Plant-derived compatible solutes proline betaine and betonicine confer enhanced osmotic and temperature stress tolerance to *Bacillus subtilis*

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L-Proline is a widely used compatible solute and is employed by *Bacillus subtilis*, through both synthesis and uptake, as an osmotic stress protectant. Here, we assessed the stress-protective potential of the plant-derived L-proline derivatives N-methyl-L-proline, L-proline betaine (stachydrine), trans-4-L-hydroxyproline and trans-4-hydroxy-L-proline betaine (betonicine) for cells challenged by high salinity or extremes in growth temperature. L-Proline betaine and betonicine conferred salt stress protection, but trans-4-L-hydroxyproline and N-methyl-L-proline was unable to do so. Except for L-proline, none of these compounds served as a nutrient for *B. subtilis*. L-Proline betaine was a considerably better osmotic stress protectant than betonicine, and its import strongly reduced the L-proline pool produced by *B. subtilis* under osmotic stress conditions, whereas a supply of betonicine affected the L-proline pool only modestly. Both compounds downregulated the transcription of the osmotically inducible *opuA* operon, albeit to different extents. Mutant studies revealed that L-proline betaine was taken up via the ATP-binding cassette transporters OpuA and OpuC, and the betaine-choline-carritine-transporter-type carrier OpuD; betonicine was imported only through OpuA and OpuC. L-Proline betaine and betonicine also served as temperature stress protectants. A striking difference between these chemically closely related compounds was observed: L-proline betaine was an excellent cold stress protectant, but did not provide heat stress protection, whereas the reverse was true for betonicine. Both compounds were primarily imported in temperature-challenged cells via the high-capacity OpuA transporter. We developed an *in silico* model for the OpuAC–betonicine complex based on the crystal structure of the OpuAC solute receptor complexed with L-proline betaine.

**INTRODUCTION**

When faced with increases in the external osmolarity, many micro-organisms amass compatible solutes to counteract water efflux; they thereby adjust turgor to physiologically appropriate values and promote cell growth under otherwise osmotically unfavourable circumstances (Bremer & Krämer, 2000). L-Proline is a well-known representative of this class of compounds (Csonka, 1989; Kempf & Bremer, 1998). In addition to its role as a water-attracting organic osmolyte, the function-preserving properties of L-proline for macromolecules provide an additional level of cellular protection for bacterial cells challenged by high...
osmolarity (Fisher, 2006; Ignatova & Gierasch, 2006; Street et al., 2006).

Bacillus subtilis belongs to those micro-organisms that can derive osmoprotection by l-proline (Brill et al., 2011a; von Blöhn et al., 1997; Whatmore et al., 1990; Zaprasis et al., 2013). It amasses large amounts of this amino acid under high-osmolarity growth conditions through an osmotically inducible biosynthesis route that is distinct from that employed when l-proline is produced for anabolic purposes (Brill et al., 2011a, b). Cellular l-proline pools exceeding 0.5 M can be found when the osmotic stress is severe (Brill et al., 2011a; Hoffmann et al., 2013; Zaprasis et al., 2013). Attesting to the critical role of compatible solute synthesis by micro-organisms for managing osmotic stress (Csonka, 1989; Kempf & Bremer, 1998), the genetic disruption of the osmotically inducible l-proline biosynthesis route causes an osmotically sensitive growth phenotype (Brill et al., 2011a). Osmostress protection of B. subtilis can also be achieved through l-proline uptake and the osmotically inducible OpuE transporter is key to this process (Hoffmann et al., 2012; von Blöhn et al., 1997; Zaprasis et al., 2014). However, compared with the metabolically inert compatible solute glycine betaine (Boch et al., 1994), an exogenous supply of l-proline is not a particularly effective osmoprotectant for B. subtilis (Zaprasis et al., 2013). This is rooted in (i) the different biophysical properties of glycine betaine and l-proline, and their different effects on the solvation properties of the cytoplasm (Cayley et al., 1992; Street et al., 2006), and (ii) the ability of B. subtilis to use exogenously provided l-proline as a nutrient (Moses et al., 2012) – a process that partially diverts it from fulfilling its role as an osmoprotectant (Zaprasis et al., 2013).

The genome sequence of B. subtilis carries the hallmarks of a bacterium that lives in association with plants and plant detritud (Belda et al., 2013). Indeed, most of the considerable number of compatible solutes taken up by B. subtilis (Bremer, 2002; Hoffmann & Bremer, 2011) are produced by plants (Hanson et al., 1994; Rhodes & Hanson, 1993). In addition to l-proline, plant-derived l-proline derivatives (Hanson et al., 1994; Rhodes & Hanson, 1993; Servillo et al., 2011; Trinchant et al., 2004) have been implicated as osmoprotectants under stress conditions, or as nutrients for micro-organisms. Examples are the betaines of l-proline and hydroxyproline (Alloing et al., 2006; Amin et al., 1995; Bayles & Wilkinson, 2000; Haardt et al., 1995; Kumar et al., 2014; Watanabe et al., 2012; White et al., 2012; Zhao et al., 2013).

Here, we asked whether the l-proline derivatives D-proline, N-methyl-l-proline, N,N-dimethyl-l-proline (l-proline betaine; also known as stachydrine), trans-4-hydroxy-l-proline and trans-4-hydroxy-l-proline betaine (betonicine) (Fig. 1) could be catabolized by B. subtilis, and, more specifically, whether these compounds could be used by this soil bacterium as protectants against osmotic and high/low-temperature challenges. L-Proline betaine and betonicine were identified as metabolically inert cell protectants against extremes in osmolarity and growth temperatures.

**METHODS**

**Chemicals.** Glycine betaine, l-proline, d-proline, the chromogenic substrate p-nitrophenyl-1,2-glucopyranoside (PNPG) for the Trec enzyme (Gotche & Dahl, 1995), and the ninhydrin reagent for the quantification of proline by a colorimetric assay were purchased from Sigma-Aldrich. l-Proline betaine and betonicine were obtained from Extrasynthese, and N-methyl-l-proline (Alloing et al., 2006) was a gift from D. Le Rudulier (University of Nice, France). Trans-4-hydroxy-l-proline, trans-4-fluoro-l-proline and cis-4-fluoro-l-proline were obtained from Bachem. Anhydrotetracycline hydrochloride (AHT), desthiobiotin and Strep-Tactin Superflow chromatography material were purchased from IBA, and the antibiotics ampicillin and spectinomycin were obtained from Carl Roth. Anion-exchange chromatography material (HiTrap Q Sepharose FF) was purchased from GE Healthcare Bio-Science and the protease factor Xa was obtained from Merck.

**Bacterial strains.** The genetic properties of the B. subtilis strains used in this study are summarized in Table 1. All strains were described previously, except RMKB27, which was constructed by transforming strain GN88 [Δ(opuA::erm)]4 (Kappes et al., 1999) with chromosomal DNA of strain RMKB20 (Table 1) and selecting for spectinomycin-resistant colonies in order to transfer the opuC::Tn10(tpc) mutation. Osmostress and heat stress protection growth assays were conducted with the B. subtilis laboratory strain JH642 (trpC2 pheA1) and its mutant derivatives (Table 1). Strain JH642 carries a mutation in the acetolactate synthase gene that makes it cold sensitive (Wieghoff & Marahiel, 2007); hence, cold stress protection growth assays were conducted with the B. subtilis laboratory strain 168 (trpC2) and its mutant derivatives. The overproduction of the B. subtilis OpuAC ligand-binding protein was carried out in the Escherichia coli B strain BL21 carrying plasmid pMH24 (opuAC+) (Basir et al., 2014; Smits et al., 2008).

**Media and growth conditions.** B. subtilis strains were grown in Spizizen’s minimal medium (SMM) enriched with a solution of trace elements (Harwood & Archibald, 1990) and 0.5 % (w/v) glucose as the carbon source. This medium was supplemented with...
l-tryptophan (20 mg l⁻¹) and l-phenylalanine (18 mg l⁻¹) to satisfy the auxotrophic requirements of the B. subtilis strains JH642 (trpC2 pheA1) and 168 (trpC2), and their mutant derivatives (Table 1). NaCl from a 5 M stock solution was used to increase the osmolarity of the SMM growth medium. When l-proline, N-methyl-l-proline, l-proline betaine, trans-4-hydroxy-l-proline and betonincine were used as sole carbon sources, they were added to SMM at concentrations of 33, 28, 24, 33 and 24 mM, respectively. These concentrations were equivalent in carbon content to 28 mM glucose that was used as a control in the growth assays. The ammonium source ([NH₄]₂SO₄ (15 mM)] present in SMM was replaced by 30 mM of the various l-proline derivatives to test their use as sole nitrogen source. The use of l-proline and its derivatives as nutritions by B. subtilis was assessed by measuring the OD₅₇₈ of the cultures in a spectrophotometer after 20 h of incubation of the cultures at 37 °C in a shaking water bath. For growth experiments assessing the osmostress protective potential of l-proline and its various derivatives, cultures were pre-grown in SMM at 37 °C and then used to inoculate 20 ml SMM (in a 100 ml Erlenmeyer flask containing 1.2 M NaCl to an OD₅₇₈ ~0.1; the cultures were grown at 37 °C in a shaking water bath set to 220 r.p.m.). Pre-cultures of strains used for temperature stress experiments were grown at 37 °C until they reached mid-exponential growth phase (OD₅₇₈ 2.5), the cells were harvested by centrifugation and the supernatant was used containing centrifugation with the solutes were extracted with 20 ml 80% (v/v) ethanol as described previously (Kuhlmann & Bremer, 2002). Cellular debris was removed by centrifugation at 25 000 g at 4 °C for 30 min; the supernatant was lyophilized to dryness. For natural abundance NMR measurements, the dried samples were dissolved in 0.6 ml D₂O together with 3 mg D₄-3-(trimethylsilyl) propionate as an internal standard. ¹³C-NMR spectra (125 MHz) were recorded on a Bruker Avance 500 MHz NMR spectrometer equipped with a 5 mm BBFO probe; the spectra were processed with the program Topspin 3.1 (Bruker). To verify resonance signals for l-proline betaine and betonincine in the cell extracts, we recorded ¹³C-NMR spectra on authentic samples of l-proline betaine and betonincine under conditions identical to those used to assess the total cell extracts. ¹³C chemical shifts of individual compounds were referenced with respect to the signal of the internal standard D₄-3-(trimethylsilyl) propionate.

### Measurements of Intracellular Proline Pools
To determine the pool size of de novo synthesized l-proline in osmotically stressed cells (Brill et al., 2011a; Hoffmann et al., 2013), we grew the B. subtilis cultures in SMM that contained 1.2 M NaCl in the absence or presence of various compatible solutes until they reached an OD₅₇₈ ~1.7. We then used a colorimetric assay that detected proline as a coloured proline-ninhydrin complex, which could be quantified by measuring absorbance of the solution in a spectrophotometer. Harvesting of the cells, their processing for the l-proline assay and the specific of the calculation of the intracellular volume of B. subtilis cells have all been described previously (Hoffmann et al., 2012, 2013).

### Preparation of cell extracts for ¹³C-NMR spectroscopy
The B. subtilis mutant strain JSB8 [Δ(profH::tet)] (Table 1) was grown in SMM (culture volume of 600 ml in a 1 l Erlenmeyer flask) containing 1.2 M NaCl in the absence or presence of 1 mM (final concentration) l-proline betaine or betonincine. After the cultures reached late exponential growth phase (OD₅₇₈ 2.5), the cells were harvested by centrifugation and the solutes were extracted with 20 ml 80% (v/v) ethanol as described previously (Kuhlmann & Bremer, 2002). Cellular debris was removed by centrifugation at 25 000 g at 4 °C for 30 min; the supernatant was lyophilized to dryness. For natural abundance NMR measurements, the dried samples were dissolved in 0.6 ml D₂O together with 3 mg D₄-3-(trimethylsilyl) propionate as an internal standard. ¹³C-NMR spectra (125 MHz) were recorded on a Bruker Avance 500 MHz NMR spectrometer equipped with a 5 mm BBFO probe; the spectra were processed with the program Topspin 3.1 (Bruker). To verify resonance signals for l-proline betaine and betonincine in the cell extracts, we recorded ¹³C-NMR spectra on authentic samples of l-proline betaine and betonincine under conditions identical to those used to assess the total cell extracts. ¹³C chemical shifts of individual compounds were referenced with respect to the signal of the internal standard D₄-3-(trimethylsilyl) propionate.

### Measurements of TreA enzyme activity in putB–treA and opuA–treA reporter fusion strains
In the putB–treA and opuA–treA reporter gene fusion strains, a promoterless treA gene was fused to the proline-responsive regulatory region of the catabolic putBCP operon (Moses et al., 2012) and the osmostress responsive promoter of the opuA operon (Hoffmann et al., 2013). These fusions were stably inserted into the B. subtilis chromosome as a single copy via a double recombination event in the non-essential amyE gene. The details of the growth of the reporter fusion strains, the processing of the cells, the TreA enzyme assay using the chromogenic PNPG as the substrate and the calculation of the TreA enzyme specific activity have all been described previously (Hoffmann et al., 2013; Moses et al., 2012). One unit of TreA enzyme activity is defined as 1 μmol PNPG converted min⁻¹.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Relevant genotype</th>
<th>Source* or reference</th>
</tr>
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<tbody>
<tr>
<td>JH642</td>
<td>trpC2 pheA1</td>
<td>J. Hoch; BGSC 1A96</td>
</tr>
<tr>
<td>168</td>
<td>trpC2</td>
<td>BGSC 1A1</td>
</tr>
<tr>
<td>RMKB20</td>
<td>Δ(opuA::erm)4 opuC20::Tn10(sp) Δ(opuD::neo)2</td>
<td>Kappes et al. (1996)</td>
</tr>
<tr>
<td>RMKB22</td>
<td>Δ(opuA::erm)4 opuBD-20::Tn10(sp) Δ(opuD::neo)2</td>
<td>Kappes et al. (1996)</td>
</tr>
<tr>
<td>RMKB24</td>
<td>Δ(opuA::erm)4 Δ(opuBD::tet)23 opuC20::Tn10(sp)Δ(opuD::neo)2</td>
<td>Kappes et al. (1996)</td>
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<td>RMKB27</td>
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<td>R. Kappes, University of Marburg, Germany</td>
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<tr>
<td>RMKB33</td>
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<td>RMKB34</td>
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<td>Kappes et al. (1996)</td>
</tr>
<tr>
<td>JGB23</td>
<td>16Δ(opuA::erm)4 Δ(opuBD::tet)23 opuC20::Tn10(sp)Δ(opuD::neo)2</td>
<td>Hoffmann &amp; Bremer (2011)</td>
</tr>
<tr>
<td>JGB24</td>
<td>16Δ(opuA::erm)4 Δ(opuBD::tet)23 opuBD::tet23 Δ(opuD::neo)2</td>
<td>Hoffmann &amp; Bremer (2011)</td>
</tr>
<tr>
<td>JGB25</td>
<td>16Δ(opuBD::tet)23 opuC20::Tn10(sp)Δ(opuD::neo)2</td>
<td>Hoffmann &amp; Bremer (2011)</td>
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<tr>
<td>JGB26</td>
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<td>Hoffmann &amp; Bremer (2011)</td>
</tr>
<tr>
<td>JGB27</td>
<td>16Δ(opuA::erm)4 Δ(opuBD::tet)23 opuC20::Tn10(sp)Δ(opuD::neo)2</td>
<td>Hoffmann &amp; Bremer (2011)</td>
</tr>
<tr>
<td>JSB8</td>
<td>Δ(profH::tet)1</td>
<td>Brill et al. (2011b)</td>
</tr>
<tr>
<td>SMB10</td>
<td>JH642 amyE::Δ[putB–treA] A cat] (treA::neo)1</td>
<td>(Moses et al., 2012)</td>
</tr>
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</table>

*BGSC, Bacillus Genetic Stock Center (Columbus, OH, USA).
Overexpression, purification and ligand-binding assays with the OpuAC solute receptor protein. Plasmid pMH24 (opuAC+) was a derivative of the expression plasmid pASK-IBA6 (IBA), and it allowed the expression of the recombinant opuAC gene under the control of the TetR-responsive and AHT-inducible tet promoter present on the backbone of the expression plasmid. Overproduction and purification of the recombinant OpuAC protein by affinity chromatography were carried out in the E. coli B strain BL21 as described previously (Bashir et al., 2014; Smits et al., 2008). The affinities of the OpuAC protein for its ligands glycine betaine, L-proline betaine and betonicine were measured by fluorescence spectroscopy, based on a ligand-binding assay that exploited changes in the intrinsic tryptophan fluorescence of the OpuAC protein upon substrate binding (Horn et al., 2006; Smits et al., 2008). A Cary Eclipse fluorescence spectrometer (Varian) was used for these experiments. The fluorescence spectrum of OpuAC and its changes incurred upon ligand binding were monitored at wavelengths between 300 and 400 nm. Ligand-binding assays were conducted at 22.5 °C in a buffer solution containing 10 mM Tris/HCl (pH 7.0) and 10 mM NaCl. The concentration of the OpuAC protein in the assay was 1 μM, and the concentration of the ligands glycine betaine, L-proline betaine and betonicine was varied between 10 and 1000 μM. Michaelis–Menten kinetics were deduced by comparing the maximum fluorescence intensities in the absence and presence of various ligand concentrations as described previously (Smits et al., 2008). The corresponding fluorescence intensity maxima of the OpuAC protein were at 336–343, 340–346 and 344–348 nm for the glycine betaine, L-proline betaine and betonicine ligands, respectively. Analysis and fitting of the spectrophotometric data were performed using Prism 5 software (GraphPad).

In silico docking of betonicine into the ligand-binding site of the OpuAC protein. The experimentally determined crystal structure of the OpuAC–L-proline betaine complex at 2.8 Å resolution [ Protein Database (PDB) ID: 2B4M (Horn et al., 2006) ] was chosen as the starting point for in silico modelling of the OpuAC–betonicine complex. We first exchanged in silico the ligand in the available crystal structure by a betonicine molecule – a process that only involved the substitution of a hydrogen atom at position C-4 in the L-proline ring by a hydroxyl group (Fig. 1). This in silico generated OpuAC–betonicine model was then refined against the structure factors of the experimentally determined OpuAC–L-proline betaine complex (Horn et al., 2006) using the programs COOT (Emsley & Cowtan, 2004) and REFMAC (Murshudov et al., 1997) to define the bond length and angle of the placed betonicine ligand with the in silico model. Contacts of the betonicine ligand with the OpuAC binding protein were manually analysed and considered with a distance range of 2.8–3.5 Å.

Preparation of figures of crystal structures. Figures of the crystal structure of the OpuAC–L-proline betaine complex (Horn et al., 2006) and of the in silico generated model for the OpuAC–betonicine complex generated in this study were prepared using the PyMOL software package (http://www.pymol.org).

RESULTS

Assessing the use of proline derivatives as nutrients and their influence on the expression of proline catabolic genes

L-Proline can be used as a sole carbon, energy and nitrogen source by B. subtilis (Moses et al., 2012). We tested whether the L-proline derivatives N-methyl-L-proline, L-proline betaine, trans-4-hydroxy-L-proline and betonicine (Fig. 1) could be used by B. subtilis as nutrients, either as sole carbon or as sole nitrogen sources. We also tested the potential use of these compounds as nutrients under high salinity (0.6 M NaCl) growth conditions as we considered the possibility that their uptake would be stimulated by increased osmolality of the growth medium (Moses et al., 2012; von Blohn et al., 1997; Zaprasis et al., 2014). Catabolic routes for trans-4-hydroxy-L-proline, L-proline betaine and betonicine have been identified in a variety of micro-organisms (Kumar et al., 2014; Watanabe et al., 2012; White et al., 2012; Zhao et al., 2013), but we found that B. subtilis cannot use any of the studied L-proline derivatives as nutrients (Fig. 2).

The presence of low concentrations of L-proline in the growth medium induces the expression of the catabolic putBCP operon in a fashion that is dependent on the L-proline-responsive activator protein PutR (Belitsky, 2011; Huang et al., 2011; Moses et al., 2012). To test a possible influence of the various L-proline derivatives on the expression of the putBCP catabolic operon, we used a putB–treA reporter strain in which the production of the TreA reporter enzyme was under the control of the L-proline-responsive PutR activator protein (Belitsky, 2011; Huang et al., 2011; Moses et al., 2012). Except for L-proline, none of the tested proline derivatives triggered enhanced putB–treA expression in cells that had been grown in SMM (Table 2). However, when the salinity of the growth medium was raised with 0.6 M NaCl, L-proline betaine significantly increased putB–treA transcription, whereas N-methyl-L-proline, trans-4-hydroxy-L-proline and betonicine did not cause such an effect (Table 2). Natural abundance 13C-NMR spectroscopy of salt-stressed cells (with 1.2 M NaCl) proved that externally provided L-proline betaine was accumulated by B. subtilis in unmodified form (see below). Hence, L-proline betaine served as a gratuitous inducer for the putBCP L-proline catabolic operon (Moses et al., 2012); we surmised that this effect was mediated through PutR.

Osmostress protection by proline derivatives

Next, we tested the ability of N-methyl-L-proline, trans-4-hydroxy-L-proline, L-proline betaine and betonicine to serve as osmoprotectants for B. subtilis. We benchmarked their performance against that of exogenously provided L-proline and glycine betaine (Boch et al., 1994; von Blohn et al., 1997; Zaprasis et al., 2013). High salinity severely inhibited the growth of B. subtilis in a chemically defined medium (SMM) with 1.2 M NaCl, and both glycine betaine and L-proline exerted osmoprotective effects on cell growth, with glycine betaine being the better osmoprotectant than L-proline (Fig. 3a). L-Proline betaine was about as effective as glycine betaine in relieving osmotic stress, whereas the osmoprotective potential of betonicine resembled that of L-proline (Fig. 3a). In contrast, N-methyl-L-proline and trans-4-hydroxy-L-proline did not serve as osmoprotectants (Fig. 3a). Hence, small differences in the chemical structure of the L-proline derivatives (Fig. 1) could...
make a big difference with respect to their stress-protective function for high-salinity-challenged B. subtilis cells. We also tested the osmoprotective potential of the D-stereoisomer of proline, but D-proline was not osmoprotective for B. subtilis, and neither were the synthetic L-proline derivatives trans-4-fluoro-L-proline and cis-4-fluoro-L-proline (Fig. S1, available in the online Supplementary Material).

Detection of intracellular L-proline betaine and betonicine in osmotically stressed cells by \(^{13}\text{C}-\text{NMR spectroscopy}\)

Natural abundance \(^{13}\text{C}-\text{NMR}\) spectroscopy can be used to detect the dominant compatible solutes accumulated by osmotically stressed cells (Kuhlmann & Bremer, 2002). We used this technique to assess the presence of L-proline betaine and betonicine in B. subtilis cells grown in SMM with 1.2 M NaCl. We used a mutant strain that was unable to synthesize osmoprotective levels of L-proline for these experiments (Brill et al., 2011a) in order to reduce the complexity of the NMR signals from the cell extracts. Both L-proline betaine and betonicine were readily detected in the cell extracts, and the NMR traces showed that they were present in an unmodified form (Fig. 4). Although these experiments could not be interpreted quantitatively, they showed that L-proline betaine and betonicine were accumulated from the medium by osmotically stressed B. subtilis cells as main organic osmolytes.

Genetic identification of the uptake systems mediating L-proline betaine and betonicine import

As both L-proline betaine and betonicine conferred osmostress protection (Fig. 3a), we asked which compatible solute uptake systems of B. subtilis (Bremer, 2002) were used for their import. We used a genetically well-characterized set of mutant strains for this experiment in which only one of the known compatible solute uptake systems (Opu) of B. subtilis (Table 1) was functional (Hoffmann & Bremer, 2011). Growth of these strains in high-salinity medium (with 1.2 M NaCl) in the absence or presence (1 mM) of L-proline betaine and betonicine revealed that L-proline betaine was imported via the two ATP-binding cassette (ABC) transporters OpuA and OpuC, and through the betaine-choline-carnitine-transporter-type import system OpuD (Fig. S2). However, betonicine was only taken up via the OpuA and OpuC systems (Fig. S2).

Influence of L-proline betaine and betonicine on the osmostress-adaptive L-proline pool

The size of the L-proline pool formed by B. subtilis through de novo synthesis is sensitively tied to the severity of the imposed osmotic stress (Brill et al., 2011a; Hoffmann et al., 2013; Whatmore et al., 1990). Notably, an exogenous supply of the potent osmoprotectant glycine betaine (Boch et al., 1994) strongly downregulates the pool size...
The B. subtilis putB–treA fusion strain SMB10 (Table 1) was grown in SMM with the indicated salinity. When the cultures reached the early exponential growth phase (OD$_{578}$ 0.3–0.5), various compatible solutes (final concentration 1 mM) were added, growth of the cells was allowed for an additional 1 h and the cells were then processed for TreA enzyme activity assays.

<table>
<thead>
<tr>
<th>Compatible solute</th>
<th>TreA activity [U (mg protein)$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without NaCl</td>
</tr>
<tr>
<td>Without</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>l-Proline</td>
<td>120 ± 3</td>
</tr>
<tr>
<td>N-Methyl-l-proline</td>
<td>13 ± 2</td>
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<tr>
<td>l-Proline betaine</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>Trans-4-hydroxy-l-proline</td>
<td>5 ± 1</td>
</tr>
<tr>
<td>Betonicine</td>
<td>5 ± 1</td>
</tr>
</tbody>
</table>

of l-proline in osmotically stressed cells (Hoffmann et al., 2013). We therefore wondered whether l-proline betaine and betonicine would confer a similar effect. B. subtilis cells grown in SMM with 1.2 M NaCl contained an intracellular l-proline pool of ~560 mM (Fig. 3b). Titration of the concentrations of either glycine betaine or l-proline betaine in the growth medium successively decreased the l-proline pool (Fig. 3b). When either one of these compounds was present in the medium at a concentration of 1 mM, the l-proline pool was reduced to a value (18 mM) found in osmotically non-stressed B. subtilis cells (Hoffmann et al., 2013; Whatmore et al., 1990). However, betonicine influenced the l-proline content of the osmotically stressed cells only modestly (Fig. 3b).

Modulation of opuA gene expression by l-proline betaine and betonicine

The uptake of glycine betaine downregulates the expression of osmotically induced genes in B. subtilis on a genome-wide scale (Kohlstedt et al., 2014). We therefore asked if this would also be the case for l-proline betaine and betonicine, and tested this by using an opuA–treA promoter fusion as a read-out – a reporter system that responds to both osmotic stress and the presence of various types of compatible solutes (Bashir et al., 2014; Hoffmann et al., 2013; Kempf & Bremer, 1995). The sustained increase in opuA promoter activity in response to continued increases in salinity was reduced strongly by glycine betaine, carnitine and l-proline betaine, whereas betonicine downregulated the expression of the reporter fusion to a much lower extent (Fig. 5). The presence of compatible solutes in the growth medium also affected the non-induced level of opuA–treA expression; opuA transcription remained salt-inducible, albeit at a much lower level, even in the presence of the tested compatible solutes (Fig. 5). There was an approximately ninefold osmotic induction in the expression level of the reporter fusion in cells grown in the absence of a compatible solute, and similar values of induction were found in cells grown in the presence of glycine betaine (fivefold), l-proline betaine (sevenfold), betonicine (12-fold) and carnitine (eightfold) (Fig. 5). Hence, these data support the previous conclusion that the activity of the opuA promoter was responsive to both an increase in the external salinity and the intracellular compatible solute pool (Hoffmann et al., 2013).
Heat and cold stress protection by L-proline betaine and betonicine

Previous studies have shown that most of the compatible solutes conferring cellular protection to \textit{B. subtilis} cells against high osmolarity (Bremer, 2002) also serve as protectants against extremes in either high or low growth temperatures (Hoffmann & Bremer, 2011; Holtmann & Bremer, 2004). The beneficial effects of the uptake of these solutes become most notable at the very edges of the upper (52–52.2 °C) and lower (13 °C) boundaries of growth. We found that betonicine was a very good heat stress protectant at 52 °C, with a degree of effectiveness that matched that of glycine betaine; in contrast, L-proline betaine exhibited no heat stress protection (Fig. 6a). Heat adaptation of the cells was improved to an extent that the lag phase of the culture was shortened for ~3 h by betonicine and 4.5 h by glycine betaine (Fig. 6a). At 52.2 °C, a temperature at which the \textit{B. subtilis} WT laboratory strain JH642 could no longer grow in a chemically defined medium (Fig. 6b), betonicine still afforded cell growth, but it was much less effective than glycine betaine (Fig. 6b). Uptake of betonicine under heat stress conditions (52 °C) was mediated primarily by the OpuA ABC transporter, whereas each of the glycine betaine uptake systems (OpuA, OpuC and OpuD) of \textit{B. subtilis} (Kappes et al., 1996) contributed to the import of glycine betaine in high-temperature-challenged cells (Fig. S3a).

When we tested the cold stress protection potential of betonicine and L-proline betaine, we found that L-proline betaine was an excellent cold protectant at a growth temperature of 13 °C, with effectiveness similar to that of glycine betaine. In contrast, betonicine did not confer cold stress protection (Fig. 6c). Under sustained cold stress growth conditions, OpuA served as the major uptake system for betonicine (Fig. S3b).

\textbf{Heat and cold stress protection by L-proline betaine and betonicine}
The three glycine betaine transporters operating in *B. subtilis* all possess a high affinity for their substrate with $K_m$ values in the low micromolar range. However, the OpuA system dominates glycine betaine import due to its high capacity ($V_{max}$) (Kappes et al., 1996). This property is probably also the reason why L-proline betaine and betonicine were imported primarily via the OpuA system under temperature stress conditions (Fig. S3). The functionality and substrate specificity of the OpuA transporter are dependent on an extracellular ligand-binding protein (OpuAC) tethered with a lipid anchor to the cytoplasmic membrane of *B. subtilis* (Horn et al., 2006; Kempf & Bremer, 1995).

We overexpressed a recombinant version of the *B. subtilis* OpuAC protein in *E. coli* and purified it to apparent homogeneity using previously described procedures (Bashir et al., 2014; Smits et al., 2008). Ligand binding by OpuAC is reflected by changes in the intrinsic Trp fluorescence and these changes can be used to quantify the affinity of the OpuAC protein for its various ligands (Bashir et al., 2014; Horn et al., 2006; Smits et al., 2008). Ligand binding of glycine betaine and L-proline betaine by OpuAC resulted in an increase in the fluorescence intensity (Smits et al., 2008), whereas the newly tested betonicine caused a decrease. Using fluorescence spectroscopy, we measured the stability constant ($K_d$) of OpuAC–ligand complexes, and $K_d$ values of $38 \pm 3$, $135 \pm 23$ and $324 \pm 65$ nM were obtained for glycine betaine, betonicine and L-proline betaine, respectively (Fig. 7). The $K_d$ values for glycine betaine (Fig. 7a) and L-proline betaine (Fig. 7b) agreed quite well with previous measurements (Horn et al., 2006), whereas that of betonicine (Fig. 7c) had not been determined previously.

**In silico docking of betonicine into the OpuAC ligand-binding site**

Crystal structures of OpuAC in complex with either glycine betaine (PDB ID: 2B4L) or L-proline betaine (PDB ID: 2B4M) have been reported (Horn et al., 2006), and the observed contacts between these ligands and the OpuAC protein have been buttressed via site-directed mutagenesis experiments (Smits et al., 2008). As L-proline betaine and betonicine are chemically closely related (Fig. 1), we were able to use the crystal structure of the OpuAC–L-proline betaine complex (Fig. 8a) as a template for *in silico* modelling studies. The aim of this modelling approach was to (i) reveal the likely position of betonicine within the OpuAC ligand-binding pocket and (ii) understand the molecular underpinnings for the somewhat higher affinity of OpuAC for betonicine in comparison with the non-hydroxylated L-proline betaine (Fig. 1).

In our *in silico* model, the betonicine ligand fitted well into the binding pocket of the OpuAC protein, with a spatial orientation that was comparable with the L-proline betaine molecule (Fig. 8). As observed in the crystal structures of the OpuAC–glycine betaine and OpuAC–L-proline betaine complexes (Horn et al., 2006), the positively charged head group of betonicine resides in...
an aromatic cage created by the side-chains of three Trp residues and is stabilized via cation–π interactions (Trp72, Trp178 and Trp252) (Horn et al., 2006). To accommodate the hydroxyl group at position C-4 within the L-proline ring of betonicine (Fig. 1), our model suggests that this ligand is slightly rotated in comparison with the position of L-proline betaine within the ligand-binding site (Fig. 8). This rotational movement by ~20° is needed to firmly accommodate the positively charged dimethlyammonium head group as well as the negatively charged hydroxyl group of betonicine within the OpuAC ligand-binding site. As a further result of this slight rotational movement, the hydroxyl group of betonicine was now able to interact with the positively charged nitrogen in the ring of the Trp178 side-chain and the carboxylate of betonicine could interact with the backbone amide groups of Gly26. Further contacts were via electrostatic interactions with the side-chain of His230. This latter protein–ligand interaction has also been observed in the OpuAC–glycine betaine complex and is a key determinant for the higher affinity of OpuAC for glycine betaine than for L-proline betaine (Horn et al., 2006; Smits et al., 2008). Taken together, the interaction of the hydroxyl group of betonicine at position C-4 in the proline ring structure, as well as the additional interaction of its carboxyl group with the side-chain of His230, not only compensated for the loss of the interaction with the backbone of Ile27 (Fig. 8), but also fostered stronger interactions of the ligand with the OpuAC protein. Our in silico model thus provided an explanation for the experimentally observed two- to threefold higher binding affinity of OpuAC for betonicine ($K_d = 135 \pm 23 \mu M$) in comparison with L-proline betaine ($K_d = 324 \pm 65 \mu M$).

**DISCUSSION**

The soil-dwelling bacterium *B. subtilis* lives in a challenging habitat in which desiccation processes lead to increases in the environmental osmolarity (Bremer, 2002). Organic matter, including compatible solutes, is primarily brought into the soil via root exudates and decaying plant tissues

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**Fig. 7.** Binding of glycine betaine, L-proline betaine and betonicine by the OpuAC solute receptor protein. Ligand binding by OpuAC is reflected by corresponding changes in the maximal intensity of the intrinsic Trp fluorescence of this protein; the extent of these changes ($\Delta$ intensity) is dependent on the ligand concentration (Horn et al., 2006; Smits et al., 2008) and was used to determine the affinity of the OpuAC protein to its ligand ($K_d$). The Michaelis–Menten fittings for OpuAC binding to (a) glycine betaine, (b) L-proline betaine and (c) betonicine are shown.

**Fig. 8.** Coordination of L-proline betaine and betonicine within the ligand-binding site of the OpuAC solute receptor protein. (a) The structural data for the OpuAC–L-proline betaine complex were taken from the PDB database (PDB ID: 2B4M) (Horn et al., 2006). (b) In silico model for the OpuAC–betonicine complex.
The release of newly synthesized osmo-protectants by osmotically down-shocked or decayed microbial cells is also a key contributor to the compatible solute cocktail found in the soil (Warren, 2013, 2014). Consequently, the uptake of compatible solutes provides soil micro-organisms such as *B. subtilis* with the opportunity to derive protection against osmotic (Bremer, 2002; Kappes et al., 1999) or temperature challenges (Hoffmann & Bremer, 2011; Holtmann & Bremer, 2004). The data presented here add the OpuA/OpuC/(OpuD)-mediated uptake of the plant-derived l-proline derivatives l-proline betaine and betonicine (Hanson et al., 1994; Rhodes & Hanson, 1993) to the physiological defence arsenal of *B. subtilis* against high salinity and growth-restricting extremes in temperatures (Bremer, 2002; Hoffmann & Bremer, 2011; Holtmann & Bremer, 2004). In contrast to l-proline (Moses et al., 2012), l-proline betaine and betonicine cannot be catabolized by this soil bacterium (Fig. 2), regardless of the fact that l-proline betaine can serve as an inducer (Table 2) for the l-proline catabolic putBCP operon (Moses et al., 2012).

Despite the close chemical relatedness of l-proline betaine and betonicine to l-proline (Fig. 1), both compounds are not imported through OpuE – the dominating uptake system for l-proline when it is acquired by *B. subtilis* as an osmoprotectant (von Blohn et al., 1997; Zaprasis et al., 2013). Instead, l-proline betaine and betonicine are taken up by transporters mediating the uptake of various di- or trimethylated osmoprotectants, OpuA/OpuC/(OpuD) (Bremer, 2002; Hoffmann & Bremer, 2011). Crystallographic analysis has revealed that cation–π interactions between the fully methylated and positively charged head group of l-proline betaine (Fig. 1) and the side-chains of aromatic residues present in the OpuAC proteins from *B. subtilis* (Horn et al., 2006; Smits et al., 2008) and *Lactococcus lactis* (Wolters et al., 2010), and the ProX proteins from *E. coli* (Schiefner et al., 2004a) and the archaeon *Archaeoglobus fulgidus* (Schiefner et al., 2004b), are key contributors to ligand binding. Our modelling study of the OpuAC–betonicine complex suggests that such an aromatic cage is also involved in the recognition and capturing of this ligand by the OpuAC substrate-binding protein (Fig. 8b). Furthermore, this *in silico* model provides hints as to why OpuAC can bind betonicine with a higher affinity than l-proline betaine (Fig. 7).

The level of osmoprotection afforded by l-proline betaine is similar to that of glycine betaine, whereas that conferred by betonicine is more modest and resembles that of l-proline. A correlation seems to exist between the osmoprotective effects of these solutes (Fig. 3a) and their influence on (i) the size of the l-proline pool build-up through *de novo* synthesis (Fig. 3b) and (ii) the transcriptional activity of the osmotically controlled opuA promoter (Fig. 5). This set of data can most easily be interpreted within the physiological context of osmotically stressed *B. subtilis* cells (Bremer, 2002) if we assume that the Opu-mediated uptake processes attain an intracellular betonicine pool smaller than that of l-proline betaine. However, such presumed differences in the pool sizes of these compounds remain to be verified experimentally. Factors other than the actual intracellular concentrations of l-proline betaine and betonicine also need to be taken into account when assessing the data. The physico-chemical properties of these solutes, their influence on the functional-ity of macromolecules, the transcriptional machinery of the cell and the solvation status of the cytoplasm might be sufficiently dissimilar to cause different physiological effects with respect to cell growth under osmotically challenging conditions (Cayley et al., 1992; Jackson-Atogi et al., 2013; Street et al., 2006; Wood, 2011).

*B. subtilis* adapts to decreases or increases in temperatures suboptimal for growth by inducing a set of complex stress management systems, e.g. cold-shock and heat-shock proteins, the induction of the SigB-controlled general stress response system, and the production of a lipid-modifying enzyme that prevents the rigidification of the cytoplasmic membrane at low temperature (Budde et al., 2006; Graumann & Marahiel, 1996; Hecker et al., 2007; Martin & de Mendoza, 2013; Schumann, 2003). All these well-studied temperature stress response systems fail completely to ensure growth at the very cutting upper (52–53 °C) and lower (11–13 °C) boundaries of the temperature spectrum that *B. subtilis* cells can populate. Remarkably, for temperature-challenged cells tinkering with death, the uptake of compatible solutes permits cell proliferation (Bashir et al., 2014; Hoffmann & Bremer, 2011; Holtmann & Bremer, 2004). The molecular and biochemical underpinning(s) of this type of temperature stress protection are far from clear (for a discussion of this issue, see Hoffmann & Bremer, 2011), but studies with glycine betaine have shown that the intracellular concentrations required for *B. subtilis* to sustain growth at very high or very low temperatures (Hoffmann & Bremer, 2011; Holtmann & Bremer, 2004) are far lower than those needed to achieve osmoprotection at high salinity (Hoffmann et al., 2013). Hence, it seems possible that the temperature stress protection afforded by l-proline betaine and betonicine is rooted in the physico-chemical properties of these molecules (Cayley et al., 1992; Jackson-Atogi et al., 2013; Street et al., 2006) and the ensuing chemical chaperone function of compatible solutes that preserves the functionality of macromolecules and biosynthetic processes (Bourot et al., 2000; Chattopadhyay et al., 2004; Diamant et al., 2001; Fisher, 2006; Ignatova & Giersch, 2006; Jackson-Atogi & Giersch, 2006; Jackson-Atogi et al., 2013; Manzanera et al., 2002). The chemical differences between l-proline betaine and betonicine appear to be rather minor (Fig. 1), but their stress-protective activities at high and low growth temperatures are strikingly different (Fig. 6). Unless these disparate physiological effects are rooted in different steady-state intracellular pool sizes that result from a different efficiency in l-proline betaine and betonicine import, it will be a challenge to understand in biophysical and molecular terms the foundation(s) for their dissimilar cell-protective properties. Collectively, the data presented here highlight the
notion that small differences in the chemical structure of a given compatible solute can make a big difference with respect to its physiological properties for a given micro-organism.

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