deduced protein product of its co-transcribed, downstream ORF3 with proteins known to regulate the activity of certain sigma factors in Bacillus, we see differences between the way that the genes are organized and regulated in the two organisms. In contrast to both the spoIIA and rsb operons from Bacillus, a sigma factor is not encoded at the bldG locus. So far, there are no reports in the literature of genes for an anti-sigma factor antagonist and its anti-sigma factor lying at a distant location from the gene for the cognate sigma factor. If bldG and ORF3 do in fact encode an anti-sigma/anti-sigma factor pair, this raises the possibility that the regulatory pair might regulate the activity of more than one sigma factor, or that they may regulate a particular sigma factor only in a subset of the conditions in which that sigma factor directs gene expression. The antibiotic- and aerial-mycelium deficient phenotype of bldG mutants then presents us with two possibilities: the regulatory pair could control one or more globally acting sigma factors that serve to activate transcription of both antibiotic and sporulation-specific genes; or alternatively, the pair could regulate two sigma factors, one of which activates transcription of antibiotic bio-synthetic genes and one which activates sporulation-specific gene expression. Interestingly, of two sporulation-specific sigma factors so far identified in Streptomyces (Kelemen et al., 1996; Méndez & Chater, 1987), one (σF) is of the subfamily regulated by homologues of BldG/ORF3 in Bacillus. Sigma factors recognizing antibiotic-biosynthetic-gene promoters have not been definitively identified. It is attractive to suggest that immobilization of the putative anti-sigma factor on an affinity column might lead us to one such sigma factor. A search of the S. coelicolor database reveals that there is no shortage of potential sigma factor targets. The Bacillus sigma factors that are regulated by anti-anti-sigma/anti-sigma factor pairs make up a subfamily of σ²-like sigma factors (Lonetto et al., 1992), and so far at least 9 sigma factors that would fall into this subfamily are found on the S. coelicolor chromosome; several of them (in addition to sigF) are not located next to bldG/ORF3-like gene pairs (Gabriella Kelemen, personal communication).

The C-terminal region of sigma factors in this subfamily shares homology with the DNA-binding region of a group of bacterial transcriptional-activator proteins (Kahn & Ditta, 1991; Lonetto et al., 1992). Our analysis of the σF sequence using the Prosite ProfileScan server revealed similarity between region 4.2 near the σF C terminus and the helix–turn–helix domain of LuxR-related DNA-binding proteins. This raises the alternative possibility that the BldG and ORF3 regulatory pair could target a DNA-binding protein rather than a sigma factor. However, this possibility seems unlikely since the candidate σF contact residues for SpoIIAB are not located in region 4.2 of σF. SpoIIAB contacts σF in three areas corresponding to conserved regions 2.1, 3.1 and 4.1 of σ²-like sigma factors (Decatur & Losick, 1996). So far, only two putative contact residues on SpoIIAB have been identified (Garsin et al., 1998); and one of these two residues, R20, is conserved in the ORF3 gene product.

In addition to the absence of an operon-encoded sigma factor, the bldG operon differs from the Bacillus operons in the way that the expression of the genes is controlled. In the case of both the spoIIA and rsb operons, the genes for the anti-anti-sigma factor, the anti-sigma factor and the sigma factor are expressed as a single transcript, from either a σH-dependent promoter in the case of spoIIA (Wu et al., 1991) or a σF-dependent promoter in the case of rsb (Wise & Price, 1995). Expression of the genes is also upregulated from a second promoter that is recognized by the operon-encoded sigma factor (Schuch & Piggot, 1994; Wise & Price, 1995). For the spoIIA operon, upregulation is dependent on the activity of a prespore-compartment-specific phosphatase, SpoIIE, that activates the SpoIIAA anti-anti-sigma factor by dephosphorylation, allowing the formation of SpoIIAA/SpoIIB complexes and the liberation of σF (Duncan et al., 1995; Wu et al., 1998). Upregulation of σH occurs either in response to energy stress, where reduced ATP levels in the cell influence the phosphorylation state of the anti-anti-sigma factor, RsbV, or in response to environmental stress signals that activate a phosphatase that dephosphorylates RsbV and results in the liberation of σH (Voelker et al., 1995).

For the bldG operon we also see a complex transcription pattern involving not only two different promoters, but also the generation of two differently sized bldG-containing transcripts. Based on the Northern analyses, the longer and less abundant of the two transcripts extends through bldG to include the downstream putative anti-sigma ORF3. The shorter, more strongly expressed transcript appears to terminate in the inter-
genic region, and includes only the bldG coding sequence, a situation not seen with either the spoIIA or rsb operons. Analysis of the intergenic sequence for potential RNA secondary structures revealed two inverted repeats that could give rise to stem–loop structures with ΔG values of −22.2 and −31.3 kcal mol⁻¹ (−93 and −131 kJ mol⁻¹) (see Fig. 3), respectively, and either of which might play a role in mRNA stabilization or as a transcription-termination signal. Although a string of U residues is not present downstream of either inverted repeat, it is well documented that inverted repeats without poly(U) tails can act as terminators in Streptomyces (Deng et al., 1987; Ingham et al., 1993). The existence of the shorter transcript that hybridizes only to the bldG probe might suggest that a terminator is functional; however, an alternative mechanism for the generation of the shorter transcript could be endo- or exo-nucleolytic removal of the 3' ORF3-containing end of the longer transcript. Similarly, although a comparison of transcript abundance as seen by Northern analysis, primer-extension and S1 nuclease protection studies may suggest that the longer transcript arises from initiation at the more upstream promoter, and that transcripts initiating from the proximal bldG promoter terminate in the intergenic region, our analyses do not allow a definitive conclusion.

For both the Bacillus spoIIA and rsb operons, the genes appear to be translationally coupled such that they are expressed in equimolar concentrations (Magnin et al., 1997; Benson & Haldenwang, 1993b; Kalman et al., 1990). The lack of a promoter in the intergenic region between bldG and the downstream ORF3 encoding the putative anti-sigma factor suggests that these two genes might also be translationally coupled. However, the very long intergenic region means that there cannot be a straightforward mechanism of coupling that involves either closely spaced or overlapping start and stop codons to ensure a 1:1 stoichiometry. This, together with the added complication of a bldG monocistronic transcript that might lead to an excess of BldG, highlights the need to address the levels of the BldG and ORF3 proteins throughout the life cycle. By analysing the protein levels we should be able to answer questions about how the equilibrium between BldG and the ORF3 product is shifted at different stages of growth. Certainly, appearance of a transcript does not mean that the RNA is being translated to protein, a fact that warrants further investigation because of the expression of a putative RNA helicase from a divergently expressed promoter that overlaps the −10 region of the most upstream bldG promoter (J. Stoehr & B. K. Leskiw, unpublished).

The availability of the purified proteins and antibodies to those proteins will also help us to explore the role, if any, of the conserved phosphorylation site on BldG. Although mutation at this site does abolish BldG activity in the same way that Ser58 mutation in SpoIIAA does, the existence of a second mutation in this region in bldG107, together with the lack in the putative anti-sigma factor of conserved residues found in bacterial histidine protein kinases, makes it difficult to draw any conclusions.

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